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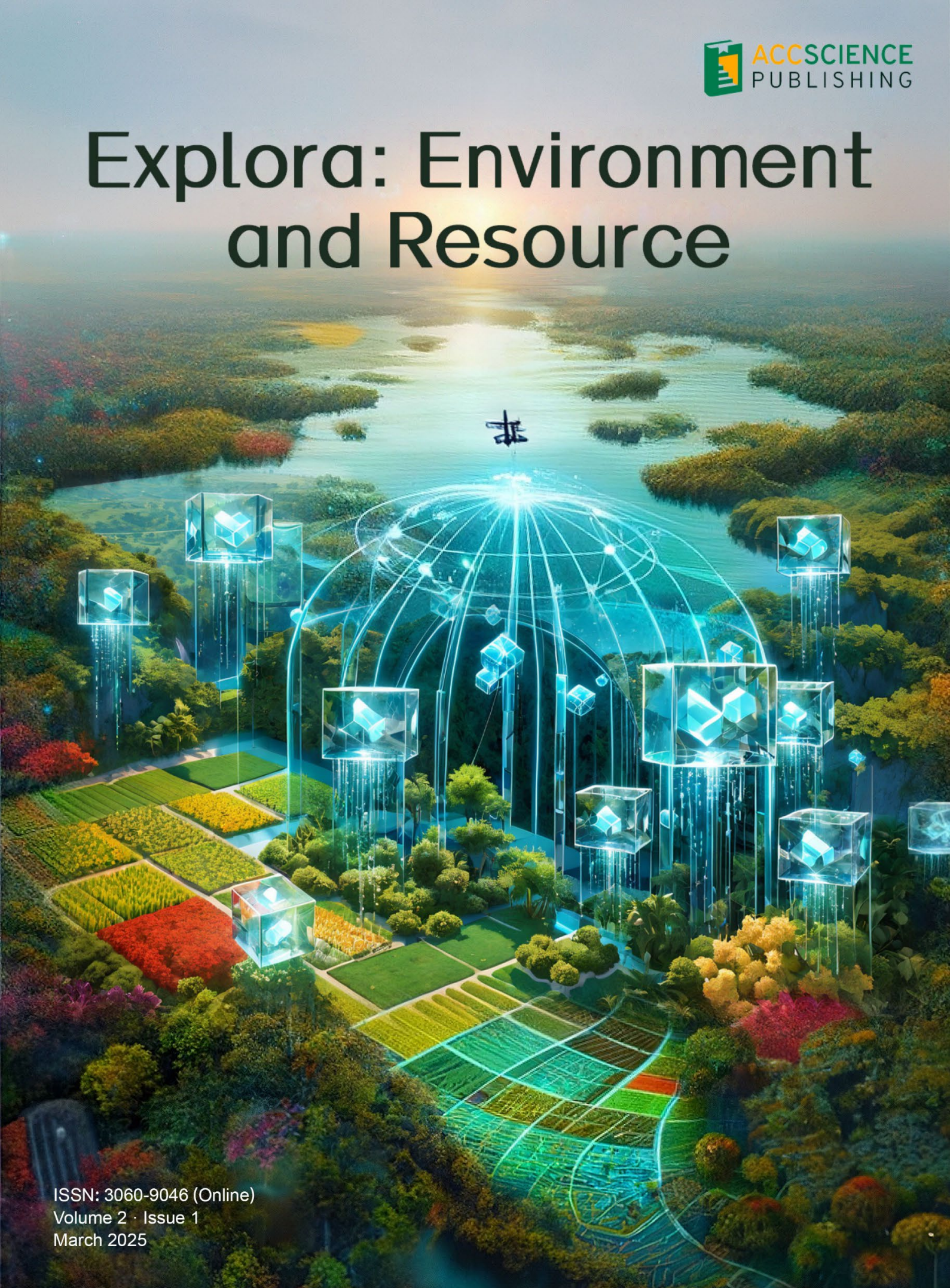

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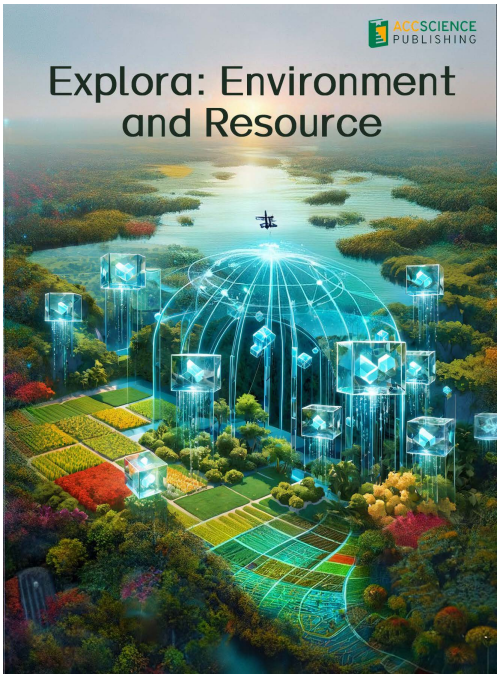

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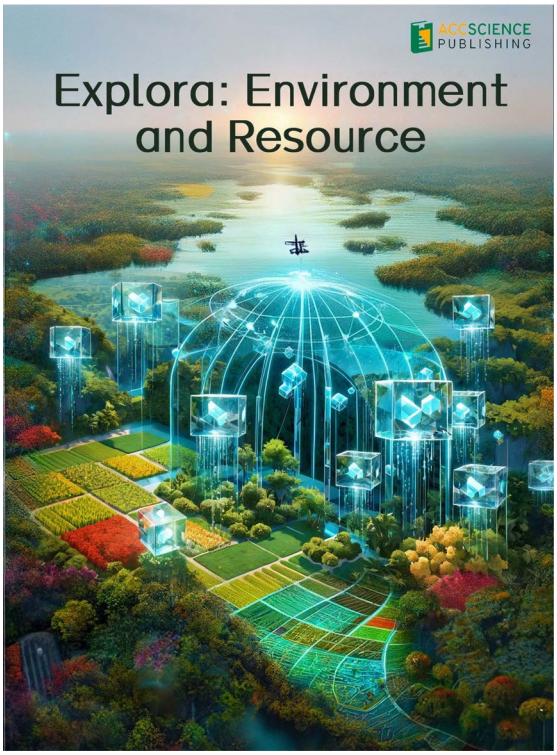

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REVIEW ARTICLE

Prioritizing scientific data over expert opinion in the valid assessment of Australian *Acacia* biocontrol success

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Abstract

Invasive species are such a pervasive problem that, in many cases, the management of this global change driver appears close to impossible. Biological control using natural enemies from these invasive species' native ranges is an attractive option to restore the balance in the invaded environment. The biological control of Australian *Acacia* spp. in South Africa is a lauded example of textbook biological control of invasive species management. However, we propose that this apparent success of biological control agents in reducing population levels of the alien trees is largely unfounded, as it is not based on ecological data but rather on scientific assumptions by experts. We argue that the fundamental question, "Does biocontrol reduce the impact of invasive tree populations?" is not being asked. Instead, the onus is on researchers to prove that biological control agents do not work. If experts act as reviewers for work that shows the contrary to their expert opinion, we have a potential conflict of interest. The result of this dispute is that contrary empirical data are slow to enter the policy decision-making sphere. The status quo of producing policy recommendations to manage biological invasions is based on expert opinion from the scientists who released the biocontrol agents. We propose that an overhaul of this approach is urgently needed. The scientific burden of proof should not be on whether biocontrol agents are not effective but rather on whether they are effectively reducing the impacts of the host plant. Any corrective management to solve environmental problems should be based on open, multidisciplinary science that provides the necessary supporting evidence. Our case study on biological control of Australian *Acacia* spp. is an illustrative example of why scientific data should guide decision-making for sustainable environmental management.

Keywords: Invasive species; Classical biological control; *Acacia*; Seed-reducing agents

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1. Introduction

Invasive species are such a pervasive problem that, in many cases, the management of this global change driver appears close to impossible.[1,2] Biological control ("biocontrol")

using natural enemies from these invasive species' native ranges is an attractive option to reduce the effect of alien plants in the invaded environment.[3,4] South Africa is a world leader in the biocontrol of weeds with extensive programs on a multitude of different plant species.[5,6] Among these programs is the biocontrol of Australian *Acacia* spp. using seed-reducing agents, which is lauded as a classic example of biocontrol of invasive species management.[7-12]

We propose that the purported success of the mostly gall-forming biocontrol agent programs on Australian *Acacia* spp. is largely unfounded, as it is not based on ecological data but rather on scientific assumptions by experts. In reality, these weeds continue to remain abundant and are still persisting and spreading in invaded ecosystems despite the long-term presence of their associated biocontrol agents.[13-16] We argue that the fundamental question, "Does introduction of host-specific biocontrol agents reduce the impact of the invasive plant population?" is not being asked. Instead, the onus is on researchers to prove that biocontrol agents do not work.

In the case of biocontrol of alien Australian *Acacia* spp. in South Africa, recent data support an unpopular finding that biocontrol agents have little or no effect in reducing the alien plant population levels and are not controlling the spread, density, or area of occupancy of the alien plants.[13-15] Furthermore, if expert biocontrol practitioners who are involved in the introduction process act as reviewers for work that shows contrary to their expert opinion, we have a potential conflict of interest. Such a system of knowledge creation is broken and can lead to misinformed policy decision-making. Importantly, as pre-agent release invasive plant population-level data are not canonically collected, there is a violation of the potentially powerful experimental approach that quantifies biocontrol agent impact. In addition, after agent establishment, studies quantifying the long-term success of the agent are warranted.[17-20] However, what has happened in the case of biocontrol of Australian *Acacia* spp. in South Africa is that expert opinion of biocontrol practitioners is used to qualitatively assess biocontrol success.[12,21,22] The result of doing this is that effective management is misconstrued, leading to the promotion of the so-called "success" of the biocontrol program despite being contrary to the actual data. Furthermore, of great concern is that this expert opinion process has fed into policy decision.[23]

Science progresses by testing hypotheses with data generated using accepted or defendable methods. To ensure rigor, such research requires peer-review, as such primary research papers are more important and reliable than conference proceedings, book chapters, and reviews. Here, we challenge the assertion that the biocontrol program of Australian *Acacia* spp. in South Africa is a success story that has benefited invasive management actions that are purported to be an exemplar for other countries experiencing similar *Acacia* invasions.

This critical review highlights the weak scientific base for the current perceptions, which have been based on the predominance of expert opinion in shaping environmental policy around the management of invasive plant species and motivation for government funding. We show here that: (1) there is very little primary data to support the contention that alien *Acacia* biocontrol agents are in reality effective; (2) the available empirical data support the opposite effect (*i.e.*, alien *Acacia* biocontrol are not effective); (3) the perception of non-biocontrol scientists that the invasive plants are under control is based largely on expert opinion; and (4) the willingness to believe such a success story in dealing with a global change problem influences the decision to release the same biocontrol agents in other countries. Furthermore, this specific field is so biased that to challenge the current paradigm that current biocontrol agents are effective, data are required to prove that biocontrol does not work and that this has delayed the proper use of the scientific method for several decades. In other words, there is belief without sufficient proof.

Here, we will show that despite the lauded success of the biocontrol program of Australian acacias, there is no evidence to support the claims that these agents have been successful in reducing the invasive impact of their target weeds. We also show how the application of scientific hypothesis testing is inherently wrongly applied. Regardless of whether the biocontrol agents have had any measurable positive impact, the burden of proof should not have to require data to show that biocontrol does not work. Proper application of the scientific method should entail collecting data that is statistically analyzed to prove that these agents do work. The assertions of expert opinion from biocontrol practitioners are not sufficient for testing the null hypothesis that biocontrol has no effect on the invasive impacts of Australian *Acacia* spp.

2. Context of invasive plant biological control

South Africa is one of the leading countries in the biocontrol of weeds (invasive plants).[5,6] Biological control of many invasive plant species is seen as a huge success.[5,6,12] This is based on the perceived reduced rate of spread, the extent of invasion, and management costs. Based on these benefits, it has been suggested that biocontrol should form part of any invasive plant management program.[5,6,12] One group in particular, the seed biocontrol of invasive Australian

acacias (wattles – *Acacia* spp.), is a lauded example of success,[10] which has been a major focus in invasive alien plant management in South Africa in terms of effort and funding.[12,24,25]

Management of invasive Australian *Acacia* spp. can potentially include any one or combination of biological, chemical, and mechanical controls.[25,26] Although all strategies are potentially viable depending on the *Acacia* species being managed, a preconceived bias exists toward using biocontrol as a management intervention. In this instance, the biocontrol program on invasive Australian *Acacia* spp. in South Africa has become a classic example of perceived success.[7-12]

The biocontrol program on invasive *Acacia* spp. in South Africa has widely been reported as successful over the past 34 years.[5-12,27] This program has included 17 seed-reducing biological control agents released on 10 invasive Australian *Acacia* spp. (Table 1). The reported success has been based on the qualitative assessment of the extensive control of these agents on their target species.[10] "Extensive" implies that damage levels are very high or the agents cause reduced plant survival, arrested plant growth, or minimal or even no production of seed.[10] This was later further qualified as "substantial" that means agents reduce the amount of effort and management to control the target weeds.[12] It has also been argued that the agents have impacted their host populations by reducing the area of occupancy, rate of spread, and management costs.[16,28-30]

Based on this perceived success described in the peer-reviewed literature, it has been argued that seed-reducing biocontrol agents are the most effective and practical means of managing these invasive plants.[27] Furthermore, and based on the success of these programs, it has been suggested that biocontrol should form an integral part of any invasive plant management program.[27] For example, Moran *et al.*[32,p.438] state the following: "*There is overwhelming evidence from the studies of biological control of invasive trees in South Africa that any reduction in seeding levels aids management. Agents that reduce seed production should always be in the front line of the attack (De Loach 1981). As a general principle in weed biological control, we advocate that agents that reduce seed production should take priority during the exploration phases and be amont the first agents released.*"

The reported success of the biocontrol program on invasive Australian *Acacia* spp. in South Africa has also stimulated motivation for the use of these agents in other parts of the world where these plants have become invasive.[25] Subsequently, these agents have been released in Portugal, Israel, and New Zealand.[31] Although an abundance of literature exists arguing for the success of the biocontrol program on invasive Australian *Acacia* spp., we argue the opposite based on a lack of quantitative data in the literature to support this qualitative notion. For a biocontrol program to be successful, the released biological control agent should reduce the area of occupancy and rate of spread of its host plant to such an extent that it has benefits for biodiversity, ecosystem functioning, or management (reduced costs).[19]

To properly test the asserted assumption that seed biocontrol agents have meaningfully reduced the reproductive potential and subsequent area of occupancy of Australian *Acacia* spp. in South Africa,[8,10,21,28] pre-release data available on seed set, germination rates, and recruitment to the reproductive population of trees over its full geographic extent of the invasion are needed. Failing this, collecting data in the core range of these species should be attempted. After agents are released and enough time has elapsed to facilitate establishment and autonomous spread, the same data should be collected again. However, due to a paucity of research with the aim of collecting this type of data,[28] such complete information has still not been collected in South Africa, despite new agents being released as recently as 2016 (Table 1).

A basic assessment of whether released biocontrol agents have been successful in reducing the area of occupancy or rate of spread of their host plants is to consider their distribution in their invaded range over time.[33] In general, there is a lack of adequate distributional and population data for all species on all relevant spatial scales to prove that the released biocontrol agents have caused a decline in the area of occupancy and rate of spread of their host plants. This is further exacerbated by available data having been collected and expressed in different ways over time.[30,33-35] However, with regard to available distributional data for the invasive Australian *Acacia* spp. in South Africa, there is no evidence that they have disappeared from any areas occupied before the release of their associated biocontrol agents or that their area of occupation has been reduced.[30,34-37] On the contrary, the distribution range of these plants in South Africa has increased since the release of their biocontrol agents.[30,35] This is also the case even after the biocontrol agents have been reported to have established across their entire host's distribution range[30,35] and have been present at all localities long enough to have a demonstrable impact.[13-16]

Consequently, based on distributional data, the suggested impact of the released seed-reducing biocontrol agents on their invasive *Acacia* hosts has not translated into a measurable reduction in the area of occupancy of these plants. Furthermore, there is also no evidence from distributional data that a change in the rate of spread

Table 1. All Australian Acacia species subjected to weed biocontrol in the world

Weed	Biological control agent	Feeding guild	Released	Date first released	Damage to weed
Acacia longifolia (Andr.) Willd.	*Trichilogaster acaciaelongifoliae* (Frogatt)	Bud galler	South Africa	1982	Extensive*
			Portugal	2015	Not assessed
			New Zealand	2022	Not assessed
	Melanterius ventralis Lea	Seed feeder	South Africa	1985	Extensive
Acacia melanoxylon R.Br.	*Melanterius acacia* Lea	Seed feeder	South Africa	1986	Extensive*
Acacia cyclops A.Cunn.exG.Don	*Melanterius servulus* Pascoe	Seed feeder	South Africa	1994	Considerable*
	Dasineura dielsi Rübsaamen	Flower galler	South Africa	2001	Extensive*
Acacia mearnsii De Wild.	*Melanterius maculatus* Lea	Seed feeder	South Africa	1994	Considerable*
	Dasineura rubiformis Kolesik	Flower galler	South Africa	2006	Considerable*
Acacia dealbata Link	*Melanterius maculatus* Lea	Seed feeder	South Africa	1998	Moderate
	Dasineura pilifera Kolesik	Flower galler	South Africa	2016	Not assessed
Acacia decurrens (Wendl.)	*Melanterius maculatus* Lea	Seed feeder	South Africa	2001	Moderate
Acacia saligna (Labill.) H.L.Wendl.	*Uromycladium morrisii* Doungsa-ard, McTaggart, Geering and R.G.Shivas	Gall former	South Africa	1987	Extensive*
	Melanterius castanaeus Lea	Seed feeder	South Africa	2001	Extensive
Acacia pycnantha Benth.	*Trichilogaster signiventris* (Girault)	Bud galler	South Africa	1987	Extensive*
	Melanterius maculatus Lea	Seed feeder	South Africa	2003	Not assessed
Acacia baileyana F.Muell.	*Melanterius maculatus* Lea	Seed feeder	South Africa	2006	Not assessed
	Dasineura pilifera Kolesik	Flower galler	South Africa	2016	Not assessed
Acacia podalyriifolia A.CunnexG.Don	*Melanterius maculatus* Lea	Seed feeder	South Africa	2008	Not assessed

Notes: Information extracted from Impson *et al.* [10,31] Damage to weed supplemented with Zachariades *et al.* (most recent assessment).[12] The asterisk (*) indicates biological control agents on plant species, providing 'substantial' control and thereby reducing other management measures to be used.

for these plants has occurred. Henderson and Wilson[30] claimed that the rate of spread of invasive Australian *Acacia* spp. had been reduced by their released biocontrol agents through having compared this to the relative rate of spread of other invasive plants in South Africa. The validity of this comparison is questionable, as the authors were comparing plants with different growth forms, longevity, and stages of invasion. A reduction in the rate of spread for many of the invasive Australian *Acacia* spp. may also not be of relevance as they are in the last stage of the invasive process, having now occupied the most suitable habitats. Rouget *et al.*[38] indicated that at least for *Acacia mearnsii* and *Acacia saligna*, a reduced rate of spread will not be meaningful in curbing their invasive status in South Africa. This is because these plants have already realized their potential distribution in South Africa. Therefore, there has been no indication, based on distributional data, that the released biocontrol agents on invasive Australian *Acacia* have been successful in reducing the area of occupancy or rate of spread of their hosts. On the contrary, distributional data have suggested that despite biocontrol agent presence and impact, these invasive plants have maintained their population density and area of occupancy. Furthermore, the data also suggests that these invasive plants can still spread into and establish in previously unoccupied suitable habitats. Biocontrol agents should also not be the only factor to consider when assessing a change in the area of occupancy or rate of spread of invasive plants in their invaded range. In the case of invasive Australian *Acacia* spp., the influence of large-scale mechanical clearing operations under the auspices of the working for water program,[28] use of fire wood (main source in Western Cape), land use change (*e.g.*, residential and agricultural development), and frequent disturbance events (*e.g.*, fire) should also be considered.[39] To date, only biocontrol has been considered a potential factor influencing the area occupied by invasive Australian *Acacia* with a total disregard for any other potential factors.[30]

Besides the methodological challenges associated with the current distributional data, it can also be argued that no decline in the invaded ranges of these plants has been

observed due to a possible latency to the observed change in the area occupied.[16] This view is based on most of the released agents being seed-reducing agents which do not directly influence plant occupancy. Rather, the agents have an indirect effect through influencing the rate of recruitment into existing and new populations. Therefore, studies on the plant's seed bank dynamics are required to assess whether any changes in the long term can be expected (Figure 1).

In general, the seed bank dynamics of these plants are poorly understood.[27,41] For many of the invasive Australian *Acacia* spp. on which seed-reducing biocontrol has been instigated, there is a lack of data for all stages of their seed bank dynamics (*e.g.*, *Acacia baileyana*, *Acacia podalyriifolia*, *Acacia pycnantha*) (Table 2). Furthermore, for many of the species for which data have been collected, not all stages of the seed bank dynamic process have been investigated, data on the various stages have been collected in isolation, or data on the stages before the release of the agents were not collected (Table 2).

At present, only one investigation was made during the same season on most of the seed bank dynamic stages of three of the worst invasive Australian *Acacia* spp. in South Africa (*i.e.*, *Acacia longifolia*, *A. pycnantha*, and *A. saligna*).[13-15] This investigation was done many years after the biocontrol programs on these invasive *Acacia* spp. were declared successful.[8-10,12] Studies by Strydom *et al.* (covering all aspects of these species' reproductive cycle) clearly demonstrated that the seed-reducing biocontrol agents have not been effective in curbing pod and seed production to the extent that changes in the seed banks can be observed.[13-15] For *A. saligna*, the only species for which pre-biocontrol release seed bank data are available for statistical testing, no change in the plant's seed banks was found between pre- and post-biocontrol releases.[13] Furthermore, there are also no data to suggest that the seed banks of the other Australian *Acacia* spp. will behave differently pre- and post-biocontrol release (Table 2).

It has been assumed that current seed banks of invasive Australian *Acacia* spp. in South Africa are the legacy of

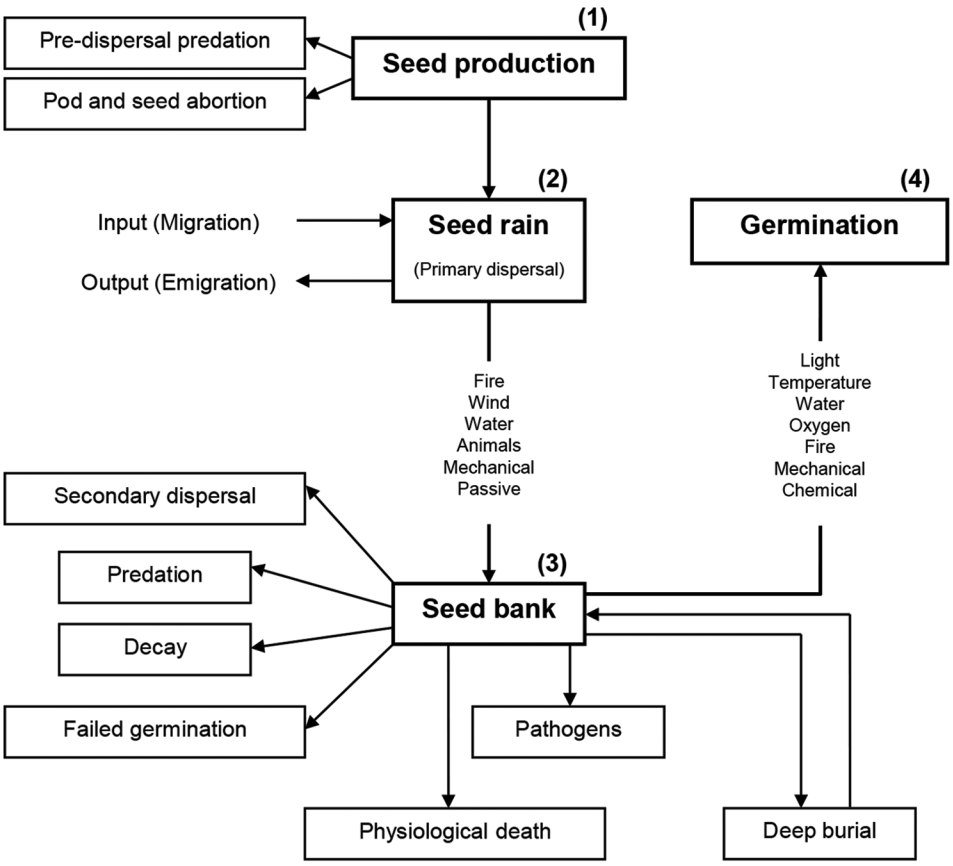

Figure 1. Simplistic model illustrates the seed bank dynamics of any sexually reproducing plant (adapted from Simpson *et al.*[40]). At each phase in the process, namely seed production (1), primary dispersal (2), the seed bank (3), and seed germination (4), every individual seed has to overcome mortality factors (*e.g.*, predation, decay, *etc.*). At each phase, a proportion of the seed population will be lost and the surviving individuals will continue to overcome the next set of obstacles. Comprehensive studies of processes linked to seed banks can measure the effectiveness of seed-reducing biological control agents.

Table 2. Seed bank dynamics data of invasive Australian *Acacia* (*Acacia cyclops, Acacia saligna, Acacia longifolia, Acacia melanoxylon, Acacia pycnantha,* and *Acacia mearnsii*)

Species	Pods tree^{-1}	% LG	Seeds tree^{-1}	% Pred	% Abor	% Viab F	% Dor	Seed rain	% M	% Ant	% Lost	Seed bank	% Viab S	Country	References
A. cyclops			25197			78	98	1197				2031	94	ZAF	42,43
A. cyclops			5000 – 10000											ZAF	44
A. cyclops				28										ZAF	45
A. cyclops				81	16	77 – 78								ZAF	46
A. cyclops				61		77 – 78								ZAF	47
A. cyclops				1 – 67		35 – 90						28 – 11400	77 – 100	ZAF	48
A. cyclops				1 – 80										ZAF	49
A. cyclops				0.3 – 97										ZAF	50
A. cyclops						72	86							ZAF	51
A. cyclops						7599	80 – 98						46 – 95	ZAF	52
A. cyclops						100	68							ZAF	53
A. cyclops						84	91				97			ZAF	54
A. cyclops						99	98					2832 – 7792		ZAF	55
A. cyclops						84	90 – 91				82			ZAF	56
A. cyclops							91							ZAF	57
A. cyclops								800 – 1300	31	35		5170		ZAF	58,59
A. cyclops									74	13				ZAF	60
A. cyclops										32 – 40				ZAF	61
A. cyclops												1370 – 5140	46 – 95	ZAF	62
A. cyclops				25	39									AUS	63,64
A. cyclops						60 – 80	40 – 85		27	23				AUS	65
A. dealbata												319 – 12507	83 – 90	PRT	66
A. dealbata	2369		10765											AUS	67
A. dealbata	10765		62735											PRT	67
A. saligna			48563					530 – 5443				145 – 11920	99	ZAF	43
A. saligna			605 – – 2463					446 – 13472						ZAF	29
A. saligna				0.3 – 42				286 – 13627				137 – 37316	90 – 100	ZAF	68
A. saligna						96	94							ZAF	51
A. saligna						98	97							ZAF	53
A. saligna						100	90				45			ZAF	54
A. saligna						100	7 – 90				46			ZAF	56
A. saligna								2100	31	94		7920		ZAF	58,59

(Cont'd...)

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Table 2. *(Continued)*

Species	Pods tree^{-1}	% LG	Seeds tree^{-1}	% Pred	% Abor	% Viab F	% Dor	Seed rain	% M	% Ant	% Lost	Seed bank	% Viab S	Country	References
A. saligna										68				ZAF	61
A. saligna												7920 – 45800	86 – – 100	ZAF	62
A. saligna												2000 – 212000		ZAF	69
A. saligna												925 – 7444		ZAF	70
A. saligna												2354 – 15058		ZAF	71
A. saligna												715 – 8097		ZAF	72
A. saligna												2400		ZAF	73
A. saligna												306 – 58716	77 – 100	ZAF	74
A. saligna												14880 – – 26560		ZAF	75
A. saligna	70 – 1756	26 – 84	128 – 3284	2 – 65	13 – 44	95 – 99	82 – 84	1314 – 2629			65 – 66	4144 – 30307	87 – 99	ZAF	13-15
A. saligna				3										AUS	76
A. saligna						76 – 100	0 – 100							AUS	77
A. saligna												1389 – 3600		AUS	78
A. saligna						91 – 100	87							ISR	79
A. longifolia			2941	37 – 67										ZAF	80
A. longifolia				0	7	100								ZAF	81
A. longifolia				95 – 99										ZAF	82
A. longifolia				73 – 95										ZAF	83
A. longifolia				0	1	100	100	4754	34	57	10	3474 – 27912	99	ZAF	84
A. longifolia					1									ZAF	85
A. longifolia					6	98		5200				7600		ZAF	86
A. longifolia						100	93							ZAF	87
A. longifolia							93 – 97	11500				34000		ZAF	88
A. longifolia							96	4754	45	45		2449		ZAF	89
A. longifolia								2923				7600	97	ZAF	90
A. longifolia								2923				7646	99	ZAF	43
A. longifolia									34	57				ZAF	91
A. longifolia												2078 – 3473	99	ZAF	92
A. longifolia												3958		ZAF	93
A. longifolia												204 – 815	100	ZAF	74
A. longifolia												3912 – 4528	99	ZAF	94
A. longifolia	242 – 1163	44 – 86	1276 – 2894	20 – 58	16 – 26	95 – 100	73	300 – 1963			78	85 – 2266	92 – 100	ZAF	13-15

(Cont'd...)

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Table 2. ***(Continued)***

Species	Pods tree^{-1}	% LG	Seeds tree^{-1}	% Pred	% Abor	% Viab F	% Dor	Seed rain	% M	% Ant	% Lost	Seed bank	% Viab S	Country	References
A. longifolia	6132		38650											AUS	67
A. longifolia			116 – 338	28 – 44		96 – 98								AUS	95
A. longifolia				2 – 32										AUS	76
A. longifolia				19 – 34		65 – 84		33 – 568			93.8	17		AUS	96
A. longifolia					75	44		14			89	16		AUS	86
A. longifolia						97								AUS	97
A. longifolia								364				8	75	AUS	90
A. longifolia							55	300			94	10 – 30		AUS	98
A. longifolia						90	60 – 70	2000 – 12000				500 – 1500	70 – 100	PRT	99
A. longifolia	6662		50427											PRT	67
A. melanoxylon								3218				48739	100	ZAF	43
A. melanoxylon												0 – 1262	87	ZAF	100
A. melanoxylon				20 – 25										AUS	101
A. melanoxylon				89										AUS	76
A. melanoxylon			543 000			95		10900				44640	92	ESP	102
A. pycnantha	71 – 236	22 – 92	27 – 3324	12 – 44	12 – 33	93 – 99	64 – 89	95 – 542			49 – 75	2117 – 62846	93 – – 96	ZAF	13-15
A. pycnantha			105	5	28	99								AUS	103
A. pycnantha				9 – 19	7									AUS	76
A. mearnsii						92	100							ZAF	104
A. mearnsii						98-100	100							ZAF	105
A. mearnsii							72-75	254-1990				7743	78	ZAF	106
A. mearnsii												20000		ZAF	107
A. mearnsii												38340		ZAF	43
A. mearnsii												13 – 5314*		ZAF	108
A. mearnsii				37 – 51	12 – 51	97 – 99	73 – 78				74 – 79	1230 – 33869	93 – 100	ZAF	13-15
A. mearnsii												57 – 35060	91	ZAF	100
A. mearnsii				0 – 84										ZAF	109
A. mearnsii				4 – 12	7									AUS	76
A. mearnsii				20 – 25										AUS	101

Notes: * Seed bank size of *A. mearnsii* after a fire event, *i.e.*, residual seed bank. Data on aspects of seed bank dynamics of Australian Acacia contained in Hoffmann *et al.*,[110] Correira *et al.*,[111] and Impson *et al.* [16,112,113] could not be shown in table, as values were not expressed in text but in figures. Consequently, accurate values could not be obtained from these papers for any of the various seed bank dynamic stages.

Abbreviations: % Pred: % Seeds lost to predation on trees; % Abor: % Seeds lost to natural abortion; % Ant: Seeds taken by ants on the soil surface; % Dor: % Dormancy of fresh non-predated seeds; % Lost: % Seeds that are lost within the first year to either germination or decay; % M: % Seeds taken by animals (*e.g.*, birds and rodents); % Viab F: % Viability of fresh non-predated seeds; % Viab S: % Viability of soil stored seeds; Seeds tree-1: Seed production of trees; AUS: Australia; ESP: Spain; ISR: Israel; PRT: Portugal; ZAF: South Africa.

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seed production before the agents were released.[16] This is based on these plants having persistent seed banks with seeds being able to remain dormant in the soil for over 50 years.[43] There is, however, a misconception in the interpretation, as it is often implied that the seed banks of invasive Australian *Acacia* spp. in their entirety (i.e., all seeds in the soils) are persistent in the long term. However, seed bank data suggest otherwise, with the seed banks of three evaluated Australian *Acacia* spp. being short-term (<5 years) and long-term (>5 years) persistent.[13] Most of the seeds in the seed banks of invasive Australian *Acacia* spp. are short-term persistent, and only a small proportion are long-term persistent.[16,54,56,62,86,90,91] Milton and Hall[43] and Holmes *et al.*[62] also demonstrated that seed banks of invasive Australian *Acacia* spp. decline with 80% lost within 4 – 6 years of populations having been cleared through felling and with more than 94% lost within 7 – 8 years after felling followed by burning. The recorded seed banks after the release of their biocontrol agents are, therefore, not a consequence of seed production before their release but rather in their presence.[13] This was further demonstrated by the pod production and seed rain of Australian *Acacia* spp. (*A. longifolia*, *A. pycnantha*, and *A. saligna*) being 131 – 437 pods m^{-2} and 307 – 1942 seeds m^{-2}, respectively, even when 45 – 444 pods m^{-2} and 5.6 – 41.9% of seeds were lost respectively to their seed-reducing biocontrol agents.[14,15] Consequently, there is no quantitative data to support the notion that there is a paucity in the decline in the seed banks after the release of their associated biocontrol agents due to a seed dormancy mechanism. Seed bank data recorded after the release of the biocontrol agents indicates that invasive Australian *Acacia* spp. populations are able to maintain their area of occupancy with potentially the same number of trees having to be managed over time.[13]

This conclusion is further supported by seed bank and seedling density data recorded after fire events (Table 3). Invasive Australian *Acacia* spp. populations are exposed to frequent natural and increasingly frequent human-induced fires.[39] During these events, seed banks are often reduced to a fraction of the pre-fire seed bank size with post-fire *Acacia* seed banks of 6 – 100 seeds m^{-2} being able to recruit 2 – 88 seedlings m^{-2} (Table 3). These seedling densities are enough to form stands with a complete canopy cover. For example, Strydom *et al.*[13] worked in mature stands with closed canopies where within tree densities of stands were often found to be 0.14 trees m^{-2} in older parts of the population. The high prevalence of fire over the distribution range of invasive Australian *Acacia* spp. and its influence on seed banks further support the observation that seed banks observed after the release of the biocontrol agents is the consequence of current seed input and that seed banks are able to recover after disturbance events.

Besides few data being available for many aspects of the general biology and ecology of invasive Australian *Acacia* spp., the determination of further control of these plants is exacerbated by different methods having been used over time to investigate the same factors relating to these plant invasions in South Africa. For example, distributional data on these plant invasions have been kept since the 1990s but have not consistently been reported in the same format over time.[30,34,35] Furthermore, the distributional data for the same plants have not been indicated in subsequent publications, making assessments of the increase or decline of these plant distributions in South Africa problematic. Another example is Impson *et al.*[16] not expressing average seed bank size as previously reported by authors (*i.e.*, Table 3) but as box-and-whisker plots.

Besides considering the distribution and seed bank dynamics of invasive Australian *Acacia* spp., data on population changes can also be considered over time. For example, the area covered by a population at a stand scale over time can be assessed to ascertain whether biocontrol agents have caused a decline in the extent of invasion.[19] This assessment of biocontrol agent effectiveness was used to determine the impact of *Uromycladium morrisii* (Pucciniales) (Figure 2) (formerly *Uromycladium tepperianum*) on *A. saligna* populations in South Africa.[29,69]

Morris,[69] and Wood and Morris[29] have argued that *U. morrisii* has caused a decline in the area occupied by *A. saligna* on a population level. This view is based on the observation that the gall-rust fungus has caused a decline in the number of trees within fixed plots. However, the area covered by these trees was never quantified, and consequently, these results could be due to self-thinning (Figure 3A). Strydom *et al.*[13,75] conducted experiments at the same localities as Morris[69] and Wood and Morris,[29] and suggested that the study populations should be monospecific and should have a near-close to closed canopy cover. Consequently, even if *U. morrisii* causes the death of *A. saligna*, this will not cause a decline in the area of occupancy but will cause populations to be more variable in age, tree size, and tree density (Figure 3B). This has, therefore, potentially introduced another level of management complexity as these biocontrol agents may maintain seed banks of *A. saligna* at optimal levels for these plants to recover after disturbance events.[13,14] For example, where trees within populations would be of similar age and, with time, produce less seed as they mature and go into senescence, *U. morrisii* has resulted in a stand of mixed-age trees and has caused seed banks to reaccumulate within populations as seedlings are recruited into populations where trees have died, so maintaining reproductive vigor of populations.[13,14] Consequently, *U. morrisii* could potentially

Table 3. Seed bank size m^{-2} of invasive Australian *Acacia* before and after disturbance events as well as post-disturbance seedlings densities (m^{-2})

Species	Disturbance	Month and Year	Seed bank m^{-2} before	Seed bank m^{-2} after	Seedlings m^{-2}	Total emergence m^{-2}	References
Acacia longifolia	Felled	Before 1981	2110	NA	50	NA	43
Acacia longifolia	Felled and burnt	May 1982	2078	149 (4)	75 (12)	NA	92
Acacia longifolia	Burnt standing	January 1985	3958	103*	88 (16)	NA	93
Acacia saligna	Felled	Before 1981	11917	10249 (12)	175 (12)	NA	43
Acacia saligna	Burnt	Before 1981	11917	NA	NA	2388 [12]	43
Acacia Acacia saligna	Felled	Before 1981	9268	8712 (48)	23	NA	43
Acacia saligna	Felled and piled	July 1985	13200	13019 (24)	127 and 21 (8 and 24)	181 [20]	52.62
Acacia saligna	Fell, piled, and burnt piled	February 1985	13019	185 (20)	310 and 180 (12 and 20)	436 [20]	52.62
Acacia Acacia saligna	Felled and piled and burnt	July/August 2003	13686	1291 (8)	22 (8)	NA	74
Acacia saligna	Felled and piled and burnt	July/August 2003	3888	425 (8)	24 (8)	NA	74
Acacia saligna	Felled and piled and burnt	July/August 2004	3158	425 (8)	59 (8)	NA	74
Acacia saligna	Burnt standing	April 2003	58716	1392 (16)	19 (16)	NA	74
Acacia saligna	Felled and burnt	April 2013	6500	NA	440 – 1200 (20)	NA	114
Acacia saligna	Felled and burnt	April 2013	4350	NA	760 – 880 (20)	NA	114
Acacia cyclops	Felled	Before 1981	1571	880	13	NA	43
Acacia cyclops	Burnt	Before 1981	1571	110	NA	409	43
Acacia cyclops	Felled	Before 1981	2523	454 (48)	10 (48)	NA	43
Acacia cyclops	Felled	July 1985	3650	796 (48)	232 and 24 (8 and 32)	319 [32]	52,62
Acacia cyclops	Felled and piled	September 1985	2832	558 (48)	50 (48)	359 [48]	55
Acacia cyclops	Fell, piled, and burnt piled	September 1985	6774	7 – 54 (48)	2 (48)	8 – 61 [48]	55
Acacia cyclops	Burnt standing	September 1985	7792	16 (48)	7 (48)	15 [48]	55
Acacia cyclops	Felled and burnt	September 1985	4441	280 (48)	75 (48)	372 [48]	55
Acacia mearnsii	Felled and burnt	November 2001	7743	1704 (2)	6040 (2)#	6040 [2*]	106

Notes: The total seedlings m^{-2} that emerged from the seed banks over a measured period are indicated. Values in parentheses indicate the weeks between the sampling event and the disturbance event. Values in square brackets indicate the total weeks during which sampling was conducted from the disturbance event. #Emerging seeds were counted within soil samples; *Time of sampling not indicated. However, it is reported that sampling was conducted shortly after the fire; "NA" indicates that no data is available.

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have increased the complexity of managing *A. saligna*. Impson *et al.*[16] have similarly argued that the gall midge *Dasineura dielsi* (*Cecidomyiidae*) has caused a decline in tree density of *Acacia cyclops* before and after fire events. However, they have not indicated the area covered by the plant, and consequently, the extent to which this agent will cause a decline in the area occupied by *A. cyclops* is unclear.

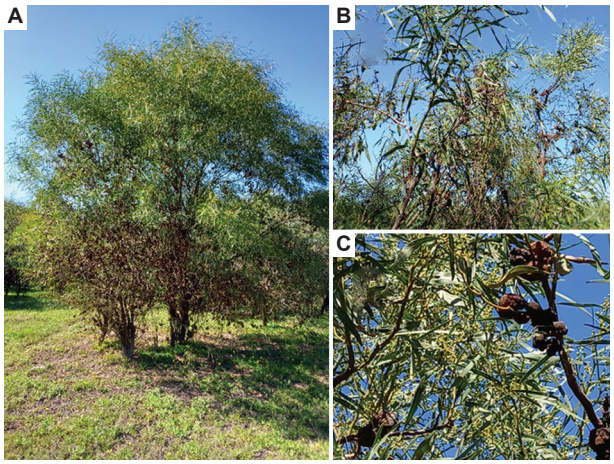

Figure 2. Galling biocontrol agents can remain visible on the target weed but do not necessarily target future flower buds, which would require new infections to prevent seed production. (A) *Uromycladium morrisii* galls on *Acacia saligna*; (B) close-up of tree branch; and (C) branch tip showing the position of new flower buds relative to existing galls.

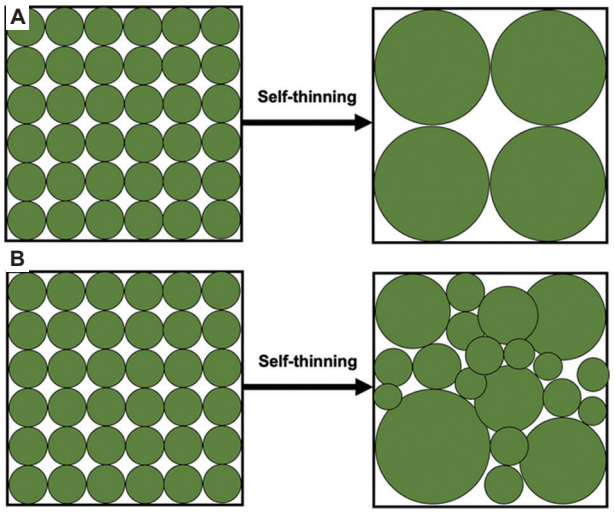

Figure 3. A reduction of the density of the target weed could be from self-thinning as certain individuals outcompete congeners. (A) Hypothetical illustration of self-thinning in *Acacia salgina* populations without disturbance events in between fire intervals resulting in a mature population with trees of similar size and age. The size of the circle indicates the relative tree size in a monospecific stand. (B) Hypothetical illustration of self-thinning in *Acacia salgina* populations with disturbance events in between fire intervals resulting in a mature population with trees of different sizes and ages. The size of the circle indicates relative tree size in a monospecific stand.

Another seed-reducing agent, the flower-bud galling wasp *Trichilogaster acaciaelongifoliae* Froggatt (Figure 4), was found to reduce the reproductive potential of *A. longifolia* (Andr.) Wild within the first few years of introduction at several sites within South Africa, although mostly sampling concentrated within the Western and Eastern Cape.[80,82,83] However, since the introduction of this agent on *A. longifolia*, there have been no direct measures of this invasive plant's abundance and distribution after 25 years of biocontrol.[10] Using scale-area curves, Veldtman *et al.*[115] showed that *A. longifolia* indeed has variable tree density across its geographic range but that *T. acaciaelongifoliae* is present everywhere throughout this range. They suggest that *A. longifolia* is a niche-limited invasive weed species in South Africa and that propagule reduction will not enforce a range limit but rather as a consequence of a combination of a lack of favorable vegetation type and climatic suitability for the invasive plant itself.[115] Using the climatic modeling by Rouget *et al.*[38] to project the potential distribution of *A. longifolia* thus overestimates the potential range by not taking soil types into account. Therefore, by comparing the realized range to the overestimated potential distribution, the proposed limiting action of *T. acaciaelongifoliae* is erroneously concluded.

Impson *et al.*[16] have also argued that there is a strong theoretical basis to suggest that biocontrol agents will reduce the rate of spread of their hosts. This was based on the work of Le Maitre *et al.*[116] where they assessed

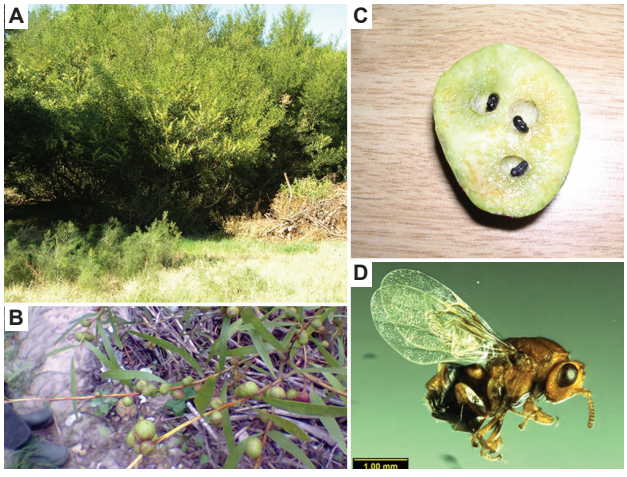

Figure 4. Galling biocontrol agents are normally species-specific with little risk of non-target host plant effects. (A) *Acacia longifolia* galled by the biological control agent *Trichilogaster acaciaelongifoliae* in a high-density stand in the Western Cape Province, South Africa. (B) This agent attacks the flower buds of the host plant before inflorescences fully develop; consequently, gall development indicates the successful prevention of seed pod formation. (C) Dissected gall showing pupae of *T. acaciaelongifoliae*. (D) Adult female wasp.

the potential impact of biocontrol on the population dynamics and rate of spread of *Hakea sericea*. However, Le Maitre *et al.*[116] used the opinion of "experts" to discern possible dispersal distances of this plant in the presence of its biocontrol agent. The theory is, therefore, largely influenced by expert opinion rather than quantitative data and, therefore, subject to possible bias. Regardless, it is questionable to use the modeled dynamics (which is an approximation of reality) of one species and growth form and agent combination to make a case for another biocontrol test case. The question should be asked why basic information, such as the rate of spread of *A. cyclops* or any other *Acacia* spp., was never collected. Any appropriately collected and analyzed data will provide far more support than modeled dynamics based on parameters derived from expert opinion.

3. How much is enough?

Irrespective of whether seed production, seed bank size, or rate of spread has changed, the pertinent question that should be asked is how much reproductive output must be reduced to have an appreciable impact on the area of occupancy, rate of spread, and management costs. To reduce a plant population's area of occupancy, seed input needs to be reduced below the carrying capacity of mature populations.[117] In this situation, density-dependent seedling mortality will not be able to compensate for the differences in seedling densities.[117] Therefore, the population needs to be seed-limited for seed-reducing agents to be effective.[118]

Considering the carrying capacity and seed bank size of mature invasive Australian *Acacia* spp. populations in the presence of their released biocontrol agents in South Africa, their associated seed-reducing biocontrol agents will have to further reduce seed input with more than 99.9% to reduce the area occupied by these plants (Table 4). This clearly demonstrates that invasive Australian *Acacia* spp. are not seed-limited and that the seed-reducing biocontrol program on these plants is a wasted effort. This is further supported by Cheney *et al.*[33,p.281] who investigated the efficacy of clearing operations on invasive Australian *Acacia* spp. and who concluded "*Even reducing plants to <1 plant per hectare (our aim) would leave a few scattered plants capable of seeding on the landscape, which could lead to problematic regeneration relatively quickly.*"

Despite these limitations, the release of gall-forming and seed-feeding agents was promoted as the best strategy to control the invasion of Australian *Acacia* spp. in South Africa while not impacting their economic use.[28,32,119] Arguably, this "win-win" approach has led to a suboptimal management decision – do not attempt to control vegetative growth but rather target the reproductive output of the tree. However, has there ever been a case where >99.9% of the reproductive output of invasive plants has been reduced by a released agent? A more realistic figure would be a 50% reduction of seeds.[14,15] However, Australian *Acacia* spp. are not seed-limited and 1 seed per m^2 is sufficient to maintain cover after disturbance (Table 4). Strydom *et al.*[13,14] documented seed production per m^2 with established agents much greater than the few seeds required (140 – 350 seeds per m^2). This critique specifically addresses the use of seed-reducing agents in the control of Australian *Acacia* spp. and we are not aware of any released biological control agents used for attacking the vegetative parts of these invasive plants. We can thus not say whether the use of the latter would be more effective. Our argument instead is that seed reduction of Australian *Acacia* spp. is unlikely to be effective given the biological response of the released agents and the fact that these plants are not seed-limited. Data on whether agents targeting reproductive or vegetative parts would be more effective for other plant species would not be relevant here because we are not making general statements on the effectiveness of different types of biocontrol agents.

The South African literature on the effectiveness of seed-reducing biocontrol agents of Australian *Acacia* spp. is characterized by review articles, especially in special issues, with few primary research papers.[5-12] The literature cited in these reviews are the few original works when the

Table 4. Average tree density (m^{-2}), average seed rain (m^{-2}), and average seed bank size (m^{-2}) of invasive Australian *Acacia* populations under biological control, with a near complete to closed canopy cover (90 – 100%) in the Western Cape of South Africa

Species	Tree density (m^{-2})	Seed rain (m^{-2})	% Damage required	Seed bank (m^{-2})	% Damage required
Acacia longifolia	1±0.2	745±406	>99.9	1017±303	>99.9
Acacia mearnsii	1.4±0.2	NA		8564±5131	>99.9
Acacia pycnantha	1.7±0.7	314±110	>99.0	17261±9800	>99.9
Acacia saligna	3.3±0.8	1942±311	>99.9	14153±4075	>99.9

Note: Data are adapted from Strydom *et al.*,[13,14] including the percentage reduction in the seed rain and seed bank size required to reduce seedling recruitment below adult-carrying capacity.

initial agents (*T. acaciaelongifoliae* and *U. morrisii*) were released in South Africa but surprisingly no further data were published. Therefore, the defined success within these review articles (that little to no seeds or plants survive, which has resulted in a reduced area of coverage and rate of spread) has remained as a qualitative notion within the scientific literature as quantitative evidence lacks for all of the biocontrol programs on invasive Australian *Acacia* spp. For example, Zachariades *et al.*[12,p.1] state that "*We used published literature, unpublished work and personal communication to assess the status of biological control of IAPs* [invasive alien plants]," essentially emphasizing successful control of Australian *Acacia* spp. through released agents. Despite this claimed success, many established Australian *Acacia* spp. still occupy a large area in South Africa and are still increasing in densities.[30] Furthermore, area managers do not see environmental gains in invasive impact reduction even when agents are present.[33]

The above-mentioned then draws into question the cost-benefit analysis that has been done for invasive Australian *Acacia* spp. using biocontrol.[120] If no quantitative information on the extent of biocontrol for these plants is available, they can only be based on expert opinion. The cost-versus-benefit of biocontrol agent introduction on Australian *Acacia* spp. was calculated as 1:3726.[22,120] Considering the bias toward the perceived success of biocontrol agents, the estimates on impact reduction were likely inflated (because experts perceive and recommend biocontrol agents as effective), providing a skewed perception of cost-benefits of using biocontrol. This is based on statements that biocontrol is more cost-effective than other control measures in terms of being self-perpetuating and reducing the extent of invasion and rate of spread of the targeted host plants.[27] However, the effectiveness of other control methods versus biological control has not been formally compared in terms of cost relative to benefit.

Recently, the seed banks of invasive Australian *Acacia* spp. have been used to provide a method to assess the impact of seed-reducing biocontrol agents in the southwestern part of South Africa.[13-15] Using quantile regression and using tree diameter as an indication of stand age, seed bank development over time could be demonstrated. These data show that insect seed-reducing agents have similar deficiencies to an introduced fungus, namely slow rates of dispersal and population growth[10,50] relative to the rate of seed bank accumulation of their Australian *Acacia* hosts.[13] How could there be such a big gap between perceived success and what empirical data is showing to be the contrary? However, such a debate would be unnecessary if pre-release data on the invasive plant were collected, which would make it possible to quantitatively measure the change in distribution of the target host. Surprisingly, these data are still not collected before agent release as a standard practice, despite the strength it would provide to statistical evaluations of control.[19]

Hill *et al.*[5,p.568] states that "*If there are any doubts about what has been achieved with biological control against invasive alien plants in South Africa over the years, the fundamental counterfactual question is: what would be the extent of the alien plant invasions if there had been no biological controls?*" Similarly, Impson *et al.*[16,p.8] states that "*While there is no definitive confirmation that the inclusion of biological control on A. cyclops in South Africa has brought about the changes in its pest status, it is not unreasonable to deduce that the introductions of D. dielsi and* M. servulus *were not a wasted effort and that biological control is almost certainly contributing to the decline of the pest.*"

These and similar statements underpin the assumption that biocontrol has an effect and that proof should be provided to prove the opposite. Fundamentally, this changes the null hypothesis of no effect to the alternate effect. Therefore, this implies that the alternate hypothesis should be used during statistical testing. This violates a basic principle of scientific inquiry. The dangers of making a type 1 versus type 2 error in the question of whether biocontrol agents are effective are as such. If it is assumed that there is a significant effect but there is none, the control program will not recommend any further control action. However, if a type 2 error is made, there is a significant effect, but this is recorded as there is none, and control actions will be further explored. Consequently, based on sound scientific practice, the current approach of biocontrol programs on invasive Australian *Acacia* spp. implicitly risks being affected by a type 1 statistical error. Based on the evidence that has been provided so far, this is the general approach that has been followed with biocontrol programs in South Africa. However, if sound scientific practice is followed, the burden of proof should be demonstrating that biocontrol has a significant effect.

4. Consequences of believing without seeing

The implications of *Acacia* spp. seed biocontrol not being effective but believed as being effective are four-fold. First, the apparent success of biocontrol of invasive wattles has been used to lobby for the release of more agents.[10,12,109] In fact, after the release of *T. acaciaelongifoliae* and *U. morrisii*, six seed-feeding beetles and six more gall formers have been released (Table 1). During this whole exercise, not one pre-release study has quantified the reproductive

success of the plants before agent release. There is thus no data to compare to if such data are not collected before release. Second, the State of Invasive Species Report[23] identifies biocontrol of weeds as one of the best-documented management actions in South Africa and suggests more investment into biocontrol in South Africa. However, as shown here for *Acacia* spp., the data does not support this assertion. Third, Australian *Acacia* biocontrol agents have been released into other continents based on South African recommendations that biocontrol will be successful in reducing the impacts of these invasive species. The question arises whether the import of these agents to other continents to initiate biocontrol programs (*e.g.*, *A. longifolia* in Portugal[121]) will potentially solve any of the invasive species-induced environmental problems faced if additional control methods (such as mechanical clearing) are not implemented simultaneously. Recently, the European Food Safety Authority–Plant Health (EFSA-PLH) (IOBC) approved the release of *T. acaciaelongifoliae* in Portugal, Jeger *et al.*[122,p.272] state that "*Given that release of the BCA would substantially reduce (1) the vegetative growth, reproductive potential and population density of invasive alien A. longifolia, (2) the negative impacts of the invasive alien A. longifolia on biodiversity and ecosystems, and (3) the negative impacts of current control measures for the invasive alien A. longifolia, the consequences of the release of the wasp on the invasive alien plant A. longifolia were rated as massive.*" This assessment by the EFSA-PLH has no empirical basis but was based on the qualitative claims in the South African literature and expert biocontrol practitioners. Surprisingly, seed banks of *A. longifolia* in Portugal pre-agent release[99] and South Africa[13] are comparable, yet *T. acaciaelongifoliae* has been present in South Africa for more than 30 years and is considered a highly successful seed-reducing agent.[123] In fact, Strydom *et al.*[13-15] show the exact opposite of the assessment by the EFSA-PLH test case, which was based on expert opinion presented in the literature. This calls into question whether subjective assessments of control,[10,28] by the biocontrol practitioners themselves, are sufficiently scientifically rigorous on which to base policy decisions, especially as it may involve in-between continent transfer of non-indigenous species (*i.e.*, the selected agents). Surely, there is a conflict of interest to ask biocontrol practitioners whether biological control is effective?

The last implication is that there are several non-native gall-forming species that have been released in South Africa and Portugal (and recently New Zealand)[31] that can form trophic connections and have other non-intended consequences compared to when the targeted host plants did not have any gall formers present. Seymour and Veldtman[124] found that the false codling moth (*Thaumatotibia leucotreta*), a major pest of citrus crops, occurs and completes its development in the galls of the agent *U. morrisii* released on *A. saligna*. When these trees occur next to citrus orchards, these galls provide an additional niche and potential source for this pest.[124] Similarly, galls of *T. acaciaelongifoliae* released on *A. longifolia* were found to contain, among several other inquilines, the litchi moth (*Cryptophlebia peltastica*), which is a known pest of several tree crops.[125] These associations by species of the same families (*e.g.*, *Tortricidae*) are also found in the native Australian range,[125] and it has been proposed that investigating ecological interactions (*e.g.*, by representatively sampling developed, pre-emergence galls and rearing out all occupants) before the release of galling agents will identify potentially problematic non-target associations.

D. dielsi released on *A. cyclops* in South Africa provides another case of an unintended consequence with one of the gall-forming biocontrol agents released on Australian *Acacia*. Recently, it was found that this biocontrol agent's galls harbor the straw itch mite, and these mites were found at coastal towns where "bite outbreaks" are periodically experienced.[126] Again by releasing the gall-forming biocontrol agent, a trophic connection has been made to another organism, which would not be associated with the invasive plant species had the agent not be released.

Carvalheiro *et al.*[127] showed that high biomass biocontrol agents have the greatest potential for non-target interactions. Targeted Australian *Acacia* spp. are still abundant in South Africa, thus there is a large biomass of various species of introduced gall-forming biocontrol agents that can now interact with native species. Overstating the benefit from a seed-reducing agent on the one hand, and downplaying any future non-target impacts on the other hand (which under current global change may become even more difficult to anticipate, Bradley *et al.*[128]), biocontrol using galling agents is unfortunately recommended without the necessary supporting data that benefits outweigh potential costs.

5. Conclusion

Scientific advances are driven by posing questions and then collecting data to test the hypotheses, followed by peer-review to support the data interpretation and conclusions. In fact, the hypothesis, "has the release of a gall-forming biocontrol agent significantly reduced the abundance of the targeted host?" has not been asked, and consequently has not been tested with empirical data. The only data that we are aware of are those from Strydom *et al.*,[13-15] which provide seed bank, seed rain, and gall to seed pod abundance data that show that the amount of seed reduced by biocontrol agents on *A. longifolia*, *A. pycnantha*, and *A. saligna* is ecologically irrelevant in terms of limiting these invasive plants. In other

words, the released seed-reducing agents in South Africa are not effective in reducing the number of seeds produced by these invasive Australian *Acacia* spp. below a level where biodiversity, ecosystem functioning, and management of the plants could benefit from. This is not surprising given that these invasive plants are not seed-limited.

The question arises as to whether invasive management that relies heavily on biocontrol agents to reduce the seed production of the target host is indeed adequate, and should this not be monitored and tested? At present, in South Africa, invasive plant species under biocontrol are considered less threatening than those species with no released agents.[21,24,27] However, if biocontrol does not reduce the invasiveness in the high-density stands of their target host species, prioritizing mechanical control on species with no agents, may allow species under biocontrol to entrench even further. Furthermore, this can also cause further loss of biodiversity and ecosystem functioning. This could lead to inefficient use of conservation and management resources in terms of managing invasions on the ground (*e.g.*, Cheney *et al.*[33]). In some cases, young invasive stands of *Acacia* spp. are not targeted as it is assumed that biocontrol will slow the build-up of the population.[22,24,129] Consequently, instead of targeting sparsely invaded areas first, established stands are targeted. Over time, however, it is the sparse populations that are increasing in density despite the presence of biocontrol agents (*i.e.*, Cheney *et al.*[33]). Indeed, there is a strong relationship between weed impact and its landscape density (Marchante *et al.*[121] for *A. longifolia* specifically).[3]

Both biological invasions and classical biological control have been recognized as unprecedented ecological and evolutionary bio-geographical experiments.[130] However, classical biological control is a planned introduction of an alien organism and does not come without risks.[17] The purposeful introduction of some classical biological control species may thus be unwarranted, given the potential for non-target effects[124-126,113-133] and the likelihood of spontaneous geographic spread after establishment.[134,135] Going forward, countries that rely heavily on classical biological control for the management of weeds (South Africa, Australia, *etc.*) should invest in standardized, long-term monitoring of the performance of released agents.

If there are data at a scale larger than a single plant (*i.e.*, at the population scale), which quantitatively shows the control exerted by a seed-biocontrol agent of an Australian *Acacia* spp. has reduced its invasive impact, we strongly encourage it to be published. Science can only progress through the formulation and testing of hypotheses, and here, of ecological processes. Hence, where to from here? We hope our review highlights the current problems with evaluating the success of biocontrol of Australian *Acacia* spp. Much greater effort is needed to gather data before release or collect baseline data just after release.

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ORIGINAL RESEARCH ARTICLE

Evaluation of agricultural efficiency and influencing factors in the context of sustainable land management

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Abstract

Given the growing global focus on sustainable development, sustainable land management has emerged as a critical concern in contemporary agricultural development. The efficacy of agricultural production and its influencing factors in Shaanxi province of China, from 2012 to 2021, were analyzed using the Data envelopment analysis (DEA)-Banker, Charnes, Cooper model. Input and output indicators of agricultural production were selected for analysis. Inputs consist of land, machinery, water, and fertilizer. Specific indicators include the total sown area of crops, effective irrigated area, total power of agricultural machinery, and total reservoir capacity. Fertilizer inputs include the discounted amount of fertilizer applied for agricultural use. The output indicators considered include the gross output value of agriculture, forestry, animal husbandry, and fishery, the economic value added from agricultural production, and the production of cereal and fruit are all considered output indicators. From 2012 to 2018, the scale remuneration of agricultural production in Shaanxi province increased, suggesting gradual improvement in scale efficiency. Conversely, the efficiency of agricultural production has remained at the "DEA strong efficient" level from 2019 to 2021, suggesting effective management of scale efficiency. The investigation indicates that the allocation of resources and the administration of agricultural production in Shaanxi province have improved in recent years, contributing to the fostering of sustainable agricultural development.

Keywords: Agriculture in Shaanxi province; Food production; Land production efficiency; Data envelopment analysis-Banker; Charnes; Cooper model

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1. Introduction

Agriculture serves as the cornerstone and critical pillar of the national economy, not only in China but also in the global economic landscape. Given the growing resource constraints and the effects of climate change, the question of how to ensure the sustainable development of agriculture while maintaining production has emerged as a significant concern for all nations.[1] Research on agricultural efficiency evaluation and sustainable land management (SLM) has gradually established a global framework, with remarkable results particularly in resource utilization efficiency, the application of innovative technologies, and integrated urban-rural development. Theoretical and practical references for sustainable agriculture in various economies have been

derived from these studies. Nevertheless, the imperative challenge of integrating international experience with local requirements and developing agricultural efficiency optimization solutions tailored to China's distinctive agricultural structure, resource endowment, and socioeconomic conditions remains unresolved.

Shaanxi province (Figure 1) is a significant agricultural province in China, boasting a long agricultural tradition and substantial agricultural resources. Nevertheless, agricultural production in Shaanxi province is currently being confronted with significant sustainability challenges due to the high utilization of land resources and the acceleration of urbanization.[2] The traditional agricultural production model and resource allocation methods are inadequate to satisfy the requirements of contemporary economic and social development. Therefore, it is imperative to optimize them through scientific management techniques and progressive technologies.[3] An exhaustive examination of agricultural efficiency and its influencing factors can offer a theoretical foundation and informed decision-making support for the rational allocation of resources and the enhancement of production efficiency, as viewed through the lens of SLM. As a result, this investigation is not only academically innovative, but it also has substantial practical implications for agricultural management and policy formulation.

To quantitatively assess the agricultural efficacy in Shaanxi province and investigate the primary factors that influence it, this study implements the DEA-BCC (Data envelopment analysis-Banker, Charnes, Cooper) model. With the complete consideration of multiple inputs and multiple outputs, the DEA-BCC model effectively measures the relative efficiency of production units as a non-parametric method. From 2012 to 2021, we selected the input and output indicators of agricultural production in Shaanxi province (Table 1). These indicators included inputs such as land, machinery, water resources, and fertilizer, as well as outputs such as agricultural output value and crop yield. Analyzing the trend and development characteristics of agricultural efficiency in Shaanxi province using these data enables the assessment of the rationality of resource allocation and production structure.[4,5]

The objective of this investigation is to provide conclusive data for a single year, as well as to elucidate the dynamic evolution of agricultural efficiency through comparative analyses of various time periods (e.g., 2012 – 2018 and 2019 – 2021). This type of longitudinal analysis is instrumental in elucidating the long-term development trend of agricultural production and identifying the primary factors that influence agricultural efficiency. In the final analysis, this investigation offers policy recommendations and scientific guidance to enhance the optimization of agricultural resource allocation and foster sustainable agricultural development in Shaanxi province.

The second section of this paper is a literature review that examines pertinent studies on agricultural efficiency assessment and SLM. The third section introduces model selection and variable selection, describing the application of the DEA-BCC model and its selection of input-output indicators. The fourth section conducts an empirical study on the implementation effect, analyzing the data based on the agricultural efficiency in Shaanxi province. The fifth section investigates the relationship between the efficiency of agricultural production and SLM, and thoroughly examines the key factors that influence agricultural efficiency. The sixth section concludes the paper by summarizing the research findings and formulating policy recommendations.

2. Literature review

2.1. Current status of research in China and abroad

Scholars, both domestically and internationally, have conducted extensive research on SLM and agricultural efficiency evaluation within the broader context of sustainable agricultural development. We present a comprehensive review of the existing literature to illustrate the value-added contribution of this study, encompassing critical issues, methodologies, and research findings.

2.1.1. Primary concerns

SLM and agricultural efficiency evaluation have emerged as significant academic subjects in recent years. The primary focus of domestic academicians is the integrated development of rural and urban areas, agricultural production technology innovation, and the efficacy of land resource utilization.[6,7] For instance, Wang *et al.*[8] empirically examined the influence of collective operating construction land entering the market on urban-rural integration development using a multi-period Difference-in-differences

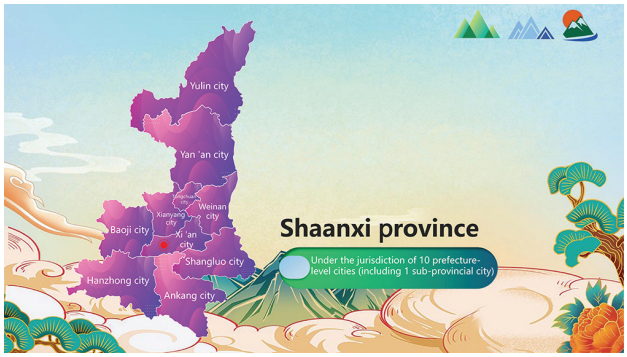

Figure 1. Regional map of Shaanxi province. Figure created by the author.

Table 1. Indicators of agricultural production efficiency in Shaanxi province

Indicator type	Name	Description of variables	Unit (of measure)	Indicator symbols
Input indicators	Land input	Total sown area of crops	Thousand hectares	X1
		Effective irrigated area	Thousand hectares	X2
	Mechanical and water inputs	Gross power of agricultural machinery	Kilowatt (unit of electric power)	X3
		Total reservoir capacity	Cubic meter (unit of volume)	X4
	Fertilizer inputs	Discounted agricultural fertilizer application	Tonnes	X5
Output indicators	Value of agricultural production	Gross output value of agriculture, forestry, livestock, and fisheries	Billions	Y1
		Value added by agriculture, forestry, and fisheries	Billions	Y2
	Crop production	Grain production	Tonnes	Y3
		Fruit production	Tonnes	Y4

(DID) model, thereby providing empirical evidence to support sustainable agricultural development. In the meantime, Yang *et al.*[9] discovered that cooperatives had a higher factor input utilization efficiency than large cultivators by examining the disparity in maize production efficiency between large growers and cooperatives. Hu *et al.*[10] conducted an analysis of the regional differences and dynamic evolution of agroecological efficiency in Jiangsu province from 2001 to 2015 using the DEA-BCC model. They proposed a scientific foundation for the advancement of eco-agriculture.

Internationally, academicians in the United States, France, Germany, Japan, South Korea, and other countries have given equal attention to the issue of agricultural resource management and efficiency development. For instance, research conducted by Iowa State University in the United States focused on the optimization of resource allocation and agricultural technological innovation to offer theoretical support for integrated rural development.[11] Research by The University of Montpellier provided the "soil moisture map applied to hydrology, agriculture, and risk assessment"[12] is noteworthy, as academicians in France concentrate on multifunctional agriculture, agroecosystem services, and land use conflicts. The German Institute of Crop and Soil Science underscored the significance of "accurate spatial and temporal estimation of crop traits for scientific modeling and decision-making in sustainable agricultural management."[13] The changing demand for agricultural products was identified as a driving force behind technological innovation in a study conducted at the Tokyo University of Agriculture and Technology in Japan, which examined consumer perceptions of agricultural products affected by natural disasters.[14] In its own right, the Korean Association of Rural Communities recognized the significance of water management systems in the context of sustainable agricultural development.[15]

2.1.2. Methodological applications

Scholars, both domestically and internationally, predominantly employ non-parametric methodologies, including data DEA, to evaluate the efficacy of agricultural production. The DEA-BCC model is more appropriate for efficiency analysis involving multiple inputs and multiple outputs, as it establishes the efficiency frontier without the need for subjectively determining the weights of the indicators.[16] This method analyses the relative efficiency of the production units. Existing research in China has extensively employed the DEA model to evaluate agricultural efficiency in various regions[10] and to propose strategies for enhancing efficiency. Nevertheless, the impacts of data distribution, variable covariance, and other factors on the applicability of DEA models have not been thoroughly investigated in the majority of these studies. Multi-equation modeling has been employed by international scholars, including Amer *et al.*,[17] to evaluate the environmental and economic efficacy of agri-environmental measures. This innovative empirical application of the DEA model highlights the model's limitations in addressing undesirable output technologies.[17] This analysis indicates that the current research does not provide a critical analysis of the applicability of the models, particularly in terms of the suitability of data characteristics, highlighting areas for potential improvement.

2.1.3. Research findings

According to both domestic and international research, agricultural efficiency evaluation is a critical instrument for the implementation of sustainable agricultural management.[7] For instance, domestic research has demonstrated that agricultural efficiency can be substantially enhanced through rational resource allocation and technological innovation. Henke *et al.*[18]

proposed that agricultural biodiversity is influenced by socioeconomic policies on a global scale, underscoring the importance of multi-party policy interventions in agroecosystems. Furthermore, a study conducted by Musters *et al.*[19] demonstrated a correlation between the abundance of agricultural insects and land use, indicating that there is a relationship between agricultural production and ecosystem services.

In conclusion, while existing research has yielded a wealth of practical and theoretical findings in the areas of agricultural efficiency evaluation and SLM, there is still significant potential for the further development of research perspectives, methodological innovation, and model applicability. Our research applies the DEA-BCC model to analyze agricultural efficiency in Shaanxi province, with a particular emphasis on the dynamic performance of specific variables. The objective is to offer a more practical reference for the enhancement of agricultural efficiency.

2.2. Databases for literature search

On the basis of the search terms "sustainable land management" and "agricultural efficiency evaluation," databases including China Knowledge Network (CNN) and PubMed were queried, yielding a variety of results (Figure 2). These keywords encompass significant topics within the field of agriculture, such as the sustainable management of land resources and the evaluation of agricultural efficacy.

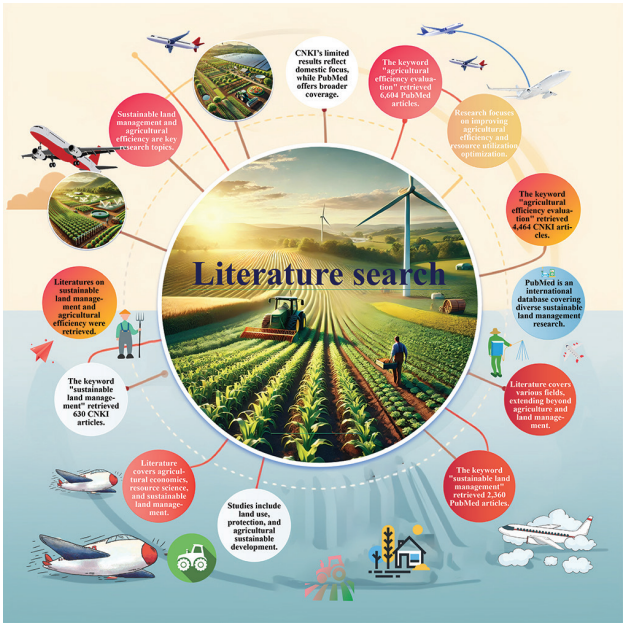

Figure 2. Analysis chart of literature search. Figure created by the author. Abbreviation: CNKI: China National Knowledge Infrastructure.

A search on CNN with the keyword "sustainable land management" resulted in 630 documents, the majority of which focused on the disciplines of agricultural economics, resource science, environmental science, and resource utilization, as well as issues associated with SLM. Some of these studies also explored aspects of land use, land conservation, and sustainable agricultural development. The search for "sustainable land management" on PubMed yielded 2,360 documents, covering a broader spectrum of disciplines, including research related to SLM in agriculture, as well as research that entails ecology and environmental protection, and more. This demonstrates the significance of PubMed as a valuable source of information on SLM, given its broad international scope and diverse subject areas.

In contrast, the CNN search for the keyword "agricultural efficiency evaluation" yielded 4,464 literature results, most of which were related to agricultural production efficiency, DEA, and efficiency research. The enhancement of agricultural efficacy and the optimization of resource utilization is two of the most significant research topics in the field of agriculture, and they were the subject of these studies. The search for "agricultural efficiency evaluation" on PubMed returned 6604 results, which cover a broader range of agricultural efficiency evaluation studies. These studies involved not only the application of DEA models but also the investigation of alternative evaluation methods and strategies for enhancing efficiency.

It is important to note that CNN has comparatively fewer literature search results, likely reflecting the limitations of this database to the domestic research field, whereas PubMed has a broader international coverage and thus more literature search results. Furthermore, it is evident that various nations have invested substantial resources in agricultural efficiency evaluation and SLM research on a global scale. In addition, the number of articles published in the PubMed database has increased over the past 5 years, indicating that the field of agricultural efficiency evaluation continues to receive global attention and research. SLM and agricultural efficacy evaluation are presently popular research topics in the field of agriculture. With a growing population and limited resources, the issue of sustainable development in agriculture is gaining in importance.

In databases such as CNN and PubMed, agricultural efficiency evaluation and the factors influencing it, from the standpoint of SLM, have received considerable attention. CNN focuses primarily on research related to SLM and agricultural efficiency evaluation, whereas PubMed covers a broader range of international research fields, including related topics like SLM and agricultural efficiency

evaluation. These studies provide substantial theoretical and practical support for promoting sustainable agricultural development and optimizing resource utilization.

3. Model selection and variable selection

3.1. DEA-BCC model

The Charnes, Cooper, and Rhodes (CCR) model and the BCC model are the primary divisions of the non-parametric analytical method, DEA. Charnes *et al.*[16] introduced the CCR model, which was subsequently used by Banker *et al.*[20] to construct the BCC model. The fundamental principle of DEA is to determine the efficiency frontier by utilizing specific input and output conditions, which represent the optimal production boundary for either cost minimization or output maximization. This frontier is used to assess the relative efficiency of decision-making units (DMUs). In this frontier, there are numerous DMUs that evaluate the efficacy of other DMUs in relation to the frontier.

The BCC model is a DEA model that is appropriate for examining the efficiency performance of decision units across various scales while accounting for scale effects. The efficiency frontier in this model is comprised of numerous decision units and is employed to evaluate the relative technical efficiency (TE) of each decision unit. In particular, the BCC model assists us in comprehending the efficiency status of each decision unit in actual production by calculating its TE, scale efficiency, and comprehensive efficiency.

The BCC model is implemented in this investigation to measure the TE, scale efficiency [SE or k], and overall efficiency [OE or θ] of agriculture in Shaanxi province, using the DEAP2.1 software (The DEAP 2.1 software was developed by the University of Maastricht, located in the Netherlands). The precise formulas for these parameters are as follows:

- TE: quantifies the degree of rationality between inputs and outputs. A value of 1 indicates that the TE has achieved its maximum potential, while a value of 0 suggests that there is still space for improvement.
- SE (k): a metric that assesses the logic of the input scale. The scale is considered scale efficient when SE equals 1, and it is non-scale efficient when SE does not equal 1.
- OE (θ): integrated TE, derived from TE × SE. A value of 1 indicates that the decision unit is effective on DEA, while a value of 0 indicates that it is effective on non-DEA.

3.1.1. Study of modeling equations

The model in this study uses the following linear programming equation (Equation I) for efficiency calculations:

$$s.t.\begin{cases}\sum_{i=1}^{n} x_i\gamma_i + s^- = \vartheta x_0 \\ \sum_{i=1}^{n} y_i\gamma_i + s^- = \vartheta y_0 \\ \sum_{i=1}^{n} \gamma_i = 1 \\ \gamma_i \geq 0, s^+ \geq 0, s^- \geq 0 \\ i = 1,2,3,\sim,n\end{cases} \quad \text{(I)}$$

where x_i and y_i denote the input and output variables, respectively, and γ_i, ϑ, s^-, and s^+ denote the combination coefficients of the units, the efficiency evaluation index, and the slack variables, respectively. In the context of Data Envelopment Analysis (DEA), "s.t." stands for "subject to," which is used to introduce constraints in mathematical models. The sentence describes the variables involved, such as input and output variables, combination coefficients, efficiency evaluation index, and slack variables. A decision unit is considered DEA efficient when the efficiency evaluation index equals one and both slack variables are zero. If the efficiency index is less than one, the unit is considered non-efficient. The decision unit is DEA efficient when $\vartheta = 1$ and $s^- = s^+ = 0$, and non-efficient when $\vartheta < 1$.

Second, for the sample set in Equation I with *n* decision units, each decision unit has *m* inputs and *s* outputs. Let *Xi* and *Yi* represent the input and output variables of the *r*th decision unit, respectively, as shown in Equation II:

$$\begin{cases} x_i = \left(x_{1i}, x_{2i}, \sim, x_{mi}\right)^T \\ y_i = \left(y_{1i}, y_{2i}, \sim, y_{si}\right)^T \end{cases} \quad \text{(II)}$$

where X_{ri} and Y_{ji} denote the input and output quantities. The weight vectors corresponding to the inputs and outputs are denoted by α and β, respectively, as shown in Equation III:

$$\begin{cases} \alpha = \left(\alpha_1, \alpha_2, \sim, \alpha_m\right)^T \geq 0 \\ \beta = \left(\beta_{1i}, \beta_2, \sim, \beta_s\right)^T \geq 0 \end{cases} \quad \text{(III)}$$

The h_k represents the efficiency evaluation value for the kth decision unit, as expressed in Equation IV:

$$h_k = \frac{\beta^T y_k}{\alpha^T x_k} = \frac{\sum_{t=1}^{s} \beta_t y_k}{\sum_{i=1}^{m} \alpha_t y_k} \quad \text{(IV)}$$

In the BCC model with constant returns to scale, the ratio of the output $\beta\ Y^{Tk}$ value to the input $\alpha\ X^{Tk}$ value of

the corresponding decision cell yields a corresponding efficiency value that does not exceed one.

3.1.2. Robustness and applicability discussion

The characteristics of the data distribution may influence the efficacy of the DEA method in practice. The following issues should be taken into account to guarantee the veracity of the analysis:

- Normality assumption: To guarantee the reliability and stability of the assessment results, DEA models typically presume that the data distribution follows a normal distribution. In the event that the data exhibit a substantial deviation from the normal distribution, data transformation or other robustness methods may be implemented.
- Collinearity issue: The efficiency measurement may be distorted if there is a significant covariance between the input and output variables. Consequently, to enhance the model's accuracy, it is imperative to identify and eradicate any significant covariance.
- Robustness analyses: To guarantee that the model's results are not substantially influenced by fluctuations in the data, robustness tests are implemented by altering various assumptions regarding the data (e.g., sample size or minor fluctuations in indicator values).

The aforementioned methodology guarantees that the DEA-BCC model is applied accurately to measure the efficacy of agricultural production and to provide dependable analyses.

3.2. Variable selection and data sources

The input indicators in this paper consist of land inputs, machinery, and water inputs, and fertilizer inputs. Indicators of land input encompass the total sown area of crops and the effective irrigated area. Indicators of machinery and water input encompass the total power of agricultural machinery and the total capacity of reservoirs. Indicators of fertilizer input encompass the pure amount of agricultural fertilizer deployed. The output indicators include the value of agricultural output and crop production, specifically the aggregate value of agricultural, forestry, animal husbandry, and fishery output, the value added by agriculture, forestry, animal husbandry, and fishery, as well as cereal and fruit production. The pertinent experimental data of the input and output indicators are illustrated in Tables 1 and 2.

3.2.1. Indicators of input

The total sown area of crops is the total area of sown or transplanted crops on all land (cultivated or non-cultivated) that should be harvested by the agricultural producer in the calendar year, including the sown area of crops harvested in the current year and excluding the area of crops harvested in the following year.[21]

Effective irrigated area is a critical metric that reflects the construction of China's agricultural water conservancy.[22] It is the area of arable land that is equipped with water sources, uniform terrain, and irrigation facilities, allowing for normal irrigation in normal years.

The total power of agricultural machinery is the aggregate of the designated power of all agricultural machinery, which is categorized as diesel engine power, petrol engine power, electric motor power, and other mechanical power based on the source of energy.[23]

The entire reservoir capacity is the entire scale of reservoir construction, which is determined by the aggregate of dead storage capacity, booster capacity, and flood transfer capacity (excluding the duplicated portion with booster capacity).[24]

The unadulterated quantity of agricultural fertilizer application is the total amount of fertilizer used in agricultural production during the present year, which includes nitrogen, phosphorus, potash, and compound fertilizers.[25]

3.2.2. Indicators of output

The total output value of agriculture, forestry, animal husbandry, and fisheries is the monetary value of all products of agriculture, forestry, animal husbandry, and fisheries, as well as related supportive service activities.[26] This value reflects the total scale of production over a specific period.

Value added by agriculture, forestry, animal husbandry, and fisheries refers to the contribution of these sectors over a specified period. It is a component of GDP and is determined by subtracting intermediate inputs; the cost of intermediate goods and services used in the production process from the total value of the output.[27]

Food production refers to the aggregate quantity of food produced by an agricultural producer in a calendar year, which encompasses cereals, potatoes, and pulses, categorized by crop variety and harvest season.[28]

Fruit production refers to the quantity of fresh fruits produced by an agricultural producer during a calendar year, excluding untamed fruits, including trees, vines, perennial vegetative fruits, and fruiting melons.[29]

4. Empirical studies of the effects of implementation

The BCC model with variable returns to scale (VRS) is used to investigate the agricultural efficiency evaluation problem in Shaanxi Province from the perspective

Table 2. Basic data of the indicator system

Year	X1	X2	X3	X4	X5	Y1	Y2	Y3	Y4
2012	4182.84	1277.18	2350.17	77.4	239.8	2309.55	1370.2	1255.92	1600.4
2013	4108.22	1209.94	2452.72	88.49	241.73	2569.78	1526	1210.55	1649.64
2014	4053.87	1226.49	2552.13	87.64	230.19	2748.59	1635.8	1183.53	1702.41
2015	4050	1236.77	2667.27	86.8	231.95	2821.56	1673.2	1204.67	1762.27
2016	4160.15	1251.39	2171.91	89.87	233.05	2994.83	1776.3	1263.96	1826.38
2017	4063.88	1263.09	2242.51	94.35	232.15	3077.62	1830.62	1194.2	1922.06
2018	4091.01	1274.99	2311.79	94.35	229.64	3239.99	1927.32	1226	1835.08
2019	4132.09	1285.16	2331.49	93.8	202.52	3536.8	2098.01	1231.13	2012.79
2020	4160.85	1336.81	2387.96	102	201.91	4056.61	2381.64	1274.83	2070.55
2021	4189.27	1336.8	2431.21	111	200.7	4313.44	2532.15	1270.43	2141.13

Note: Data compiled from Shaanxi province statistical yearbook (2013 – 2022), China Statistical Yearbook (2013 – 2022), and China rural statistical yearbook (2013 – 2022). The indicator symbols (X1 – 5, Y1 – 4) are defined in Table 1.

Table 3. Results from evaluation of agricultural efficiency

Years	TE	SE (k)	OE (θ)	s^-	s^+	Validity
2012	1.000	1.000	1.000	0.000	0.000	DEA strong and effective
2013	1.000	0.991	0.991	452.301	573.305	Non-DEA valid
2014	1.000	0.961	0.961	427.012	100.585	Non-DEA valid
2015	1.000	0.984	0.984	474.442	163.985	Non-DEA valid
2016	1.000	1.000	1.000	0.000	0.000	DEA strong and effective
2017	1.000	0.992	0.992	107.374	636.880	Non-DEA valid
2018	1.000	0.982	0.982	86.283	295.152	Non-DEA valid
2019	1.000	1.000	1.000	0.000	0.000	DEA strong and effective
2020	1.000	1.000	1.000	0.000	0.000	DEA strong and effective
2021	1.000	1.000	1.000	0.000	0.000	DEA strong and effective

Abbreviations: DEA: Data envelopment analysis; OE: Overall efficiency; SE: Scale efficiency; TE: Technical efficiency; s^-: Efficiency evaluation index; s^+: Efficiency evaluation slack variables.

of SLM. The performance evaluation is calculated by solving the optimal solution of the aforementioned linear programming problem using DEAP2.1 software, and the results are presented in Table 3.

4.1. Integrated efficiency analysis

To analyze the changes in the efficiency of agricultural inputs and outputs in Shaanxi province from 2012 to 2021, in the BCC model, VRS was employed. To achieve a comprehensive evaluation of the efficiency status of agricultural production, the BCC model's analytical framework deconstructs the comprehensive efficiency into two primary indicators: TE and scale efficiency. In addition, the idle variables were analyzed. The subsequent section provides a comprehensive examination of agricultural production efficiency by year from four perspectives: TE, scale efficiency, comprehensive efficiency, and idle variables, as illustrated in Table 3 and Figure 3.

4.1.1. TE

The efficiency that is the consequence of technical factors is reflected in TE. If the TE value is 1, it suggests that the utilization of input factors is technically optimal; conversely, if it is <1, it suggests that there is potential for improving TE. This analysis demonstrates that the TE of Shaanxi agriculture was consistently 1 from 2012 to 2021, suggesting that the technical inputs were at their most optimal during this period and that the use of technology in the agricultural production process was relatively consistent and reasonable.

4.1.2. SE

The SE is a metric employed to assess the influence of scale factors on efficiency. The optimal state of scale is indicated by a SE value of 1, which is equivalent to constant returns to scale. A SE value of <1 suggests that efficiency can be enhanced by expanding the scale, while a SE value of >1

indicates that the returns to scale are diminishing and that the scale must be reduced to increase efficiency.

From the data collected from 2012 to 2021, the SE reached a value of one1 only in 2012, 2016, 2019, 2020, and 2021, suggesting that the scale of agricultural production in these years has reached the optimal state. Conversely, the scale efficiency in the other years (2013, 2014, 2015, 2017, and 2018) is <1, suggesting that the scale of agricultural production in these years can be improved by expanding the scale, and there is some room for scale efficiency improvement. In 2013, the scale efficiency was 0.991, which is marginally lower than the optimal value of 1, suggesting that the scale of agricultural production was slightly reduced in that year and may require moderate expansion to attain a higher level of efficiency.

4.1.3. OE

TE and scale efficiency are combined to calculate OE, a value employed to evaluate the decision unit's overall efficiency. The process is referred to as "DEA strongly effective" when the integrated efficiency is equal to one and the slack variables (s^- and s^+) are both 0. It is referred to as "DEA weakly effective" when the integrated efficiency is = 1 but the slack variables (s^- and s^+) are >0, and "non-DEA efficient" when the integrated efficiency is <1.

From 2012 to 2021, the OE of agricultural production in 2012, 2016, 2019, 2020, and 2021 was 1, while both s^- and s^+ were 0, indicating that the efficiency of agricultural production in Shaanxi during these years had reached its optimal level and was situated on the optimal production frontier. This is considered "DEA strongly effective." In other years, the comprehensive efficiency is <1, as evidenced by the score of 0.961 in 2014. This suggests that there is still room for the efficiency of agricultural production in those years, as it has not yet reached the optimal level.

4.1.4. Variables of relaxation (s^- and s^+)

To achieve the target efficiency, the slack variable s^- denotes the quantity of inputs that can be reduced, while s^+ denotes the quantity of outputs that can be increased. Based on these variables, it is possible to optimize resource allocation and identify instances in which outputs are inadequate or resources are squandered.

In 2013, the slack variables were larger than those in 2015, with s^- at 452.301 and s^+ at 573.305. This suggests that agricultural productivity can be enhanced in 2013 by reducing certain inputs and increasing outputs. Conversely, both the slack variables were 0 in 2012, 2016, 2019, 2020, and 2021, suggesting that resource allocation had been optimal in these years and that there was no wastage of resources or insufficient output.

4.1.5. An analysis of the overall trend

All in all, the aggregate agricultural production efficacy in Shaanxi province exhibited volatility from 2012 to 2021. In 2012 and 2013, the comprehensive efficiency experienced a decline, followed by a minor increase from 2013 to 2016. However, it underwent another decline in 2017 and subsequently stabilized after 2019. The instability of agricultural development in Shaanxi province is reflected in this volatility, which may be influenced by a variety of external factors, including policy changes, fluctuations in market demand, and natural factors.

Overall, the agricultural production efficacy of Shaanxi province attained its maximum in certain years between 2012 and 2021; however, there was still room for improvement. In the future, there is still potential for additional exploration in the areas of optimizing resource allocation, increasing output, and expanding scope to accomplish the sustainable and efficient development of agricultural production.

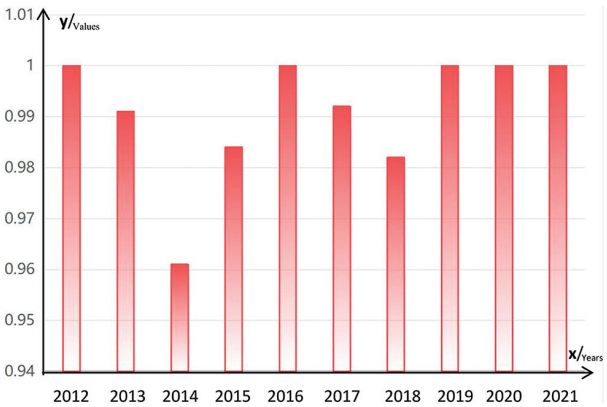

Figure 3. Track chart for overall efficiency in 2012 – 2021

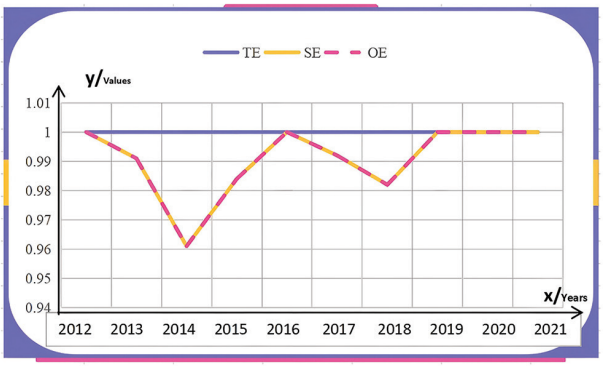

Figure 4. Efficiency analysis chart for 2012 – 2021
Abbreviations: OE: Overall efficiency; SE: Scale efficiency; TE: Technical efficiency.

4.2. Analysis of pure TE

Based on the data analyzed in Table 3 and Figure 4, the pure TE of agricultural production in Shaanxi province has consistently remained at 1 from 2012 to 2021. Throughout the study period, Shaanxi province maintained the technically optimal level of agricultural input management, utilizing all available resources to achieve the highest possible outputs. There was no deficiency of pure TE in any of the years. According to this performance, Shaanxi province maintains a consistent technical efficacy between inputs and outputs and a high technical level of agricultural production.

4.2.1. The stability of sheer technical efficacy

Over a 10-year period, the pure TE of agriculture in Shaanxi had been maintained at 1, demonstrating the high efficiency and stability of agricultural production. Throughout this period, Shaanxi's agricultural production has maintained a high level of TE, effectively avoiding resource waste caused by inadequate technical management, despite fluctuations in external conditions. The technical management of Shaanxi's agricultural production system is highly adaptable and risk-resistant, as evidenced by this stability, which demonstrates its efficacy in the application and management of agricultural technology.

4.2.2. Pure TE in comparison to other efficiencies

On further examination, it is evident that the value of pure TE was consistently equivalent to 1, whereas SE and OE were usually <1. According to this discrepancy, the technical administration of agricultural production in Shaanxi province had achieved its maximum efficiency; however, there is still space for development in SE. For instance, the level of SE did not surpass 1 between 2013 and 2018, indicating that the production scale could be further optimized during this period.

4.2.3. The effect of sheer technical efficacy

Agricultural production can optimize resource allocation by relying more on the extant technical management system when fluctuations in pure TE are minimal. At the same time, the fundamental conditions for further optimizing scale efficiency are established by the high value of pure TE (1). The efficiency of agricultural production in Shaanxi province is anticipated to be further enhanced by the appropriate expansion of the scale of agricultural production and the improvement of the scale management strategy in years when the SE does not reach 1. This is expected to maintain the technical optimality while enhancing the comprehensive efficiency.

4.2.4. Potential for upgrades and the direction of future enhancement

Although Shaanxi province has maintained a consistent level of pure TE throughout the study period, there is still room for further enhancements in the overall agricultural production. Improvements in scope and incorporated efficiencies could provide a fresh impetus to the overall improvement of efficiency. To improve the overall efficacy and sustainability of the agricultural system, Shaanxi province can leverage the technical administration that has been established to investigate innovative methods of scaling up and optimizing resource allocation.

From 2012 to 2021, the pure TE of Shaanxi agriculture has consistently maintained an optimal level, which is indicative of the effective management of inputs and the application of agricultural technology. There is still some space for optimization in terms of scale efficiency and comprehensive efficiency, despite the fact that there is no way to enhance TE. The future work could concentrate on the further optimization of scale management to facilitate the overall enhancement of agricultural production efficiency in Shaanxi province and to establish a more sustainable agricultural development model.

4.3. Rewards of scale analysis

In the fields of economics and management, SE is a critical factor in determining the rational allocation of resources and the optimal scale of production. Scale efficiency is the ratio of pure TE to comprehensive efficiency, which is employed to assess the efficiency of resource utilization within the current scale of inputs and outputs. When the SE is 1, it suggests that the scale of production is optimal and resource allocation is reasonable. Conversely, when the SE is <1, it suggests that the scale of production can be expanded to further optimize resource allocation. This is evident in Table 4.

4.3.1. Modifications in the nature of returns to scale

The scale remuneration in Shaanxi Province agriculture experienced two phases between 2012 and 2021, as shown in the table: "fixed scale remuneration" and "increasing scale remuneration".

The coefficient of returns to scale (when SE = 1) was 1 in 2012, 2016, 2019, 2020, and 2021. This indicates that the scale of agricultural production in these years has already reached the optimal level, the allocation of resources is reasonable, and the relationship between inputs and outputs has remained stable. Consequently, there is no need to improve efficiency by manipulating the scale of production.

In 2013, 2014, 2015, 2017, and 2018, the coefficients of returns to scale were <1, suggesting that the scale of

Table 4. Rewards of scale analysis

Years	Coefficient of return to scale	Typology
2012	1.000	Fixed remuneration for size
2013	0.958	Increasing returns to scale
2014	0.936	Increasing returns to scale
2015	0.959	Increasing returns to scale
2016	1.000	Fixed remuneration for size
2017	0.956	Increasing returns to scale
2018	0.966	Increasing returns to scale
2019	1.000	Fixed remuneration for size
2020	1.000	Fixed remuneration for size
2021	1.000	Fixed remuneration for size

agricultural production could have been further expanded to achieve higher resource use efficiency. This is indicative of an increase in returns to scale (SE < 1). This suggests that a proportionately greater increase in output can be achieved by increasing inputs during these years.

4.3.2. Examinations of incremental scales

The agricultural production in Shaanxi province was in the process of increasing returns to scale during the years 2013 – 2018, as evidenced by the coefficient of returns to scale being <1. In this state, agricultural production is effective in increasing output by expanding inputs. Specifically, the marginal output of resources increases as the scope of production increases. For instance, in 2013, the coefficient of returns to scale was 0.958, which implies that the production scale expansion could result in a more efficient allocation of resources that year. This is also corroborated by the coefficients of returns to scale of 0.936 and 0.959 for 2014 and 2015, respectively.

4.3.3. Examination of the fixed state of returns to scale

The coefficient of returns to scale of agricultural production in Shaanxi province is 1, which is in the stage of fixed returns to scale, for the years 2012, 2016, 2019, 2020, and 2021. The allocation of resources was reasonable, and the inputs and outputs of agricultural production had already attained the optimal state. The efficiency of the production scale was not significantly affected by further expansion or reduction. This state suggests that Shaanxi province has optimized the utilization of its agricultural resources in recent years, and there is no requirement for additional scale adjustments to enhance efficiency.

4.3.4. The practical importance of returns to scale adjustments

Fluctuations in returns to scale provide policymakers with crucial insights for guiding resource allocation in agricultural production. In years where the returns to scale are increasing, the scale of production can be moderately expanded to generate higher economic benefits and improve the efficiency of resource use. In contrast, the production scale is already optimal in years with fixed returns to scale, and further expansion may result in a decline in output returns or resource squandering. Consequently, the present production scale should be maintained.

4.3.5. Variables that influence the efficacy of scale

Various factors, such as changes in market demand, optimization of resource allocation, advancements in agricultural production technology, and policy support, may influence the coefficient of returns to scale. The incremental increase in the coefficient between 2013 and 2018 may be associated with the enhancement of agricultural technology and resource utilization efficiency. Conversely, the fixed state of returns to scale after 2019 indicates that agricultural production in Shaanxi province has reached a relatively stable and efficient phase, which may be attributed to the optimal allocation of resources and the accumulation of technology in the preceding period.

4.3.6. Prospective avenues for optimizing SE

To ensure the sustainable development of agricultural production in Shaanxi province in the future, it is advisable to continue optimizing resource allocation and investigating the potential for production scale expansion during periods of increasing returns to scale. During periods of fixed returns to scale, it is beneficial to prioritize technological innovation and management to enhance the quality of outputs and the utilization rate of resources while maintaining the optimal scale.

In conclusion, the scale remuneration of agricultural production in Shaanxi province has undergone a process of incremental growth and stabilization between 2012 and 2021, which is indicative of the efficiency status of agricultural production in various years. The continuous optimization of scale efficiency is of great importance in enhancing the efficiency of the utilization of agricultural resources and attaining greater economic and social benefits. Shaanxi province can continue to advance sustainable, stable, and efficient agricultural development in the future by optimizing SE.

4.4. Analysis of input redundancies and output deficiencies

The input redundancy and output deficiency analysis, which is based on the data in Table 5, enables the evaluation of the efficacy of resource utilization to ascertain the presence of waste or output deficiency. The data analyzed from 2012

Table 5. Analysis of input redundancies and output deficiencies

Years	Relaxation variable, s^-						Input redundancy rate				
	X1	X2	X3	X4	X5	Aggregation	X1	X2	X3	X4	X5
2012	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
2013	85.056	0.000	349.419	1.582	16.244	452.301	0.021	0.000	0.142	0.018	0.067
2014	0.000	6.347	417.529	0.000	3.136	427.012	0.000	0.005	0.164	0.000	0.014
2015	0.000	0.000	462.540	0.000	11.901	474.442	0.000	0.000	0.173	0.000	0.051
2016	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
2017	59.439	16.866	0.000	0.000	31.069	107.374	0.015	0.013	0.000	0.000	0.134
2018	0.000	2.340	68.388	0.000	15.555	86.283	0.000	0.002	0.030	0.000	0.068
2019	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
2020	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
2021	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Years	**Relaxation variable, s+**						**Output shortfall rate**				
	Y1	**Y2**	**Y3**	**Y4**		**Aggregation**	**Y1**	**Y2**	**Y3**	**Y4**	
2012	0.000	0.000	0.000	0.000		0.000	0.000	0.000	0.000	0.000	
2013	298.500	175.241	0.000	99.564		573.305	0.116	0.115	0.000	0.060	
2014	61.086	30.553	0.000	8.946		100.585	0.022	0.019	0.000	0.005	
2015	103.814	60.171	0.000	0.000		163.985	0.037	0.036	0.000	0.000	
2016	0.000	0.000	0.000	0.000		0.000	0.000	0.000	0.000	0.000	
2017	407.462	229.418	0.000	0.000		636.880	0.132	0.125	0.000	0.000	
2018	166.651	81.405	0.000	47.095		295.152	0.051	0.042	0.000	0.026	
2019	0.000	0.000	0.000	0.000		0.000	0.000	0.000	0.000	0.000	
2020	0.000	0.000	0.000	0.000		0.000	0.000	0.000	0.000	0.000	
2021	0.000	0.000	0.000	0.000		0.000	0.000	0.000	0.000	0.000	

Note: The indicator symbols (X1 – 5, Y1 – 4) are defined in Table 1.

to 2021 indicates that agriculture in Shaanxi province has experienced input redundancy and output insufficiency in multiple years, with the most significant years being 2013, 2014, 2015, 2017, and 2018.

The years 2013, 2014, and 2015 exhibit notably high redundancy in terms of input redundancy, particularly in agricultural machinery (X3) and fertilizer inputs (X5). For instance, in 2013, the redundancy of agricultural apparatus was 349.419 and the redundancy of fertilizer input was 6.7%, indicating that resources were squandered during that period. 2017 and 2018 also witnessed smaller redundancies, albeit of a lesser magnitude.

In 2013, 2015, and 2017, there were substantial output deficits in gross agricultural output (Y1) and value added (Y2). The output deficits in 2012 and 2013 were 11.6% and 11.5%, respectively, reflecting the relative output deficits in these years. The cumulative output deficits in 2013 were 573.305. The low productivity of 2017 was further emphasized by the fact that the total output deficits were even higher, totaling 636.880.

In the years without redundancies and deficiencies (e.g., 2012, 2016, 2019, 2020, and 2021), both inputs and outputs achieved their target efficiencies, indicating a high level of production efficiency and a reasonable allocation of resources. Thus, Shaanxi province can enhance the efficacy of agricultural production and optimize resource utilization by reducing redundancy and increasing output.

5. Discussion

SLM is significantly influenced by agricultural production efficiency, which has a significant impact on the efficient utilization of resources and the development of rural areas. Improved agricultural production efficiency not only optimizes resource allocation but also promotes the sustainable development of rural economies, particularly in resource-constrained rural areas. In this section, we focus on the role of agricultural production efficiency in the context of SLM, providing a critical comparison of our findings with the existing literature to emphasize the novel contributions of this investigation.

The initial discovery of this study is that the TE of agricultural production in Shaanxi Province is consistent; however, there is potential for development in scale efficiency. Compared to the current literature, a significant number of studies concentrate solely on the inputs of agricultural production resources and neglect the interaction between land management and production efficacy. The innovation of this study lies in its focus on enhancing scale efficiency to achieve greater land resource utilization, with an emphasis on the sustainability of land resources. This methodology aligns with the concurrent objectives of ecological preservation and the effective utilization of agricultural resources in recent years, and it offers a novel perspective on enhancing the overall production efficiency of agriculture.[30]

The second principle of SLM is the optimization of resource allocation. This study analyses input redundancy and output insufficiency to identify the issues in agricultural resource allocation in Shaanxi province, and it proposes optimization strategies, in contrast to previous studies on single resource optimization. Existing literature identifies inadequate resource allocation as one of the primary factors influencing agricultural productivity,[31] a conclusion supported by our findings. However, this study offers specific recommendations for rationally adjusting resource allocation based on specific scale efficiency, thereby enhancing the practical applicability of the research findings.

SLM has also emphasized the influence of agro-technological innovations on the enhancement of agricultural productivity. Production efficiency is significantly enhanced by the implementation of agricultural technology, as indicated by the existing literature.[32] In this study, TE remained consistently high throughout the study period, suggesting that technology management was relatively effective. Nevertheless, during periods of inadequate economies of scale, it is advisable to allocate additional resources to technological advancements to establish a more sustainable production model and further enhance overall efficacy.

The cultivation of specialty industries is also emphasized in this study as a critical component of SLM. Contrary to other studies that concentrate solely on the improvement of agricultural production, this study suggests that the development of specialty agricultural industries can stimulate regional economic growth, thereby augmenting the overall efficacy of resource utilization. As an illustration, the distinctive agricultural products of Shaanxi province possess substantial market advantages. Regional productivity can be further improved by promoting their industrialization through rational land management policies.[33,34]

Lastly, SLM is particularly concerned with the enhancement of producers' income. According to research, the enhancement of production efficacy not only enhances yields but also enhances the quality of life for producers by increasing output income.[35,36] In contrast to previous research, the results of this study emphasize the importance of land management in achieving a balance between ecological and economic benefits with regard to efficiency development.

In summary, this study, in conjunction with the concept of SLM, comprehensively investigates the strategies for enhancing agricultural productivity, particularly the optimization paths of resource allocation and technological innovation, based on the existing literature. The implications of these discoveries are significant in the promotion of sustainable development in rural regions. The impact of various land management modes on production efficiency can be further investigated in future research to provide more detailed data support for policy formulation.

6. Conclusion

In this study, the agricultural efficacy in Shaanxi province is systematically assessed and the factors that influence it are analyzed based on the perspective of SLM. The DEA-BCC model is employed to analyze food production data from 2012 to 2021. This analysis exposes the optimization trend in resource allocation and technology application, as well as the prospective areas for efficiency improvement in Shaanxi's agriculture.

Over the course of the investigation, the findings indicate that agricultural efficiency in Shaanxi province has been on the rise, which is indicative of the ongoing enhancements in the application of technology and the allocation of production factors. However, the investigation also discovered that there is still room for improvement in agricultural efficiency, particularly during periods of increasing scale, and that farmers' incomes and production efficiency can be substantially enhanced by moderately adjusting inputs. For instance, agricultural production experienced output deficits and input redundancies in 2013, 2014, 2015, 2017, and 2018, particularly in the areas of agricultural output and fertilizer input. This implies the existence of irrational resource utilization in these years, which has a negative impact on the future enhancement of agricultural production efficiency.

One of the novel aspects of this study is that it provides specific recommendations for optimizing scale efficiency and resource allocation to resolve efficiency constraints within the context of SLM. In addition, agricultural efficacy was found to be not solely influenced by scale factors but also closely associated with technological advancements, policy

support, climate change, and land resource utilization. The dynamics of these factors provide valuable insights for future research, which should explore their long-term effects on agricultural efficiency, particularly in the areas of agricultural technological innovation and ecological protection. This will help inform the development of more targeted land management policies.

In terms of policy recommendations, this study emphasizes the significance of fostering agricultural technology innovation and optimizing resource allocation. To enhance overall efficiency, it is recommended that the government increase inputs when there is increased scale efficiency to facilitate the development of specialty industries. Simultaneously, pragmatic land management policies should be established, striking a balance between the sustainable utilization of resources and the preservation of the environment to advance agricultural production.

This study's comprehensive analysis of agricultural efficacy is not without its limitations. For example, the long-term consequences of external environmental factors, such as climate change, were not investigated. A more exhaustive understanding of the numerous factors influencing agricultural efficacy could be achieved by integrating these external factors into the model in future research. This study, in conclusion, offers effective strategies and policy recommendations for the sustainable development of agriculture in Shaanxi province and provides critical references and guidance for rural agricultural planning and land management.

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Conflict of interest

The author declares that there are no conflicts of interest regarding the publication of this paper.

Author contributions

This is a single-authored article.

Ethics approval and consent to participate

Not applicable.

Consent for publication

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Availability of data

The data used to support the findings of this study are included within the article.

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ORIGINAL RESEARCH ARTICLE

New method for statistical analysis of climate time series

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Abstract

After publishing four articles utilizing a new method for the statistical study of climate time series, we found it useful to provide a detailed review of the method itself, which is the primary objective of this work. Unlike the methods most commonly used by scientists analyzing such data, this new method does not seek to identify trends for explorative forecasts. Instead, it enables the detection of precise signals indicating interactions with other climate entities, thereby enhancing our understanding of the underlying phenomena. As illustrated through three example articles, the mechanisms uncovered using this method can be integrated into a mathematical model. The simulations thus obtained are more deterministic than stochastic – a significant advantage for producing high-quality forecasts in the context of global warming. Even if this was the sole application of the method, it would be sufficient to demonstrate its value. However, as a final example detailed in this work shows, reconsidering the original series using different periods (e.g., month, quarter, semester, year) can further refine our understanding of the mechanisms at play. We conclude this work by exploring the potential applicability of this method for analyzing non-climatic temporal data series.

Keywords: Climate time series; Markov chains; Signals; Statistical analysis method

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1. Introduction

Time series theory[1] has enabled great advances in sciences as well as in econometrics, information theory, demography, and astronomy.[2-5]

The application of this theory facilitates the isolation of trends as well as the identification of value stability and variations within the analyzed series. Based on this approach, it is possible to generate robust future or past projections, which often demonstrate greater reliability compared to those derived from even highly sophisticated structural models.

A major challenge in climatology is to obtain, from data collected in the form of time series, projections on the future of the parameters in question, accompanied by error bars, without which these projections would not be of real use.[6]

The classic approach begins with a climate equation that projects the climatic variable X(t) at time step t as the sum of a "trend" component $X_{trend}(t)$ and a "noise" component $X_{noise}(t)$, which reflects, for example, natural variability.

Often the equation is in this simple form: $X(t) = X_{trend}(t) + S(t)\, X_{noise}(t)$.

The main difficulty lies in obtaining a reliable estimate for the X_{trend} statistical trend from the known time series. Estimation methods are well developed and include linear curves (e.g., classic linear regression),[7,8] which may incorporate breaks,[9] accelerated increases or decreases,[10,11] along with "bootstrap" confidence intervals.[12,13] These methods also extend to non-linear behaviors or even non-parametric descriptions.[14-16] Mudelsee[6] gives a fairly complete overview of these methods, which are numerous and more or less complex, aiming to extract estimates from the data, accompanied by measures of uncertainty.

Even though the method presented in this article also starts from the raw data provided by climate time series, the initial approach is not the same. It does not seek to obtain estimates of future trends from the data but simply looks for possible "signals" of interactions with the time series of other climate entities whose signals are compatible with that of the initial series. These signals are obtained from the average lengths of increasing or decreasing chains of the studied climate parameter. The method is therefore referred to as the method of average lengths, or simply "MAL." Once these signals are detected and the climate mechanisms underlying their interactions are thoroughly explained, they can be incorporated into a climate model. Each instance in which the method isolates new interactions and elucidates their mechanisms contributes to significant improvement in the climate model.

Other methods exist to check the compatibility of time series and investigate the causal relationships. Starting with the calculation of the correlation coefficient between the two series concerned. But as we will see, it is possible that two series do not have a significant correlation and yet signals MAL are in agreement. This therefore indicates that MAL can detect invisible interactions by more classic means. This is also the case with techniques that are nevertheless much more sophisticated than the simple calculation of the correlation coefficient. For example, the use of the concept of co-integration introduced by Granger and Newbold[17] in econometrics facilitates the detection of long-term relationships between two or more time series. Several algorithms can be used to verify this, such as the Granger–Engle algorithm,[18] the Johansen approach,[19] the Stock–Watson test,[20] or the Phillips–Ouliar test.[21] Tests are also available to verify causal relationships and their significance between two digital entities represented by time series, such as the Granger causality test.[22] These methods are often well-suited for analyzing econometric time series in particular. However, in the studied climate series, we observed that traditional methods could be inapplicable or inconclusive in terms of co-integration or causality, despite the presence of MAL signals that showed strong correspondence. In other words, MAL proves to be more efficient and capable of detecting interrelationship signals that remain invisible to classical techniques. These signals, in turn, enable a deeper understanding of the underlying climate mechanisms.

This article is divided into three main parts:

1. Description of MAL: This first part presents the main idea of the MAL and what are the stages of its implementation.
2. Examples of MAL utilization in climatology: Four recent articles on mathematic models applied in climatology (Zeltz[23-26]) employ this new method for the statistical analysis of time series. As will be discussed in subsequent sections, MAL enables the identification of interactions that would likely remain undetected using traditional methods for studying numerical series, such as those presented by Mudelsee.[6] In the four sections of this second part, we show the implementation of MAL and address the questions that arose during its initial applications.[23-26]
3. Evaluation and perspective of MAL: We summarize here the strengths and weaknesses of MAL and provide a detailed example illustrating its utility in understanding the mechanisms at play across different time steps (e.g., months, quarters). Finally, we explore the potential applicability of MAL in fields beyond climatology.

2. Description of MAL

2.1. Sample introduction

Suppose there is a well-balanced coin with an equal probability of 0.5 for landing heads (denoted as H) or tails (denoted as T). If this coin is tossed 100 times, we record each successive outcome. The probability of obtaining a perfectly alternating sequence such as HTHTHT.HTHT is exceedingly small, specifically $(½)^{100}$, or less than one chance in a billion billion billion. This scenario is governed by a binomial law X~B (n = 100, P = 0.5). According to Delmas,[27] the expected distribution of successive heads (and similarly for tails) follows the mathematical expectations shown in Table 1.

In addition, the theoretical average length of the substrings is approximately 1.94.

Table 1. Theoretical frequencies for substrings of heads (H) or tails (T) of a certain length in a series of 100 coin tosses

Length	1	2	3	4	5	6	7 and more
Theoretical frequencies (%)	51	25	12.5	6	3.5	0.9	1.1

Now let's return to our sequence of one hundred throws. The experiment completed, we realize that in fact, the average length of the chains of successive H (or T) is clearly less than the theoretical figure of 1.94, that there are many more chains of 1 and 2 than predicted by the frequencies and much less for channels of 3 and more. The alternation is therefore much faster than predicted by theory. This can happen, and at this point, there is no reason to question the truly binomial character of the experiment.

On the other hand, if we repeat this experience of 100 tosses ten times in a row, and each time we find a clearly accelerated alternation, it becomes necessary to question the underlying cause. It is almost impossible for this to be a result of pure chance, and since the coin is perfectly balanced, the cause is most likely an interaction with an external phenomenon. The precise origin of this interaction – whether a periodic electromagnetic influence or another factor – cannot be determined without further investigation. Nonetheless, we can assert with high confidence that an external interaction is at play. This consistently shorter-than-expected average length of successive H (or T) chains serves as a "signal" indicating such an interaction.

This is the core concept of MAL: if, in a given time series with two equally probable outcomes A or B, the vast majority of chains of 100 successive outcomes exhibit significantly lower average lengths of successive A (orB) subchains at 1.94, it is reasonable to suspect the existence of an interaction with another entity that explains the stronger-than-expected alternation. Conversely, if the average lengths are significantly higher than 1.94, the hypothesis of an interaction must also be seriously considered.

If the time series in question concerns a certain climatic entity with two equally probable outcomes, these average lengths can serve as the "signals" indicating the presence of interactions with other climatic entities. A priori, it will be necessary to identify potential interactions among entities whose numerical data exhibit concordant signals, enabling effective selection for further investigation.

2.2. The main steps of MAL

Consider a certain time series concerning a climatic parameter with numerical values. The following steps outline its processing using MAL:

1. From the initial series, generate a second series consisting of "gaps," defined as the difference between each term in the initial series and the one immediately preceding it.
2. Verify whether this series of gaps can be modeled as "white noise" (p. 45 of Hamilton[1]). "White noise" refers to a series with no trend in either its mean or the standard deviation and with empirically calculated correlations that are nearly zero and independent of their positions in time.
3. Create a third series consisting of 1s and 0s by assigning the value 1 to each gap if it is positive and 0 otherwise. Then, verify that the point frequencies of 0s and 1s are both close to 0.5, ensuring that increases and decreases in the studied parameter can reasonably be considered equiprobable.
4. If either of the previous two steps fails, MAL cannot be used. However, if both conditions are satisfied, all prerequisites are met for modeling the binary series of 1s and 0s using a Markov chain (p. 682 of Hamilton[1]).
5. The temporal spacing (e.g., day, month, quarter, year) used in the initial time series, along with the "climatic memory" of the phenomenon, must be taken into account to determine the appropriate orders for the Markov chains. Based on these two parameters, only orders 0 and 1 were applicable in the four studies.[23-26] The following terminology is used to describe average chain lengths: (A) Close to 1.94: Markov-0 signal; (B) Significantly lower than 1.94: Markov-1 alternating signal; (C) Significantly higher than 1.94: Markov-1 lengthening signal. However, nothing precludes the possibility that higher-order Markov chains may be more adequate, especially when the climatic memory of the phenomenon significantly exceeds the length of the time series.
6. In the event of uncertainty between two possible orders, calculating the probabilities of obtaining the observed chain lengths for each potential order allows for determining which order is most appropriate for modeling the series.
7. In the case of order 0, the MAL does not reveal any signal of interaction with another climatic entity, though this does not mean there is none. However, as soon as the order is ≥1, as seen in the introductory example, it is a strong indication of an interaction with one or more other entities.
8. In this latter case, the next step is to identify these entities and verify that the signals observed in them are consistent with the proposed explanation.
9. The MAL method concludes at this point. It is then the responsibility of climatology and modeling to validate the proposed explanations.

3. Examples of MAL application in climatology

3.1. The first application of MAL

In the first study on MAL,[23] fluctuations in the global monthly average atmospheric temperature were analyzed

over the period 1880 – 2015. The detailed statistical study yielded two key findings:

1. Regardless of the sub-period of 100 consecutive months examined among the sixteen covering the 1880 – 2015 time frame, the frequencies of temperature rise or fall were approximately the same – very close to equiprobability.
2. Taking into account, the average lengths of the chains of ascents or descents – all <1.94 and most of them very clearly on the sixteen chains of 100 months analyzed – it was highly improbable (probability less than 1 in 60,000) that these fluctuations were governed by a binomial distribution with parameters $n = 100$ and $P = 0.5$. The result obtained in a given month (rise or fall) appeared to significantly increase the probability of reversal in the following month (fall or rise). Hence, the author proposed that these fluctuations are better modeled as first-order Markov chains, which he describes as "alternating," since the alternation is faster than what is expected under a binomial model.

All the steps described in Section 2.2 were then carefully verified, allowing the author to conclude that these chains were of Markov-1 alternating type.

MAL, therefore, was already largely developed and finalized in this first article.

The hypothesis put forward to explain this accelerated alternation was the following:

1. "When the atmosphere of the globe warms up, whatever the reason, the evaporation that this causes on the oceans and the land ends up increasing the low cloud cover. This development of low clouds then refreshes the atmosphere through the strong albedo effect of these clouds, as well as through the precipitation they bring.
2. If, on the contrary, the globe's atmosphere cools, there is less evaporation, therefore, fewer low clouds. The overall albedo effect of clouds decreases, which allows solar heat to better penetrate to the surface of the globe (Section IV-2 of the first study[23])

Its validation was based only on very partial cloudiness data (period 1983 – 2005) obtained from slide 10 of Taboada.[28] At the time, the author did not have more complete data on cloud cover and he was aware of the fragility of his conclusions since he added this:

"It is also regrettable that we do not have such a study over a much longer period because this would have made it possible to directly study the correlation between NOAA data and that of low cloud cover." (Section IV-2 of the first study[23]).

3.2. The second applications of MAL

As the previous explanation did not seem sufficient to be entirely conclusive, the author proposed a second explanatory hypothesis in another study.[24] This time, the second variable considered for interaction with the global average atmospheric temperature was the heat received by the Upper Oceanic Stratum (UOS) within the 0 and −700 m depth range.

For this analysis, he used quarterly data on the anomalies of this heat over a period of nearly 70 years (1955 – 2022), a duration long enough for a reliable study of the proposed hypothesis.

After processing the data as outlined in Section 2.2, he observed a distinct Markov-1 alternating behavior, similar to that seen in atmospheric temperature data, though with the key difference that these data were recorded quarterly rather than monthly.

In summary, as detailed in Section 3.1 of this study,[24] the author proposed the following principle of interaction:

The warming of the atmosphere in a given month causes evaporation, which requires calories drawn from the UOS, resulting in its cooling. With a certain inertia of the order of a month, this cooling propagates by conduction or convection into the ambient atmosphere, which increases the probability of atmospheric cooling in the following month. On the contrary, the cooling of the atmosphere in a given month reduces evaporation, meaning fewer calories are drawn from the UOS. As a result, incoming heat, particularly from solar rays, is more readily retained in the UOS, causing it to warm. This heat is then transferred to the surrounding atmosphere, thereby increasing the probability of atmospheric warming in the following month.

The quarterly, rather than monthly, alternation of the UOS heat anomalies is explained by the author in the following way: the thermal inertia of the UOS is significantly greater than that of the atmosphere. As a result, a duration on the order of a quarter is required for atmospheric events to produce visible and measurable repercussions on the heat received by the UOS. However, due to the accelerated monthly alternation of atmospheric conditions – faster than what would be expected under a binomial distribution – there is a higher likelihood that, over the course of a quarter, the monthly atmospheric averages follow one of the two patterns.

- Rise, then fall, then rise, leading to a greater likelihood of positive than negative results for the quarter in question.
- Fall, then rise, then fall, resulting in a greater likelihood of a negative than positive balance for the quarter in question.

To verify the consistency of this proposed explanation with the observations, the author developed a mathematical model (called Z.1) that takes into account the energy exchanges between the sun, the troposphere, and the UOS while integrating the hypothesized interaction between the UOS heat and atmospheric temperature. The constants in the model were calibrated using the data observed during the period 1955 – 2022. The Z.1 program is explained and summarized in Table 7 of the study.[24] We have reproduced Figure 1 of the study[24] as Figure 2 here. The figure presents the observed evolutions of the atmospheric temperature and UOS heat over the period 1955 – 2022, as well as the simulations obtained for these two temperatures over the period 1955 – 2095, generated by the Z.1 model.

Ultimately, the study[24] did not bring anything new for MAL itself compared to the previous study.[23] However, the validation of the explanations for the signals obtained through MAL is notably more thorough, and the simulations obtained using Model Z.1 provide strong support for the consistency of the proposed hypothesis with the observations. Furthermore, these simulations, generated quickly on a simple microcomputer, provide fairly precise information on the medium-term evolution of two of the most important parameters of the Earth's climate.

We can also note that on certain aspects, the method used in the study is reminiscent of Hasselmann's theory.[29] Like our approach, Hasselmann's theory involves Markov chains and takes into account different climatic memories of the world ocean and the atmosphere. It, therefore, seems interesting to precisely compare these two methods.

In Hasselmann's theory, short-term random noise (atmospheric weather) leads to longer-term variations (red spectra at the ocean level). This is mathematically modeled using a first-order autoregressive process, where the next step y_{t+1} of the long-term variation depends on the previous step y_t, weighted by the climatic memory m of the ocean, and is disturbed by short-term variability x_t:

$$y_{t+1} = m\, y_t + x_t$$

In our case, it is the "signals" detected that initially guide us: A Markov-1 alternating-type signal is observed for both atmospheric (monthly) and oceanic (quarterly) temperatures. This suggests the presence of an interaction, and the hypothesis formulated in the Z.1 model posits a direct interaction between the two. The difference in periodicity between the two signals is attributed to the vastly different climatic memories of the atmosphere and the ocean.

The Z.1 model is built on this interaction and has nothing stochastic apart from the fact that we introduced random coefficients to take into account natural variability. Thus, our model is more deterministic and less stochastic compared to Hasselmann's, even though both emphasize the critical role of climate memory in the framework.

3.3. The third application of MAL

In another subsequent study,[25] the author returns to a question that he had already addressed in the first study[23]: the influence of cloudiness on the climate. Having at his disposal oceanic cloud cover data spanning a long period

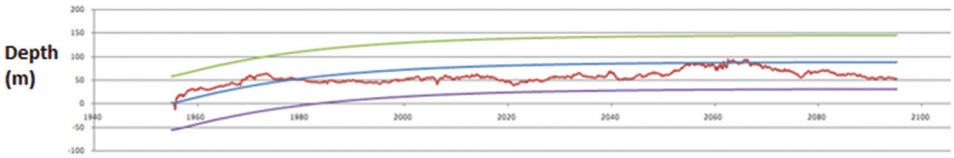

Figure 1. Simulations of Z.3 model for deepening. Reproduced from Zeltz[26]. Notes: Red curve: Simulation of anomalies of deepening, Sn (m). For the other curves: The 95% confidence interval is delimited by the upper curve and lower curve. The central blue curve is the theoretical curve (without taking into account natural variability) of the deepening anomalies.

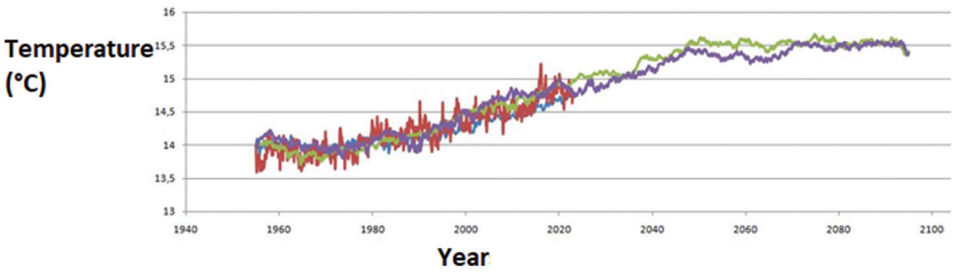

Figure 2. Simulations of t_n and θ_n over the period 1955 – 2095 compared to the observed temperatures of Ta_n and Θ_n during the period 1955 – 2022. Copyright © 2024 Author(s). Reproduced from Zeltz[24]. Notes: Red curve: observed atmospheric temperature, Ta_n; Purple curve: simulated atmospheric temperature, t_n; Blue curve: Observed upper ocean layer temperature, Θ_n; Green curve: simulated upper ocean layer temperature, θ_n.

– much longer than for those used in 2021 – the author applied MAL to the following data series:

- Ocean cloudiness (OC): The series of average quarterly diurnal anomalies for the period 1954 – 2008 obtained from meteorological reports recorded aboard ships and updated according to the standards of the World Meteorological Organization (further details on these data in Eastman *et al.*[30]
- UOS heat: The series of the quarterly average anomalies between 0 and −700 m depth range sourced from a database previously used in the second study[24] (downloadable from the provided link[1]). This dataset starts in 1955, overlapping with the OC database for 216 quarters, covering the period from 1955 to 2009.

Their analysis using MAL shows a clearMarkov-1 alternating signal for both datasets, along with a significant correlation (0.65) between them. This led to a hypothesis of an interaction between the two, which the author explains as follows:

"During a quarter the UOS warms up, this causes additional evaporation which has the consequence of increasing low and medium cloudiness, either in surface area or in opacity power by increasing their density, which in both cases increases their cooling power. Hence, when the production of this cloudiness develops following this warming, this new or more opaque cloudiness contributes to cooling what is under it, therefore the UOS, whose heat ends up starting to decrease with a certain delay. But then, the production of cloudiness also begins to decrease since there is less evaporation, which in turn leads to further warming of the UOS since it is better exposed to solar radiation. And this cycle can be repeated. In our opinion, we are therefore dealing with an interaction that can be compared to a two-stroke engine whose pistons would be the heat of the UOS and the OC. As for the 3-month cycles for the heat present in the UOS, they come from another interaction, the one that was highlighted by Zeltz[24] with the same "signal" techniques between the heat of the UOS and global average atmospheric temperature. Cycles which had been explained in particular by the cooling of the water which undergoes evaporation, but which the present study shows that they are undoubtedly further amplified by the reciprocal influence between the UOS and the OC."

The previous Z.1 model was slightly adapted into a Z.2 model to incorporate this explanation. Specifically, line 6 of Z.1, which rudimentarily modeled atmospheric albedo, was split into lines 6a and 6b in Z.2. This modification accounted for the interaction between OC and the heat of the UOS, allowing the resulting albedo to be redefined. The remaining 16 lines of Z.1 were retained in their entirety without any further addition to form the Z.2 model.

We reproduced Figure 3 of the study[25] as Figure 4 here, illustrating the "natural thermostat" effect exerted by OC. It provides comparisons of simulations of oceanic and atmospheric temperatures generated by the Z.2 model with those produced by the Z.1 model, which did not take into account the OC parameter.

Over the period 1955 – 2095, the "natural thermostat" effect played by cloudiness was evaluated using 250 simulations, revealing a negative feedback of approximately 1°C for atmospheric temperature and approximately 2°C for UOS temperature.

Concerning MAL itself, this third study[25] exploits a very interesting property. In section 2.3 of the article, the author provides probability-based justification that, even when the processed data contain significant uncertainty (as was the case for the OC data, for which Eastman *et al.*[30] ensured an uncertainty of <5%), this uncertainty largely diminishes when it comes to the 0 or 1 signals representing quarter-to-quarter increases or decreases. This demonstrates the remarkable robustness of the signals obtained through the MAL method.

This strength of the MAL method allows it to compensate for the lack of reliability that persists in the current knowledge regarding the spatio-temporal variability of cloudiness and the dynamics of the upper mixed layer. The signal detected is clear and constructed over a sufficiently long period to warrant its consideration and investigation into the interaction it signifies. Traditional statistical methods do not provide reliable trends in such cases, which is one of the most important reasons for disparities in the quantitative assessments of future global warming rates provided by leading climate institutes.[31]

3.4. The fourth application of MAL

In this last example,[26] the author's first objective was to explain the increase in the stratification of UOS observed since 1955, notably by Li *et al.*[32] and Sallée *et al.*[33]

For this purpose, he used half-yearly UOS stratification data over the period 1955 – 2023, sourced from the same dataset used by Li *et al.*[32] (downloadable from the provided link[2]).

The application of MAL to analyze these stratification data resulted in the detection of a Markov-1 lengthening type signal. According to the author, this signal reflects the interaction with the El Niño-Southern Oscillation (ENSO), which explains its nature. Other important climatic phenomena, such as Summer-Winter Seasonal Alternation and Intertropical Convergence Zone, also play a role in the

[1] https://www.climate.gov/media/13603

[2] https://pan.cstcloud.cn/web/share.html?hash=E0zjDQOeRfs

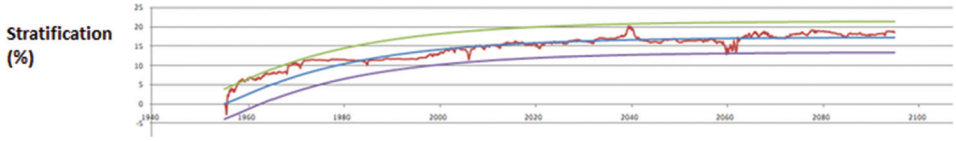

Figure 3. Simulations of Z.3 model for stratification anomalies. Reproduced from Zeltz[26]. Notes: Red curve: Simulation of anomalies of stratification, sn (%). For the other curves: The 95% confidence interval is delimited by the upper curve and lower curve. The central blue curve is the theoretical curve (without taking into account natural variability) of the stratification anomalies.

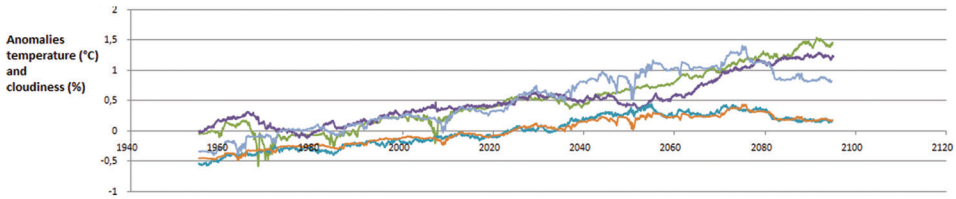

Figure 4. Graphs concerning simulations of θ_n, t_n, and cl_n for the period 1955 – 2095. Simulations of θ_n (green) and t_n (purple) anomalies (°C) were generated using the **Z.1** model. Simulations of θ_n (orange) and t_n (blue) anomalies (°C) were generated using the **Z.2** model. Simulations of cl_n (light blue)anomalies (%) were generated using the **Z.2** model (light blue curve). According to Zeltz[25]. Notes: θ_n: UOS temperature anomalies; t_n: Atmospheric temperature anomalies; cl_n: Oceanic cloudiness anomalies.

obtained signal, primarily by accelerating the half-yearly alternation. However, the dominant influence of ENSO ultimately results in a Markov-1 lengthening signal, with periodicities closely aligned with the three ENSO phases: El Niño, La Niña, and neutral events.

Once again, MAL has demonstrated its effectiveness. However, the study[26] revealed one of its limitations: the detected signal does not provide any clue to explain the observed increase in stratification within the upper 0 – 200 m ocean layer, which increased by approximately 1% per decade over the period 1955 – 2023. Moreover, there is a non-significant correlation (0.13) between the evolution of stratification and the ENSO index used.[26]

On the other hand, Zeltz[26] noted a significant correlation (0.84) between the six-monthly evolutions of this oceanic stratification and the thermal energy present in the UOS. This suggests that the increase in stratification is driven by the additional heat entering the UOS, a factor not directly identified by MAL. Summarizing the findings, the author stated: "In summary, ENSO lengthens the alternation periods, the arrival of additional heat in the UOS increases the stratification."

As this last example clearly shows, MAL can sometimes overlook very strong interactions, so users must be aware of this. That said, the MAL analysis of the stratification data successfully identified a significant interaction, which contributed to enhancing the Z.2 model by incorporating two new parameters into the global climate framework: oceanic stratification and the deepening of the mixed layer.

To help understand what may seem a paradox, Zeltz[26] uses the following metaphor:

"An analogy can help illustrate the distinction between these two types of information. Consider a musician using an electronic synthesizer: They can lengthen the cumulative duration of the ascending and descending phases of the sound power (analogous to alternation patterns) or adjust the average sound power using the potentiometer on their amplifier (analogous to quantitative variations). These are two distinct processes: the average sound power is directly influenced by the potentiometer, while the alternation speed is governed by the musician's rhythmic choices."

MAL detects the lengthening of the ascending and descending phases caused by the musician but is unable to detect the increase in power, which results from the adjustments made to the potentiometer. The Z.3 model, however, accounts for this by incorporating five of the most important parameters that define the global climate. Figures 1, 3, 5, 6 below illustrate simulations obtained from the Z.3 model (corresponding to Figures 6-9 of the last study[26]).

These graphs led the author to hypothesize a finite asymptotic growth behavior, which was mathematically proven using the relationships from the Z.3 model. The simulations produced by the model raise serious questions about some of the recent conclusions drawn by the IPCC. Specifically, while the Intergovernmental Panel on Climate Change (IPCC)[34] predicts an average global atmospheric warming of 3°C by 2100 under the same scenario, the Z.3 model forecasts a much lower increase of 1.5°C at most.

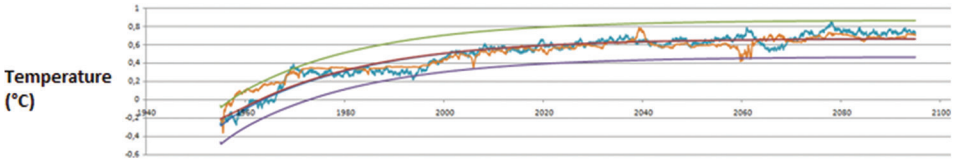

Figure 5. Simulations of Z.3 model for temperature anomalies. Reproduced from Zeltz[26]. Notes: Simulations of atmospheric temperature anomalies, tn (blue) and UOS temperature anomalies, θn (orange) anomalies (°C). For other curves: the 95% confidence interval is delimited by the upper curve and lower curve. The two central curves, which nearly overlap, are the theoretical curves (without taking into account natural variability) of tn and θn.

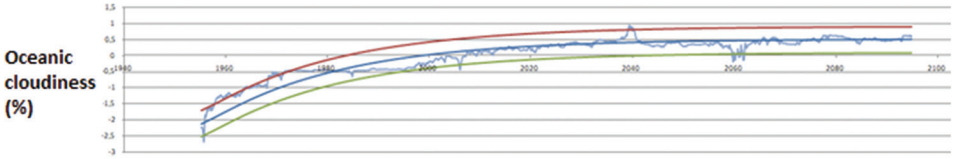

Figure 6. Simulations of Z.3 model for oceanic cloudiness anomalies. Reproduced from Zeltz[26]. Notes: Light blue curve: Simulation of anomalies of oceanic cloudiness, cln (%). For the other curves: The 95% confidence interval is delimited by the upper curve and lower curve. The central blue curve is the theoretical curve (without taking into account natural variability) of the oceanic cloudiness anomalies.

4. Evaluation and perspective of MAL

4.1. Main assets

Below is a summary of the key discoveries enabled by MAL across the four studies described in the previous section:

- Direct contributions:
  1. Interaction between the quarterly UOS heat and the monthly atmospheric temperature changes is explained by the differences in climatic memory and mediated through oceanic evaporation.
  2. Natural thermostat role played by OC on the UOS.
  3. Three-way interaction among the UOS, the OC, and the temperature of the atmosphere mediated through oceanic evaporation.
  4. The influence of ENSO on the detected signal observed in stratification data.
- Indirect contributions (through the Z.3 model):
  5. Clarity on the relationships between global warming, oceanic stratification, and the sinking of the mixed layer.
  6. Detection and mathematical demonstration of finite asymptotic growth behavior of five important climate parameters – atmospheric temperature, UOS temperature, OC, oceanic stratification, sinking of the mixed layer – in the context of current warming caused by the increase in greenhouse gases
  7. Predicting significantly lower asymptotic growth values for global warming parameters by 2100 challenging the IPCC's projections.
- Additional contributions
  8. Robustness of the generated signals, even in the event of significant uncertainties in the data series[25].
  9. The simplicity of the method – application can be performed using a simple microcomputer without any difficulty.
  10. Unlike traditional statistical methods for analyzing climatic time series, MAL results are not influenced by subjective decisions, such as the choice of the adjustment interval for estimating trends. A signal in MAL depends solely on the data series analyzed, eliminating biases introduced by arbitrary methodological choices (as highlighted by Mudelsee[6]).

In addition to the strengths already listed, some specific situations arise during the application of MAL, requiring tailored approaches to fully leverage the method's potential. The case of a Markov-0 binomial type signal (where the chains of 0 and 1 seem to be governed by a simple binomial law) is a bit special because they do not immediately impose an interaction with another climatic entity. However, this does not imply the absence of interactions – on the contrary, it is highly unlikely that any climatic parameter is entirely independent. In this case, one should search for potential interactions, prioritizing data series that exhibit similar signal characteristics.

In some instances, a signal may exhibit a "neutral" or "borderline" character, where it is neither clearly Markov-0 binomial nor distinctly Markov-1 alternating or lengthening. The following section will delve further into how changes in periodicity influence signal interpretation and how MAL can navigate these challenges effectively.

4.2. The example of stratification data

This section explores the ocean stratification data from Li *et al.*,[32] which was exploited by Zeltz.[25]

After completing the various necessary stages of the MAL (as described in Section 2.2), Table 2 summarizes the observations made on the chain lengths according to two criteria: The type of layer (0 – 2000 m or 0 – 200 m) and the period considered (month, quarter, semester, and year).

The following observations were noted:

- For the monthly data of the two layers, a mixed behavior, sometimes of Markov-1 lengthening type, other times of Markov-0 binomial type.
- For quarterly UOS data, the Markov-1 lengthening type behavior slightly prevails over the Markov-0 binomial type, though not clear.
- For the quarterly data from the upper 0 – 2000 m layer, the behavior is very pronounced Markov-1 lengthening type. Modeled by the binomial law with parameters $n = 100$ and $P = 0.5$, such a situation would be extremely improbable (less than one chance in a hundred thousand)
- For the UOS half-yearly data, the behavior is also of the very pronounced Markov-1 lengthening type. Modeled by the binomial law with parameters $n = 137$ and $P = 0.5$, such a situation would be very improbable (less than one chance in a hundred);
- For the half-yearly data from the 0 – 2000 m layer, the Markov-0 binomial type behavior takes precedence over the Markov-1 lengthening type.
- For the annual data of the two layers, the average lengths correspond well to the Markov-0 binomial case. The value of 1.92 for the ascent chains is within the required range (1.80 – 2.10). The value of 1.70 for the descent chains is certainly slightly below the lower limit of 1.80, but not significantly enough to challenge the Markov-0 binomial observation, as the 68 annual occurrences are not statistically sufficient for a tightly defined range with high confidence. It is more likely that this exceptional value, compared to all others, results from potential strong fluctuations in the average of a small sample.

Asking the following four questions, therefore, becomes imperative:

- Question 1: How can the rather Markov-1 lengthening type behavior for the half-yearly UOS stratification data be explained?
- Question 2: Why do the annual changes in the stratifications of the two layers exhibit a Markov-0 binomial-type behavior, appearing to lose all "memory" of the previous year from 1 year to the next?
- Question 3: Why are the quarterly stratification data of the upper 0 – 2000 m layer clearly of the Markov-1 lengthening type, while this is less evident for the UOS? And why is the opposite observed for the half-

Table 2. Average chain lengths of 1s and 0s for the 0 – 2000 m or 0 – 200 m (UOS) layers by month, quarter, semester, and year

Monthly	**Layers**	**0 – 2000 m**		**0 – 200 m (UOS)**	
	Chains of	**1**	**0**	**1**	**0**
1955 – 2023	Average	2.20	2.05	2.20	2.08
Total:827 values	Nb. of chains	270	257	268	262
1955 – 1965	Average	2.31	1.95	2.33	1.93
Total: 127 values	Nb. of chains	42	44	42	45
1965 – 1974	Average	2.82	2.13	2.54	1.88
Total: 100 values	Nb. of chains	34	30	35	33
1974 – 1982	Average	2.72	1.81	2.06	1.94
Total: 100 values	Nb. of chains	32	26	31	33
1982 – 1990	Average	2.06	1.97	2.75	1.96
Total: 100 values	Nb. of chains	32	34	32	26
1990 – 1999	Average	1.94	1.97	2.08	1.94
Total: 100 values	Nb. of chains	34	34	34	33
1999 – 2007	Average	2.00	1.90	1.88	2
Total: 100 valeurs	Nb. of chains	34	32	34	33
2007 – 2016	Average	1.88	2.06	1.9	2.10
Total: 100 values	Nb. of chains	32	31	32	31
2016 – 2023	Average	2.42	2.06	2.65	2.19
Total: 100 values	Nb. of chains	26	31	26	26
Quarterly	**Layers**	**0–2000 m**		**0–200 m (UOS)**	
	Chains of	**1**	**0**	**1**	**0**
1955 – 2023	Average	2. 35	2.35	2.13	2.04
Total: 275 values	Nb. of chains	80	70	84	79
1955 – 1978	Average	2.38	2.25	2.28	2.36
Total: 90 values	Nb. of chains	26	20	26	24
1978 – 2000	Average	2.66	2.63	2.21	1.93
Total: 90 values	Nb. of chains	27	16	30	26
2000 – 2023	Average	2.45	2.04	2.20	1.89
Total: 95 values	Nb. of chains	33	25	31	26
Semesterly	**Layers**	**0 – 2000 m**		**0 – 200 m (UOS)**	
	Chains of	**1**	**0**	**1**	**0**
1955 – 2023	Average	2.2	2.00	2.74	2.37
Total: 137 values	Nb. of chains	45	38	27	27
Yearly	**Layers**	**0 – 2000 m**		**0 – 200 m (UOS)**	
	Chains of	**1**	**0**	**1**	**0**
1955 – 2023	Average	1.92	1.70	1.92	1.7
Total: 68 values	Nb. of chains	24	20	24	20

yearly data?

- Question 4: Why do the monthly evolutions of the two layers oscillate between a Markov-0 binomial type and a faintly Markov-1 lengthening type?

The answer to Question 1 is provided in detail in section 3.1 of Zeltz,[26] reproduced in full in Appendix File. In summary:

As indicated by Sallée *et al.*,[33] a seasonal summer-winter alternation exists, particularly in temperate and cold zones, where a seasonal thermocline forms in summer (reinforced by the ice melting[35] and weakens in winter[36]). Likewise, the Intertropical Convergence Zone (ITCZ) contributes to a biannual alternation.[37] If only these two were at play, a biannual Markov-1 alternating signal would emerge. However, as demonstrated by Zeltz,[26] particularly through the index studied by Trenberth[38] the dominant influence of ENSO with its El Niño and La Niña phenomena, which explains that the Markov 1 lengthening type signal.

For Question 2, we propose the following explanation:

Unlike the semesters, over an entire year, the impacts of the ITCZ and the stratification caused by summer heat in the two hemispheres are balanced and neutralized. As for the "lengthening" impact, the average duration of the events involved (9 months for El Niño and La Niña, and 6 months for a neutral period), is too short to significantly increase the probability of repetition in the following year. Therefore, the annual fluctuations in the stratification of the UOS and the 0 – 2000 m layer exhibit a Markov-0 binomial-type behavior.

For Question 3, we propose the following explanation:

For the upper 0 – 2000 m layer, the quarterly stratification data strongly exhibit a Markov-1 lengthening type behavior, whereas this is not as pronounced for the UOS layer. To clarify, this does not mean that stratification increases more strongly on a quarterly basis in the 0 – 2000 m layer; rather, it means that if stratification increases (or decreases) in one quarter, the probability that it will continue to increase (or decrease) in the next quarter is higher than vice versa.

The explanation for this pattern is still largely linked to the ENSO phenomenon and this is how:

At the core of El Niño and La Niña events, there is a disruption of the trade winds compared to their ordinary regime. During an El Niño event, these winds weaken significantly due to an abnormally weak anticyclone, a phenomenon linked to the Walker convective loop but not yet fully understood.[39-42] This disruption has repercussions on the circulation of the equatorial underlying current (EUC)[43] which usually flows in the same area. The EUC, a significant and cold current equivalent to the flow of about 150 Amazon Rivers, has its core along the thermocline and generally moves eastward due to the stress exerted by westward-flowing trade winds. This creates a stratified shear flow, giving the main thermocline its characteristic slope.[44] However, when the trade winds weaken, the slope of the main thermocline is modified, causing the EUC to change direction. This, in turn, modifies the stratification of the upper 0 – 2000 m layer, which contains the thermocline located below the UOS. Given the scale of the phenomenon, its impact is readily observed in the global average stratification of the layer. Moreover, this effect manifests more quickly than temperature changes induced by El Niño-related water movement, which take longer to develop due to the thermal inertia involved.

Hence, shortly after the establishment of this new regimen, changes in stratification are felt in the 0 – 2000 m layer, becoming clearly visible during the current quarter and likely persisting into the following quarter. This explains the strongly "lengthening" character of the quarterly stratification signal for this layer. However, as the El Niño event reaches its full strength, stratification changes in this layer gradually return to standard behavior, causing the signal to quickly lose its "lengthening" characteristic at the half-year level for the upper 0 – 2000 m layer. Conversely, the UOS layer begins to be progressively affected by temperature changes that modify its stratification, eventually displaying a more pronounced "lengthening" characteristic at the half-year level. This described behavior of the EUC is certainly not a unique case; similar phenomena, such as those observed in the Weddel Sea under the influence of ENSO, further corroborate this pattern.[45]

For La Niña, unlike El Niño, deep convection is reinforced in the west of the basin while the trade winds gain intensity. Therefore, the inclination of the thermocline further increases compared to normal conditions, which strengthens the EUC in the eastward direction.[38] This results in cold temperature anomalies in the eastern Pacific and warm surface waters near the Asian coasts. These changes occur with a similar lag as in El Niño events, where the purely dynamic and mechanical modifications to stratification at the thermocline appear relatively quickly, while those of thermal origin take longer to manifest in the UOS.

And finally here is our answer to the Question 4:

Whether dynamic or thermal in nature, the effects on stratification of events such as El Niño or La Niña may not be sufficiently established to appear clearly in stratification signals during the 1st month following their onset in the Pacific zone. Furthermore, over the 100 consecutive months considered, there are long sub-periods without

the occurrence of these events. This likely explains why, for both layers, we observe a fairly balanced mix of monthly Markov-0 binomial type signals and Markov-1 lengthening type signals.

Thus, the fact that the signal may vary depending on the period considered (month, quarter, half-year, year) not only avoids real contradictions but also is well-explained and, in fact, contributes to a better understanding of the mechanisms at play.

4.3. The main reason for the effectiveness of MAL

The effectiveness of MAL lies primarily in its comparison of two "spectra"—the spectra of 0 and 1 for each of the two series being analyzed. Unlike other techniques, which rely on raw initial data or, in some cases, derived data (e.g., differences of successive terms for deseasonalization), MAL focuses solely on the binary aspect of whether the data increase or decrease. This transition from raw data to their "spectrum" leads to a huge loss of information, retaining only this critical piece: the direction of change. However, by isolating this single piece of information, MAL prevents it from being overshadowed by other elements in the raw data, enabling it to detect signals and interactions that other statistical techniques do not detect.

4.4. Possible use of MAL in sectors other than climatology

Time series have long concerned many sectors other than climatology, including econometrics, information theory, demography, astronomy, and epidemiology.[2-5,46-49]

Similar to its application in climatology, MAL can be effective in other fields, provided the digital data studied meet the necessary conditions for MAL processing, particularly that their successive deviations have the same probability of being positive or negative. Additionally, the field must be complex enough to exhibit multiple and varied interactions, a scenario where the method is well-suited for identifying potential interactions, as demonstrated in climatology. However, these conditions are restrictive, and only practical experiments can determine whether MAL proves valuable outside climatology.

It is worth noting that the concept of using Markov chains to analyze time series data is not new; for instance, it was employed as early as 1966 by Lortet-Zuckermann[3] to analyze a series of 444 successive explosions of the star SS Cygni observed from 1896 to 1957.

5. Conclusion

MAL is a new method for analyzing climatic time series based on the length of rise or fall chains in the studied climatic data. When fully implemented, the signals obtained provide valuable information, enabling precise identification of the mechanisms and interactions at play.

While this method does not reveal everything or decode all the climatic parameters at stake, MAL undoubtedly serves as a valuable additional tool for enhancing our understanding of the climate and achieving more reliable long-term projections.

The examples described in this clearly demonstrate the value of the method, yielding results of significant importance in climatology, such as:

- Detecting and explaining a phenomenon of "natural nervousness," where global average temperature differences have a greater tendency to reverse their sign than maintain it from 1 month to the next.[24]
- Demonstrating, in what seems a definitive way, that cloudiness provides clearly negative feedback on global warming, with the OC acting as a natural thermostat of the climate.[25]
- Establishing that the parameters most critical to defining the global climate exhibit limited long-term growth, predicting temperature increases by 2100 significantly lower than current IPCC projections.[26]

Moreover, nothing a priori prevents MAL from being applied in other sectors beyond climatology, as long as the system is complex and time series data are available.

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Conflict of interest

The author declares no conflicts of interest.

Author contributions

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Consent for publication

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Availability of data

Data are available from the corresponding author upon reasonable request.

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Appendix

Table A1 summarizes the average lengths of strings of 0 and 1 per semester for the UOS.

We notice the behavior of the very pronounced Markov-1 lengthening type. Modeled by the binomial law with parameters $n = 137$ and $P = 0.5$, such a situation would be very improbable (<1 chance in a hundred).

How to explain the rather Markov-1 lengthening type behavior for the half-yearly UOS stratification data?

Here is our detailed response to this question:

Sallée *et al.*[1] clearly indicate the summer-winter seasonal alternation which concerns the stratification of the UOS. Notably because in temperate and cold zones, there is in the 0 –200 m layer the presence of a seasonal thermocline in summer reinforced in particular by the melting of the ice[2] and which breaks down in winter.[3] Note that summer (winter) refers to August-October in the northern (southern) hemisphere and January-March in the southern (northern) hemisphere. Moreover, the significant imbalance in the land-sea relationship between the two hemispheres (80% of the surface area of the southern hemisphere is marine compared to only 60% of the northern hemisphere) means that there is no full compensation of the average stratification of that of the south by that of the north. Hence, if it was only this aspect that intervened, we should observe a half-yearly signal of the Markov-1 alternating type. However, it is of the Markov-1 lengthening type.

So necessarily, other phenomena intervene in the opposite direction. That of the influence of the Intertropical Convergence Zone (ITCZ) is undoubtedly one of them:

The ITCZ is more in the Southern Hemisphere during the austral summer and more in the Northern Hemisphere during the boreal summer.

However, the ITCZ brings rainy seasons and monsoons which cool the UOS in the vast ocean areas concerned and therefore reduce the stratification resulting from warming. The marine coverage of the ITCZ is much greater when it is positioned south of the Equator than in the north and therefore counterbalances the stratification caused by the austral summer on the temperate latitudes of this hemisphere. Likewise on the other hemisphere with related proportions. This phenomenon therefore certainly compensates for a large part of the summer increase in stratification present in the temperate zones of the hemisphere where the ITCZ is temporarily positioned. If there were no other influences, the signal would be of binomial Markov-0 type or close to it. However, it is clearly of the Markov-1 lengthening type. Hence, there is still at least one important additional influence which intervenes in the half-yearly evolution of the stratification of the UOS.

Table A1. Average lengths of chains of 1s and 0s following the 0 – 200 m (UOS) layer per semester

Per semester	Layers:	0 à 200m (UOS)	
Periods	Chains of:	1	0
Total (1955 – 2023)	Average:	2.74	2.37
137 values 0 or 1	Nb. of chains:	27	27

As we show below, using the statistics for El Niño and La Niña events obtained with the ONI index indicates that the "lengthening" character of the semiannual signal certainly comes largely from this influence. The ONI index used is an index provided by NOAA and downloadable from the following link: https://origin.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ONI_v5.php

The drastic rules applied to it to obtain it and the large geographical area over which it is calculated (5N-5S, 170W-120W) make it, in our opinion, the El Niño-Southern Oscillation (ENSO) index best suited for our study among those that exist (cf. Trenberth[4]).

According to him, over the 74 years of the period 1950 – 2023, the cumulative equivalent of approximately 21 years was affected by El Niño, that of approximately 22 years by La Niña and that of approximately 33 years is "normal," that is to say neither affected by El Niño nor affected by La Niña. Still according to this index, the average duration is about 9 months (more precisely 8.65) per El Niño event, about 9 months (9.21) per La Niña event and about 6 months (6.03) per neutral event. So if for example during a semester the stratification rises following an El Niño event, there is a greater probability that the following quarter it will continue to rise, since the El Niño event with an average duration of 9 months is very likely to last at least a few more months for the next semester. Likewise, if for one semester the stratification decreases following a La Niña event of average duration 9 months, there is a greater probability that it will continue to decrease the following semester, rather than it increase. Given the high frequency of such events (together, they cover 58.5% of the entire period 1950 – 2023), this is largely sufficient to explain the fact that the biannual chains concerning the stratification of the UOS and layer 0 – 2000 m above are pronounced Markov 1 lengthening type.

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Designing sustainable urban parks: A proposal backed by practical research

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Abstract

Sustainable urban park designs are essential in advancing urban sustainability by addressing environmental issues, enhancing community well-being, fostering social interactions, and boosting local economies. Hence, this study aimed to develop a sustainable urban park design model. A total of 32 design elements were identified through a comprehensive literature review. The significance of these elements to the sustainability of urban parks was evaluated through a survey conducted with 318 participants. The survey results indicated that "being clean and well-kept" was the most important design element, receiving a mean score of 4.86 out of 5. In contrast, "availability of kiosks for buying drinks and snacks" emerged as the least important element, with a mean score of 3.81. Furthermore, exploratory factor analysis was used to categorize the design elements into six factors that collectively explained approximately 60% of the total variance. These factors were labeled as management quality, life quality, social quality, esthetics and furnishing quality, environmental quality, and activity quality. In the final phase of the study, Altinpark, located in Ankara, was examined using the developed model. Altinpark is one of the largest and renowned parks in the city, encompassing an area of 640,000 m^2 and housing over 18,000 trees. The examination revealed that while the park was well-designed, it exhibited significant shortcomings in terms of sustainability. The findings of this study are anticipated to guide local governments and communities in the design and construction of urban parks, enhancing their contribution to urban sustainability through improved functionality and serving as exemplary spaces.

Keywords: Factor analysis; Park user preferences; Sustainable urban parks; Urban park model; Urban sustainability

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1. Introduction

Today, major cities have become the primary consumers of natural resources and significant producers of pollution and waste.[1,2] This transformation has led to urban centers becoming potential hotspots for various social, economic, and environmental issues, such as poverty, inequality, unemployment, inadequate infrastructure, crime, violence, and disease.[3,4] In response to these challenges, the concept of sustainable cities has emerged. Sustainable cities are defined as areas where measures are implemented to conserve energy, reduce consumption, and protect the environment while simultaneously enhancing the welfare of citizens. A key component of the built environment in sustainable cities is urban parks.

Urban parks provide numerous environmental benefits, including positive impacts on air quality, soil health, and water, while supporting biodiversity. They could economically revitalize their surroundings, increase the value of properties in the region, and contribute to urban tourism. Furthermore, urban parks can improve health issues, such as obesity and diabetes, by promoting physical activities such as walking. They offer natural areas away from traffic and noise and create educational opportunities developed in a real space with natural elements. In addition, these parks provide rest and recreational opportunities that rejuvenate individuals, thus creating vitality in business life and contributing to a distinct urban identity.[5,6] Given these benefits, urban parks can support sustainability on multiple levels – economic, social, and environmental. However, inadequate design and poor management can render urban parks unsafe and abandoned spaces that consume substantial natural resources rather than contribute to sustainability. Thus, sustainable design is important for maximizing the benefits of urban parks while mitigating potential risks. Moreover, well-designed urban parks can enhance sustainability awareness among citizens as they serve as communal spaces for all.

Numerous studies in the literature explore the relationship between urban parks and sustainability. However, many of these studies examine a specific aspect of parks, such as sustainable management of parks,[7] meeting user needs,[8-10] serving as walking paths,[11] hosting sports events,[12,13] incorporating sustainable landscape and wetland features,[14-16] examining economic benefits,[17] analyzing socioeconomic impacts,[18] assessing energy use,[19] evaluating esthetic features.[20] In addition, some studies examine the sustainability of parks in general[21-23] and those employing case study approaches.[10,24-28]

In contrast to existing literature, this study aims to create a model for sustainable urban park design. It also includes an evaluation of a specific park based on this model. First, an extensive literature review was conducted to identify 32 design elements that promote the sustainability of urban parks. A survey was conducted to gather insights from 318 participants regarding the importance of each design element for park sustainability. The survey results were analyzed using explanatory factor analysis to group the design elements into six distinct factors. Each factor was named appropriately, and a model consisting of six factors and 30 design elements for the sustainable design of an urban park was created. In the final phase of the study, Altinpark, one of Ankara's significant urban parks, was evaluated using the proposed model.

The study contributes to the literature and offers novelty by presenting a concrete model for sustainable urban park design. This model is expected to guide stakeholders involved in the design, construction, and management of urban parks, thereby enhancing the sustainability of cities through the functional attributes and exemplary nature of these urban parks.

2. Design elements to consider in sustainable urban park design

The design elements required for creating sustainable urban parks have been determined through a comprehensive literature review and categorized according to the economic, environmental, and social dimensions of sustainability. It is important to note that each function or element considered in park design often relates to more than one dimension of sustainability. To facilitate clarity, the design elements are organized under the headings corresponding to the dimensions they are most directly associated with.

2.1. Economic sustainability

Economic sustainability refers to the dimension of sustainability that aims to ensure long-term growth and survival.[29] It serves as a foundation for maintaining environmental and social sustainability. Parks and various public facilities attract buyers and investors, leading to an increased demand for nearby developments. This heightened interest often results in higher real estate prices, significantly stimulating economic growth.[30] Individuals are willing to pay more for properties located near parks or open spaces compared to those without such amenities, which contributes to higher real estate values in the area.[18] In addition to boosting property values and rental income, parks also enhance the economy by reducing pollution prevention costs, with trees playing a role in air purification. In addition, parks promote tourism and commercial activities, further stimulating economic growth.[27]

2.2. Environmental sustainability

Environmental sustainability is defined as "fulfilling the needs of present and future generations for resources and services without endangering the health of the ecosystems that provide them." Parks and green spaces, which provide easy access to nature and incorporate vegetation within the built environment, enrich the plant composition of the natural environment and enhance biodiversity. These areas have numerous benefits, including providing habitat for urban wildlife, improving urban microclimate, protecting water quality, enhancing air quality through greenhouse gas control, reducing volatile organic compounds emissions, and mitigating noise pollution by absorbing and blocking sound waves.[8,22] The main goal of designing sustainable

parks is to conserve natural resources, such as water and energy, reduce waste and water consumption, and improve the quality of life for all community members.[14] To achieve these objectives, it is essential to implement methods that focus on energy efficiency, reduce energy use costs, reduce water consumption costs per user, and economical planting in landscaping.[17] When planning parks, it is important to prioritize renewable energy practices and energy-efficient lighting systems to help reduce energy consumption.[15,31] Various measures should be considered for water conservation: (i) providing sustainable and non-potable water for irrigation of plants in the park by collecting rainwater and purifying gray water within the park, (ii) installing smart irrigation systems,[17,21,32] and (iii) xeriscaping to minimize the need for additional irrigation using local plant species.[14,33] Parks that prioritize native plants in arid urban areas can enhance year-round usability by providing drinking water and shade structures for users within the park. This not only improves human comfort but also alleviates local climate issues and reduces the urban heat island effect.[22]

Urban parks can often serve as important centers for biodiversity due to their diverse habitats and microhabitat heterogeneity.[27] Establishing policies and regulations to conserve biodiversity is essential for protecting endangered and threatened species.[8] However, it is important to note that community engagement and identity can complicate park design and management, potentially leading to conflicts between biodiversity conservation efforts and the evolving demands of park users.[34]

As part of an effective waste management strategy, strategically placed bins and recycling containers should be installed throughout the park to facilitate easy monitoring and collection by maintenance staff.[27] In addition, urban parks can function as recycling centers by allowing the composting of solid waste generated within these spaces.[8]

2.3. Social sustainability

Grigorovschi and Gheorghiță[11] define the city as "not only an anthropic landscape, but also the integration of heritage, tradition, culture, sounds, light and darkness, vegetation, air, the human element, water, sky, and all of these into the landscape that we perceive consciously or unconsciously, with spaces in constant movement and development."[11] This definition elucidates the relationship between city and social sustainability as dynamic concepts encompassing physical space and social world design while promoting infrastructure to address social needs and issues.[35]

A sustainable park fosters social interaction, cohesion, and the development of social capital.[22] Parks are significant public areas where urban residents gather for social, cultural, recreational, or entertainment activities during their free time. Parks also support mental health by harnessing the restorative power of nature and promote physical health by offering exercise opportunities, such as walking and jogging. By enhancing social, emotional, and physical well-being, parks can significantly improve residents' quality of life and thus contribute to social sustainability.[7,27]

To ensure parks fulfill their functions effectively, planners and policymakers must prioritize high standards in their design, management, and maintenance.[24] Designers should evaluate each component to ensure its relevance to users' needs in fostering interaction, holistic relationships, and systematic solutions.[10] Community participation in the design and management of parks is important for ensuring ecological, economic, and social sustainability and fostering community development.[5]

One of the primary considerations in design and planning is inclusivity; parks should be accessible to citizens from all walks of life regardless of age, gender, physical capacity, economic status, or ethnic/cultural group and easily reachable via various modes of transportation, such as walking, cycling, or public transit.[9,22,36] Consequently, transportation planning should be integrated into decisions regarding park locations, with public transportation supporting access to these parks.[5] All new playgrounds must be designed to be accessible and inclusive for children while allowing easy supervision or participation for older adults and disabled individuals.[36] In addition, parks should cater to various demographics by providing areas and activities for working adults, the elderly, individuals with special needs, and any other underprivileged group seeking relaxation.[28]

Key motivations for visiting parks include enjoying natural environments, leisure activities, sports participation, and spending quality time with family or friends.[26] The running and cycling trails and sports facilities attract visitors of all ages while walking paths encourage outdoor activity. Parks equipped with adequate sports facilities promote more dynamic behaviors,[13] while diverse sports fields enhance physical activity levels.[37] By offering playgrounds suitable for various age groups, parks become unique places in densely populated urban areas that provide free physical activities for everyone.[28]

Regardless of how well parks are designed and implemented, their sustainability depends on effective management. Parks that are poorly managed and maintained will deteriorate over time, losing their value, weakening users' sense of security, and creating a sense of isolation.[7] Inadequate cleaning and maintenance can lead to decreased park usage and a lack of security and

supervision.[37] Parks can become unsafe environments[8] due to theft and vandalism.[36] Implementing security measures – such as good lighting, security guards, and surveillance cameras[8,24,36] – well-maintained green areas, a variety of recreational activities, and environmental comfort[8] is crucial for enhancing perceived safety[9] and attractiveness. These factors are vital for promoting the active use of parks.

The design of soft and hard landscapes within a park is important for environmental amenity. In this context, "soft landscape elements" refer to plants, whereas "hard landscape elements" encompass all other features, including roads, simple buildings, park furniture, walls, and fences.[16] The quality of a park depends on the effective integration and management of these components.[21]

Soft landscaping includes trees, shrubs, bushes, hedges, lawns, and flower beds. Proper organization of these elements is important for creating an attractive park environment. For example, effective soft landscaping may involve selecting fragrant and beautiful trees, choosing shrubs without large roots, and incorporating flowering plants to cover at least 60% of the area.[38] In addition to esthetic considerations, the sustainability of materials used in hard landscaping is also important. Factors such as maintenance requirements, reuse and recycling opportunities, costs, and suitability for their intended purpose should be considered.[39] Hard landscaping features, such as paved areas, paths, benches, gazebos, and special corners, play a vital role in facilitating social interactions within the park.[6]

Elements such as seating units, lighting fixtures, sign and information boards, delimiters, and structures such as stops, canopies, pergolas, sales units, artistic objects, playground elements, garbage bins, flower beds, bicycle parking spaces, square clocks, vegetative elements, and flagpoles are all considered part of park furniture.[40] These elements must be designed to align with the city's sociocultural characteristics and meet the functional needs of the users. By doing so, they enhance user experience while beautifying the parks.[31,40] With their color, form, and practicality, park furniture is an integral component of a park.[40] It has many functions, such as adding visual appeal and identity to the space, delineating areas within the park, and connecting historical context with future aspirations.[19] Research shows that poorly maintained furniture that does not harmonize with the park's atmosphere reduces its attractiveness and comfort.[21] Conversely, parks that incorporate cheerful colors and artistic elements while addressing the needs of diverse age groups tend to have higher user satisfaction regarding rest, nature experiences, entertainment options, and recreational activities.[14]

Walking, jogging, and cycling paths are important components of hard landscapes in parks. These pathways encourage daily physical activity by providing opportunities for close contact with nature.[28,41] Studies have shown that individuals are more inclined to walk, run, and cycle in parks when the paths are comfortable, convenient, and well-designed.[28,37,41] Therefore, it is recommended that walking, jogging, and cycling paths be designed according to various standards that prioritize functionality and esthetics.[20,42]

One of the key factors influencing the frequency of park usage is the ability to meet users' basic needs effectively. Gong *et al.*[25] emphasized that the lack of basic infrastructure facilities, including toilets, sports facilities, and signage, negatively affected the use of parks in Beijing.[25] The availability of toilets and sinks, along with their accessibility, clean water, and sanitation, is essential for making parks user-friendly.[40] In addition, users often express a strong demand for service facilities, such as kiosks that provide beverages and snacks.[40,43] Access to food and water enhances the comfort and appeal of parks and is particularly, important for parents with children.[6]

Urban parks play a vital role in fostering a sense of social belonging and community, making it important to encourage their use among citizens of all ages, genders, cultures, skills, and physical abilities. For this, it is important to organize an annual program of events and activities that are socially inclusive and open to users of all ages and interests.[21] Regardless of size, all urban parks should incorporate public art, performances, and other activities that reflect cultural significance and historical context.[6] Yildizci and Yücel[23] identified several quality criteria for urban parks, including accessibility and legibility, comfort and image, sense of ownership, as well as activities and.[23]

Numerous studies in the literature provide valuable insights into design elements that can enhance the sustainable design of urban parks. While it is not feasible to discuss each study in detail here, Table 1 presents an overview of the aims, methods, and results of three studies that approach the subject more holistically, similar to this research.

3. Methods

Although numerous studies on the sustainability of parks exist in the literature, no study has developed a sustainability model, especially for parks. In this study, the method presented in Figure 1 was followed.

The study started by identifying 32 design elements, as outlined in Table 2, that can contribute to the sustainability of an urban park through a review of recent literature.

A questionnaire survey was conducted to assess respondents' perceptions of the importance of identified

Table 1. Analysis of three studies examining the sustainability of urban parks in general

Study	Aim	Method	Result
Yildizci and Yücel[23]	Determining quality criteria that effectively create a quality living environment for users in urban parks.	The criteria were determined as activities and uses (diversity), accessibility (legibility), comfort and image (security and maintenance), and sociability (sense of ownership). The criteria were examined through surveys conducted with users in Maçka, Ulus, and Zeytinburnu parks. The collected information was subjected to a Chi-square significance test.	Comfort, image, security, maintenance, and sociability were effective criteria, and diversity was ineffective. The differentiation in sociodemographic characteristics affected the perceptions of quality criteria.
Ibes[22]	Developing a vision for a sustainable urban park system and a quantitative methodology that examines four key dimensions of sustainability (physical, environmental, socioeconomic, and built environment) across the city-wide urban park system	The approach was applied to Phoenix, Arizona. A set of quantitative variables reflecting sustainable parks were selected and calculated; size, particular facilities and amenities, microclimate cooling, land cover, land uses surrounding parks, neighborhood population density, income, and ethnic mix. Descriptive statistics for variables and correlations between them were investigated.	The findings showed that multidimensional analysis of the urban park system can provide a more detailed understanding and data for sustainable urban park management and policy, as well as park planning and design.
Dizdaroğlu[21]	Contribution to making cities more sustainable by developing a set of criteria for sustainable urban park design.	The study systematically reviewed the relevant literature and determined 10 basic goals for the sustainable design of urban parks; green infrastructure, place for people of all ages, connected park systems, water and energy, conservation practices, access to fresh and healthy food, preserving biodiversity, environmental education, long-term maintenance and management, and disaster resilience.	The study contributes to a comprehensive sustainable park design. The proposed design criteria provide a basis for transforming urban parks into sustainable green spaces by promoting potential improvements.

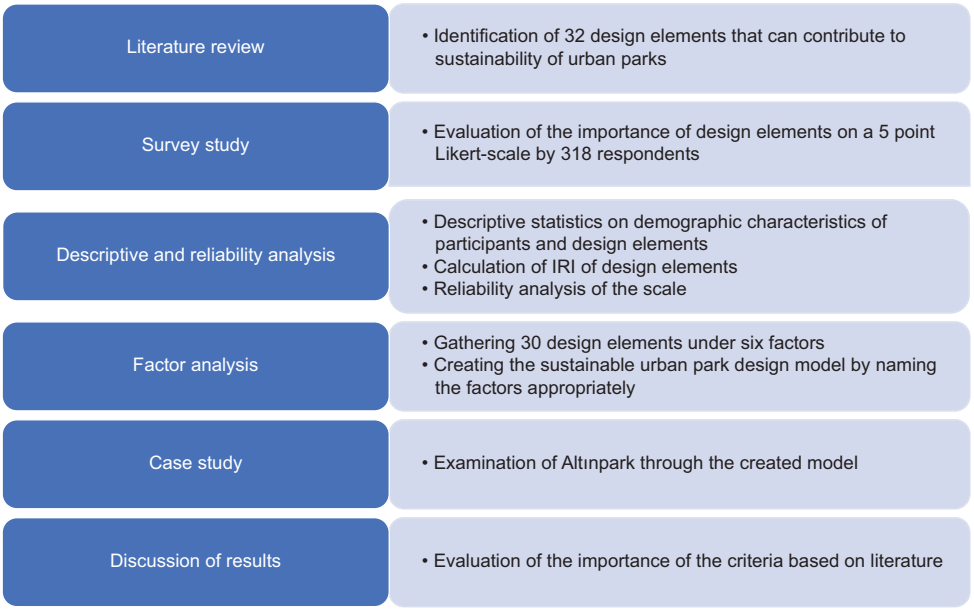

Figure 1. Methodology used in this study
Abbreviations: IRI: Index of relative importance.

criteria for park sustainability. Participants evaluated the criteria using a 5-point Likert scale. Three hundred eighteen respondents, representing a diverse range of demographic characteristics, participated in the survey. The data was analyzed using Statistical Package for Social Sciences 29.0.[44] The surveys were administered either face-to-face or online, with all participants living in Turkey, the majority of whom lived in Ankara. The sample size was determined based on recommendations from the literature regarding the number of samples required for factor analysis. While various guidelines exist for sample size, a common recommendation is to have 3 to 20 times the number of variables or a sample size ranging from 100 to 1,000 participants.[45] The 318 participants in this study

Table 2. Design elements that can contribute to the sustainability of an urban park

No	Design element	References
1	Ensuring community participation	Harnik,[5] Phetkongtong[10]
2	Preservation of existing parks	Kolimenakis *et al.*,[18] Sultana[27]
3	Can be used for resting	Harnik,[5] Yildizci and Yücel,[23] Elassal and Haron,[14] Kalansooriya[26]
4	Can be used for entertainment purposes	Yildizci and Yücel,[23] Bahriny,[24] Kalansooriya[26]
5	Contributing to residents' quality of life	Yildizci and Yücel,[23] Sultana,[27] Aly and Dimitrijevic[7]
6	Suitable for children's use	Bennett *et al.*,[36] Elassal and Haron,[14] Trojanowska[28]
7	Suitable for elderly use	
8	Suitable for physically disabled use	
9	Being clean and well-kept	Padial-Ruz *et al.*,[37] Aly and Dimitrijevic[7]
10	Safe to be used at all hours	Bennett *et al.*,[36] Dizdaroğlu,[8] Bahriny[24]
11	Being easily accessible	Harnik,[5] Bennett *et al.*,[36] Trojanowska[28]
12	Good lighting	Dizdaroğlu,[8] Bahriny[24]
13	Availability of sports fields	Padial-Ruz *et al.*,[37] Wu *et al.*,[13] Kalansooriya[26]
14	Sufficient park furniture	Paraskevopoulou *et al.*,[9] Tereci and Atmaca,[19] Dizdaroğlu,[21] Elassal and Haron,[14] Safarkhani40
15	Comfortable and useful park furniture	
16	Integrity and continuity of park furniture	
17	Comfortable and convenient walking and jogging paths	Padial-Ruz *et al.*,[37] Van Renswouw *et al.*,[42] Trojanowska[28]
18	Appropriate walking and jogging paths	
19	Energy conservation	Haredy,[15] Gholamreza,[17] Elassal and Haron,[14] Velásquez[15]
20	Playgrounds for children	Ibes,[6] Bennett *et al.*,[36] Trojanowska[28]
21	Enough toilets and washbasins	Gong *et al.*,[25] Safarkhani[40]
22	Appropriate soft landscaping	Sanmargaraja *et al.*,[38] Elassal and Haron[14]
23	Appropriate hard landscaping	Paraskevopoulou *et al.*,[9] Kurtaslan,[39] Elassal and Haron[14]
24	Using local plants	Ibes,[22] Ignatieva *et al.*[33]
25	Saving water	Ibes,[22] Gholamreza,[17] Dizdaroglu[21]
26	Establishment of rainwater collection system	
27	Availability of waste collection system	Sultana,[27] Dizdaroglu[21]
28	Recycling program	
29	Availability of bicycle lanes	Trojanowska[28]
30	Protection of biodiversity	Chao,[34] Sultana,[27] Dizdaroglu[21]
31	Availability of kiosks for drinks and snacks	Ibes,[6] Safarkhani[40]
32	Activity areas and event organizations	Yildizci and Yücel,[23] Ibes,[6] Dizdaroglu,[21] Elassal and Haron[14]

(Cont'd...)

Table 2. ***(Continued)***

correspond to approximately 10 times the 32 variables, representing an adequate sample size. Given that the study aimed to obtain opinions on the sustainability of urban parks from citizens, purposive sampling was deemed unnecessary, and convenience sampling was employed instead. Convenience sampling is a non-random sampling where participants are selected based on practical criteria, such as easy accessibility, geographical proximity, availability at a given time, or willingness to participate.[46] During the sampling process, the only criterion considered was that participants possess some level of education, as a certain degree of knowledge is required to understand sustainability concepts.

The data analysis involved descriptive analyses of participants and design elements and a reliability analysis of the Likert scale. Relative importance indices of design elements were calculated for each design element. Factors obtained through exploratory factor analysis were appropriately named, resulting in a design model with 30 design elements grouped into six factors. In the final stage of the study, Altinpark was examined based on the identified factors and their corresponding criteria. This evaluation was conducted through on-site observations, interviews with park authorities, a review of existing literature on the park, and an analysis of user evaluations on social media.

4. Results

4.1. Descriptive analysis, relative importance of design elements, and scale reliability analysis

Descriptive analysis was used to determine the participants' demographics, with the results presented in Table 3. Half of the participants were male, and half were female. The largest age group was 20 – 29, comprising approximately 30% of the sample. Given the nature of sustainability, which requires a certain level of knowledge,

efforts were made to ensure that participants had a high level of education. Approximately 57% of the participants were university graduates, and 29% held a master's or doctoral degree. The participants were predominantly individuals with 0 – 5 years or more than 20 years of work experience. Regarding income levels, the participants were approximately equally distributed. In terms of professions, the leading groups were educators (academics, teachers, and students), architects, and engineers.

Table 3. Descriptive analysis of the participants

Characteristic	Number of participants	Percentage of participants (%)
Gender		
Male	132	41.5
Female	186	58.5
Age group		
<20	30	9.4
20 – 29	99	31.1
30 – 39	62	19.5
40 – 49	62	19.5
50 and more	65	20.4
Education status		
High school and below	33	10.4
University student	14	4.4
University	180	56.6
Master's degree and/or doctorate	91	28.6
Work experience		
0 – 5 years	115	36.2
6 – 10 years	35	11.0
11 – 20 years	65	20.4
21 years and more	104	32.7
Income (thousand TRY)		
<30	117	36.8
31 – 50	81	25.5
51 – 100	89	28.0
>100	31	9.7
Occupation		
Architect/engineer	66	20.8
Real estate appraiser	44	13.8
Civil servant	35	11.0
Health sector employee	37	11.6
Education sector employee	75	23.3
Finance sector employee	14	4.4
Others	48	15.1
Total	318	100.0

Table 4 displays the reliability coefficient of the scale used in the study, along with the results of the descriptive statistics. The mean response to the questions was 4.46, indicating a rating between *very important* and *absolutely very important*. The Cronbach's alpha value of the scale was 0.929, demonstrating the scale's high reliability.[47,48]

The relative importance levels were calculated according to the participants' evaluations of the criteria. The calculation was made according to the formula below.

$$IRI = \Sigma W/A^*N \quad (I)$$

The IRI represents the index of relative importance. It is calculated using the weight (W) which ranges between 1 and 5 and is given by each participant for that proposition. The value of A represents the highest weight value, which in this case is five. N refers to the total number of participants, which is 318.

The relative importance coefficients of the criteria are presented in Table 5. Accordingly, the most important criterion was "being clean and well-kept," and the least important criterion was "availability of kiosks for buying drinks and snacks."

4.2. Factor analysis

Factor analysis encompasses a group of multivariate analysis techniques designed to reduce the number of interrelated variables into a smaller number of fundamental dimensions. This reduction facilitates the understanding and interpretation of the relationships among the variables. A good factor analysis yields results that are highly interpretable and simple. The two primary types of factor analysis techniques used are explanatory and confirmatory factor analysis. The steps involved in explanatory factor analysis can be summarized as defining the problem and collecting data, examining the suitability of data for factor analysis, determining the number of factors, rotating the factor axis, and naming the factors.

In the initial phase of factor analysis, it is crucial to verify the factorability of the items or the suitability of the data for factor analysis. One well-known technique for this purpose is sample suitability testing. Bartlett's test of sphericity, which examines the correlation matrix as

Table 4. Descriptive statistics and scale reliability value

Number of participants	Number of items	Item mean	Item min.	Item max.	Cronbach's alpha
318	32	4.458	3.810	4.860	0.929

Table 5. Relative importance indexes of design elements

No.a	Design element	IRI
9	Being clean and well-kept	0.972
10	Safe to be used at all hours	0.950
8	Suitable for use by the physically disabled	0.949
6	Suitable for childrens use	0.945
3	Can be used for resting	0.942
12	Good lighting	0.933
11	Being easily accessible	0.932
25	Saving water	0.930
14	Sufficient park furniture	0.930
5	Contributing to residents' quality of life	0.928
7	Being suitable for use by the elderly	0.925
17	Comfortable and convenient walking and jogging paths	0.909
27	Availability of waste collection system	0.908
20	Playgrounds for children	0.905
22	Appropriate soft landscaping	0.903
19	Energy conservation	0.902
15	Comfortable and useful park furniture	0.900
21	Enough toilets and washbasins	0.896
26	Establishment of rainwater collection system	0.895
28	Recycling program	0.894
30	Protection of biodiversity	0.887
29	Availability of bicycle lanes	0.880
23	Appropriate hard landscaping	0.879
4	Can be used for entertainment purposes	0.859
13	Availability of sports fields	0.854
2	Preservation of existing parks	0.843
24	Using local plants	0.832
18	Appropriate walking and jogging paths	0.828
1	Ensuring community participation	0.823
16	Integrity and continuity of park furniture	0.821
32	Activity areas and event organizations	0.796
31	Availability of kiosks for drinks and snacks	0.762

Note: [a]shows the order of appearance of the design element in the questionnaire.
Abbreviation: IRI: Index of relative importance.

a whole, is used to determine whether factor analysis is appropriate.[49] Another tool used to assess the suitability of factor analysis and the correlations between variables is the Kaiser–Meyer–Olkin (KMO) test. The KMO value ranges from 0 to 1, with a value of 1 indicating that any variable can be reliably predicted by other variables.[50]

Table 6 presents the findings from the sample suitability tests. In factor analysis, the KMO test determines whether

Table 6. Kaiser–Meyer–Olkin and Bartlett's test results

Kaiser–Meyer–Olkin measure of sampling adequacy		0.904
Bartlett's test of sphericity	Approximate Chi-square	4,847.146
	Degrees of freedom	496
	Significance value	0.000

the sample size is appropriate for factor analysis. Factor analysis is typically terminated if the KMO value is <0.50. A KMO value >0.9 indicates a perfect fit. In this study, the KMO value was 0.904. In addition, Bartlett's test tested the null hypothesis: the initial correlation matrix and the identity matrix are identical (all coefficients of correlations are zero. The test was found to be significant; hence, it was determined that the data were appropriate for factor analysis. The significance values in the correlation matrix (**Table S1 and S2**) were found to be significant, indicating the validity of the analysis.

According to the communalities table, every variable possesses a common variance ranging from 0 to 1. Items with communalities exceeding 0.5 explain a greater proportion of the variance in the dataset. Table 7 shows that two items had communalities below 0.5. However, given that the communalities of these two items were only marginally below this threshold, all items were included in the analysis.

In an effective factor analysis, the smallest possible number of factors should account for the largest proportion of variance. An ideal factor analysis explains between 50% and 75% of the total variance.[51] Table 8 presents the eigenvalues before and after factor extraction. Eigenvalues roughly indicate the correlation between two variables. Table 8 shows that six factors had eigenvalues greater than 1. Rotation was used to balance the relative importance of these factors. The six factors collectively explained 58.5% of the total variance. The fact that more than 50% of the variance is explained suggests the validity of the factor analysis.

Factor loadings are often difficult to interpret without rotation. Rotating the matrix helps to achieve a more interpretable factor structure; after rotation, the items become more optimal in terms of variance explained. Upon examining the factor loading matrix rotated using the Varimax method, it was observed that two items exhibited high loadings on multiple factors. In such situations, the load difference between factors should not be <0.1. Items explaining more than one factor are typically removed from the scale one at a time, and the matrix is re-examined after each removal. Following this procedure, two items (10 and 21) were removed from the scale, resulting in the

Table 7. Communalities explained by common factors

Item	Extraction	Item	Extraction	Item	Extraction	Item	Extraction
1	0.482	9	0.533	17	0.514	25	0.601
2	0.505	10	0.514	18	0.670	26	0.671
3	0.592	11	0.471	19	0.526	27	0.682
4	0.659	12	0.517	20	0.541	28	0.691
5	0.641	13	0.513	21	0.517	29	0.516
6	0.636	14	0.665	22	0.600	30	0.604
7	0.644	15	0.597	23	0.500	31	0.724
8	0.730	16	0.576	24	0.538	32	0.739

Table 8. Total explained variance

Comp.	Initial eigenvalues			Extraction sums of sq. loadings			Rotation sums of sq. loadings		
	Total	% of var.	Cum. %	Total	% of var.	Cum. %	Total	% of var.	Cum. %
1	10.682	33.383	33.383	10.682	33.383	33.383	4.932	15.414	15.414
2	2.137	6.679	40.062	2.137	6.679	40.062	4.241	13.253	28.667
3	1.955	6.111	46.172	1.955	6.111	46.172	3.084	9.638	38.305
4	1.470	4.593	50.765	1.470	4.593	50.765	2.522	7.883	46.187
5	1.268	3.962	54.727	1.268	3.962	54.727	2.186	6.830	53.017
6	1.205	3.767	58.494	1.205	3.767	58.494	1.752	5.476	58.494
7	0.997	3.115	61.609						
….									
32	0.172	0.536	100.000						

Note: Extraction method: Principal component analysis.
Abbreviations: Comp: Component; Cum: Cumulative; sq: Squared; Var: Variance.

final rotated component matrix presented in Table 9. As shown in Table 10, there are six factors explaining 60% of the total variance.

Naming the factors is a crucial step in the factor analysis process. Factors are named by examining the variables that load onto them and identifying a common theme between the variables. The naming process is conducted carefully to accurately reflect the meaning intended to be conveyed by the variables loading on the factor. Following this process, the factors were named and the model shown in Figure 2 was obtained.

4.3. Examination of an urban park using the model

The model was examined through Altinpark, a park in Ankara, the capital city of Turkey. The area of the park is 640,000 m² and is composed of green spaces, pond areas, hard surfaces, children's playgrounds, flower beds, shrub and soil areas, and various structures (Figure 3). It is home to approximately 18,000 trees and 81,000 shrubs in the park.[52] The park includes a fairground, a science center, indoor and outdoor sports facilities, outdoor and semi-outdoor amphitheaters, roller skating rinks, restaurants, walking areas, fitness areas, children's playgrounds, picnic areas, ponds and gardens, an Olympic-sized swimming pool, a mini golf course, horse backgammon, a senior citizens' clubhouse, a cultural center, henna and wedding halls, countryside cafes, sitting areas with gazebos, viewing terraces, and coastal pergolas.[53]

The examination of the park was conducted based on on-site observations, interviews with users and officials, academic studies on the park in the literature, and evaluations of park users on social media.

4.3.1. Management quality

Altinpark was designed through a competition project and is managed by ANFA Ankara Altinpark İşletmeleri Ltd. Şti. Citizens can submit their opinions and requests via the company's website or by contacting the authorities by phone. However, there is limited opportunity for social participation in the park's governance. Studies indicate that Altinpark has increased real estate values in the region,[55] and residents have expressed satisfaction with living near

Table 9. The loadings of each variable after rotation using the rotated component matrix

Design element	Component					
	1	2	3	4	5	6
K1	0.089	0.190	0.047	0.069	0.152	0.647
K2	0.130	−0.009	0.233	0.019	0.161	0.705
K3	0.334	0.014	0.217	0.025	0.674	0.072
K4	0.160	−0.011	0.071	0.384	0.676	0.030
K5	0.088	0.198	0.193	0.015	0.676	0.313
K6	0.285	0.064	0.716	0.185	0.070	0.106
K7	−0.028	0.351	0.672	0.033	0.244	0.109
K8	−0.047	0.437	0.676	0.032	0.267	0.071
K9	0.209	0.272	0.555	−0.101	0.322	0.007
K11	0.372	0.199	0.266	−0.027	0.508	0.190
K12	0.408	0.076	0.490	0.122	−0.092	0.306
K13	0.435	0.037	0.346	0.316	−0.006	0.205
K14	0.732	0.041	0.357	0.037	0.135	0.015
K15	0.693	0.085	0.061	0.152	0.261	0.076
K16	0.440	0.237	−0.045	0.355	−0.020	0.484
K17	0.632	0.266	0.130	0.020	0.229	0.050
K18	0.599	0.245	−0.062	0.295	−0.097	0.364
K19	0.461	0.568	0.149	−0.012	0.055	0.231
K20	0.483	0.115	0.386	0.331	0.014	−0.015
K22	0.597	0.396	−0.007	0.102	0.270	0.085
K23	0.591	0.294	−0.034	0.204	0.105	0.020
K24	0.176	0.597	0.008	0.318	0.054	0.212
K25	0.307	0.624	0.121	−0.119	0.259	0.088
K26	0.177	0.749	0.219	0.132	0.095	0.099
K27	0.158	0.776	0.211	0.170	−0.013	0.023
K28	0.196	0.767	0.202	0.150	0.001	0.037
K29	0.375	0.331	0.285	0.439	−0.043	0.089
K30	0.414	0.565	0.190	0.187	−0.006	0.176
K31	0.187	0.136	0.064	0.800	0.138	0.023
K32	0.050	0.225	0.065	0.812	0.117	0.113

Note: Extraction method: Principal component analysis.
Rotation method: Varimax with Kaiser normalization.

the park.[56] Real estate advertisements in the region often emphasize the proximity to or views of Altinpark.

4.3.2. Life quality

The park is located near the airport road, providing easy access from central points of Ankara, such as Kizilay, Sihhiye, and Ulus. The park is accessible through numerous public transportation lines and offers a parking lot with a capacity of 1,200 vehicles.[57] Pedestrians can enter the park through various entrance gates. A study indicated that 80% of Altinpark users spent 30 min or less traveling to the park.[58] In a study investigating the reasons for using the park, "getting fresh air and spending time in nature" ranked first, followed by "being a park where you can visit with your family." In the same study, the other top reasons included "relaxing physically and mentally," "spending time with friends," and "having a picnic."[58] Another study found that 45% of the participants came to the park for walking or excursion and 35% for recreation.[12] The park provides a conducive environment for recreation with its expansive green spaces and abundant trees (Figure 4). However, entertainment opportunities within the park are limited as one user stated, "A nice park suitable for walking, there are not many attractions, it is not suitable for friends looking for fun, but it is ideal for fairs and walking."[59] While the park undoubtedly contributes to the quality of life for residents with its extensive facilities, some suggest that it has declined compared to its early years. Specifically, the science center's experimental equipment has not been updated to reflect technological advancements. In addition, many park facilities have been converted into commercial enterprises such as restaurants, wedding halls, tea gardens, and buffets. The privatization of the 23 Nisan Children's Culture Center, the first of its kind in Turkey, and its conversion into a kindergarten, the abandonment of the mini golf course,[60] the cessation of fishing in the pond, and the organization of low-attendance fairs at the fair center have all contributed to a perceived decline in the park's unique characteristics and vibrancy compared to its earlier years.

4.3.3. Social quality

Numerous Tripadvisor comments about Altinpark on social media highlight its suitability for children.[59] The park features many children-friendly areas, such as horse-riding areas, mini trains, a go-kart track, a skating rink, a science center, an amusement park, playground toys in various parts of the park, and a Smurfs' house. These areas are designed to be suitable for children. While no obstacles are preventing elderly and disabled individuals from using the park, on-site observations suggest that the usage of the park by these groups of individuals is limited. A study found that the majority of users are between 25 and 34 years old, whereas users aged 45 and over are less common.[57] The senior citizens' club in Altinpark has more than 2,000 members (Figure 5). One of the club members expressed her satisfaction by saying, "I have been coming to Altinpark Elderly Club for almost a year. We love this place. Their staff is very friendly. Sometimes singers come, sing, and we accompany them. Everything is beautiful."[61] Furthermore, an initiative called Barrier-Free Ankara stated that the park is disabled-friendly due to its wheelchair

Table 10. Total explained variance accounted for by the extracted components

Comp.	Initial eigenvalues			Extracted sums of squ. loadings			Rotation sums of squ. loadings		
	Total	% of var.	Cum. %	Total	% of var.	Cum. %	Total	% of var.	Cum.%
1	10.032	33.439	33.439	10.032	33.439	33.439	4.668	15.559	15.559
2	2.095	6.985	40.423	2.095	6.985	40.423	4.035	13.449	29.007
3	1.942	6.474	46.897	1.942	6.474	46.897	2.906	9.688	38.695
4	1.469	4.896	51.793	1.469	4.896	51.793	2.425	8.082	46.777
5	1.249	4.164	55.957	1.249	4.164	55.957	2.108	7.028	53.805
6	1.127	3.756	59.713	1.127	3.756	59.713	1.772	5.908	59.713
7	0.976	3.254	62.967						
….	…….	…….	…….						
30	0.176	0.587	100.000						

Note: Extraction method: Principal component analysis.
Abbreviations: Comp: Component; Cum: Cumulative; sq: Squared; Var: Variance.

services via golf carts when needed, easy access at cafe entrances, suitable internal roads (except minor problems on the cobblestone roads), and availability of toilets for the disabled. Moreover, free parking is provided for disabled individuals, and free entry to the science center is given for companions of disabled visitors.[62] Regular cleaning and maintenance services of the park are carried out, and security guards are present throughout the day. Despite approximately 20% of the survey participants stating that the park should be cleaner and well-kept,[57] many online comments described the park as clean and well-kept.[59,63] Over 90% of participants in one study reported feeling safe in the park, with approximately 80% finding lighting sufficient.[64] Social media comments often mention a high presence of foreigners in the park, but note that they do not cause disturbances. One of the users of the park commented, "Even though Syrians are in the majority, they do not harm anyone."[59,63]

4.3.4. Esthetics and furnishing quality

The park includes numerous seating units, shade and lighting elements, and garbage bins placed at different points of the park (Figure 6). In one study evaluating these elements, approximately 86% of the participants found the lighting adequate, 67% considered garbage bins sufficient, and 54% deemed seating units satisfactory. The same study found that there were problems with compliance with standards regarding seat depth and backrest height in the seating units and non-compliance of garbage bins with the standards, while the lighting elements were found suitable.[64] Walking, jogging, and sports are popular uses of Altinpark.[57] Citizens appreciate walking in natural settings as it helps them feel calm and peaceful. This preference was reflected by the positive comments on social media. One user said, "Perfect hours if you are going to exercise between six to nine in the morning. There are only people around you who come for sports purposes," while another commented, "I wish I lived in the neighboring area so I could walk every day."[65]

The park is equipped with many sports areas, such as walking and running tracks, the sports center, the indoor swimming pool, and outdoor sports areas, providing sports opportunities across all age groups. Studies show exercising is one of the prominent reasons for using the park.[57] A study determined that 35% of the participants used the park to exercise, whereas 18% used it for team sports.[66] Another study found that 20% visited primarily for jogging.[58] A significant portion of the comments made on social media emphasize areas designed for children.[59] A citizen commented, "Picnic area, train tour, mini amusement park, water bike on the lake, bird cages, art museum, Smurf's village, etc. It is one of the rare places to travel and spend time with children; there are endless activities, number 10, 5 stars." In addition, another citizen commented, "There are many activity options for you and your children, such as playgrounds, skating rinks, pedal boats, etc. If you have time, you can evaluate it."[59]

Altinpark was designed based on several key principles: locating buildings near ring roads where human traffic is high, incorporating large surface water elements, using topographic features as planning themes, and transforming valleys into ponds,[56] contributing positively to its esthetic appeal. In a study evaluating esthetics based on surface materials quality, plant arrangements, and aquatic decorations, Altinpark received a medium level of esthetic appreciation.[67] Another study evaluated Ankara's three important urban parks, Altinpark, Gençlik Park, and Botanik Park, based on walking or jogging paths, sports

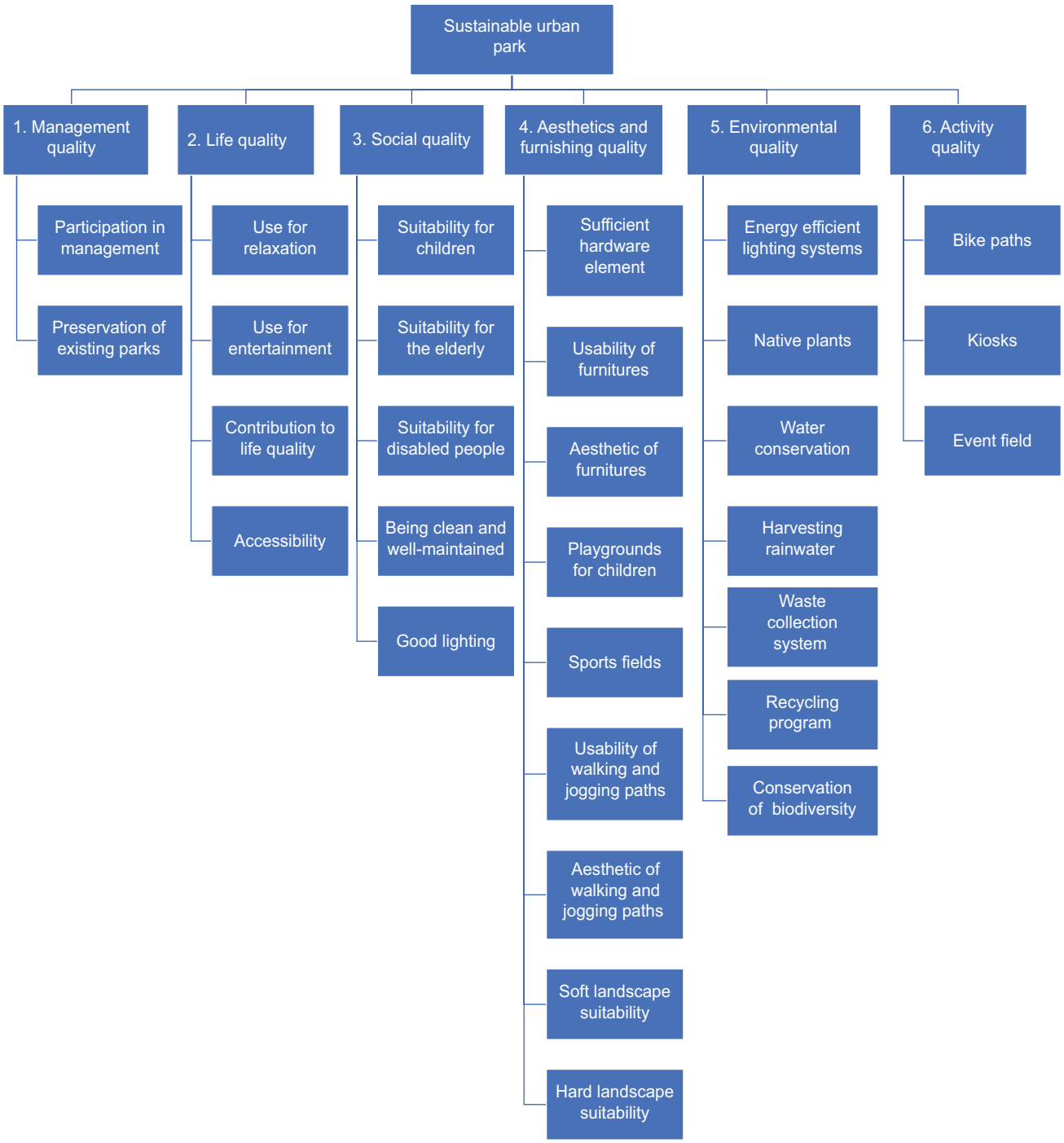

Figure 2. Sustainable urban park model

fields, free green activity areas, width, flooring quality, location within the park and surroundings. The evaluation, made on a scale of 1 – 3, ranked Altinpark ahead of Botanik Park (1.70) but behind Gençlik Park (1.92) with an average of 1.88. Moreover, evaluation of the furniture based on its functionality, adequacy of distribution within the park, and harmony with the surrounding elements, revealed that Altinpark received the highest evaluation with an average of 2.20.[68] In the same study, Altinpark received an average value of 2.53, close to Botanik Park (2.60), when plant elements were examined according to their dimensions, such as suitability of species selection, adequacy of

distribution within the park, species diversity, color and odor effect, and compatibility with the surrounding elements. Another study found that the use of plant species that signal the arrival of spring in Altinpark promotes effects such as orientation, revealing a certain object, creating space, and positively influencing the increase in awareness.[69] The soft landscape of the park is enriched with pruned and shaped plants and compositions of rocks and plants (Figure 7).

Figure 3. Altinpark and its surroundings. Image adapted from Google Maps.[54]

4.3.5. Environmental quality

Most of the water consumed in the park is used for green areas and plants. A study[71] showed that approximately 55% of the woody landscape plant taxa identified in the park have moderate water consumption, whereas 29% have low to moderate water consumption, 8% have moderate to high water consumption, 4% have high water consumption, and 4% have low water consumption. Consequently, plants with moderate water consumption are the most prevalent. Interview park officials highlighted their focus on water conservation due to Ankara's status as a water-poor city. To achieve this, they avoided expanding grass areas; instead, they opted for plants requiring minimal water, such as

Figure 4. Landscapes in Altinpark. Image taken by the authors, 2024.

Figure 5. Altinpark senior citizens' club. Image taken by the authors, 2024.

Figure 6. The entrance of Altinpark and some furniture within it. Image taken by the authors, 2024.

Figure 7. Examples of landscape in Altinpark[70]

lavender, xeric horizontal thuja, rosemary, marigold, and dwarf roses. They also transitioned from tanker irrigation to sprinkler irrigation in some areas and implemented irrigation programs to prevent water loss. Although they collect rainwater for irrigation purposes, the amount collected is minimal.

Park officials reported that solar energy-powered lamps were installed to save energy but were not very efficient due to shading from trees; hence, photocell lighting was also employed. Waste management within the park is handled by BelPa – a municipal affiliate – which converts pruning waste into pellets used as fuel due to their high cellulose content. In addition, old pipes and plastic waste are recycled into irrigation pipes and given to citizens who bring in old pipes and plastic. A project aimed at purifying wastewater for use in parks and gardens is ongoing. A study conducted on Altinpark plant species found that out of 180 plants identified in the park, 110 were classified as exotic and 70 as native. The study recommended favoring natural plant taxa as they generally require less irrigation, are well adapted to local soil and climate conditions, and are more resistant to diseases and pests.[72]

4.3.6. Activity quality

Although there are no bicycle paths in Altinpark, the wide roads in the park facilitate bike usage without issues. There are a total of 24 buffets, cafes, tea gardens, and restaurants in the park. Although these areas are important in meeting the users' needs, their increasing number causes the park to be used beyond its intended purpose.[73] Altinpark, with an area of 640,000 m^2, contains 24 such facilities, whereas Central Park, covering 3,410,000 m^2, has 12, and Hyde Park, with an area of 1,400,000 m^2, has eight such facilities.[60] The only activities considered as events in Altinpark are the fairs. Initially offering high-quality fairs in terms of quality and quantity upon opening, recent years have seen a decreased interest from companies participating in these events. One user commented, "The park, where the Tüyap book fair was once organized, was abandoned after a few fairs on the grounds of loss."[63] Another citizen who attended one of the local product and food fairs frequently held in Altinpark said, "I went to the fair in Ankara Altinpark with my mother. The presentation and food we ate were extremely bad and expensive. I will never go and eat at a fair again."[59]

5. Discussion

This study utilized explanatory factor analysis to develop a model consisting of six factors and 30 design elements. The first factor, which includes social participation in the management and protection of parks, is called "management quality." The second factor, called "life quality," consists of elements such as using parks for recreation and entertainment, improving the quality of life of citizens, and ensuring accessibility. The third factor is called "social quality," which consists of the appropriate park designs for the elderly, children, and the disabled, cleanliness, maintenance standards, and adequate lighting. The fourth factor, which consists mainly of the suitability of furniture, walking and running paths, and hard and soft landscaping, is called "esthetics and furnishing quality." The fifth factor consists of elements such as energy and water conservation and waste systems for environmental sustainability is named "environmental quality." The last factor, which consists of features such as bicycle paths, kiosks, and activity areas in the park, is called "activity quality."

Altinpark, one of Ankara's important and large urban parks, was examined within the framework of the created model. Some quantitative data obtained from on-site observations of the park, interviews with users and officials, and examination of academic studies on the park are summarized in Table 11.

Ensuring social participation in management is one of the first and most important conditions for sustainability in urban areas. The review conducted on Altinpark revealed that more effective ways of ensuring social participation in management should be implemented. Through active engagement, it becomes possible to reflect the will and needs of citizens, use parks more effectively and efficiently, and ultimately create a more inclusive and egalitarian society. The review highlighted that accessibility to urban parks and their use for recreational purposes are among

Table 11. Summary of the data obtained on the examination of Altinpark

Factor	Data
Management quality	– ANFA Ankara Altinpark İşletmeleri Ltd. Şti. manages the park, and there is no citizen participation in the management.
Life quality	– 1,200-vehicle capacity parking lot – 80% of the users reach the park in[30] minutes or less.[58] – 45% of the participants come to the park for walking or touring, 35% for recreation.[12] – Most of the uses in the park have changed over the years and have turned into commercial enterprises.[60]
Social quality	– A wide variety of playgrounds for children in the park – The park is mostly used by people aged 25 – 34.[57] – The seniors' club for citizens over 60 has over 2,000 members. – The park is disabled-friendly, with a wheelchair service, golf carts, toilets for the disabled, and a free parking service.[62] – 80% of users find the park clean and well-maintained, 57 90% feel safe in the park, and 80% find the lighting sufficient.[64]
Esthetics and furnishing quality	– Approximately 86% of the participants found the lighting units sufficient, 67% found the garbage bins sufficient, and 54% found the seating units sufficient. – 35% of the participants use the park for exercise, 18% for team sports, and 20% come to the park for jogging. [58,66] – Park received an average score of 1.88 out of 3 for features such as walking/jogging paths, sports areas, and free green activity areas, an average score of [2,20] for the adequacy of park furniture, and an average score of 2.53 for plant elements.[68]
Environmental quality	– Approximately 55% of the woody landscape plant taxa in the park have moderate water consumption, 8% have moderate to high water consumption, and 4% have high water consumption[71] – There are a small number of solar-powered lamps and photocell lighting. 110 out of the 180 plants are exotic, and 70 are native.[72]
Activity quality	– There are no bicycle paths in the park. – There are 24 kiosks, cafes, tea gardens, and restaurants in the park, which is high in number compared to similar urban parks.[60] – The only activities that can be considered events organized in Altinpark are the fairs.

citizens' top priorities. For urban parks to provide the expected social benefits, they must first be easily accessible. Research revealed a negative correlation between travel time to the park and visit frequency.[57] A study by Nielsen and Hansen[74] found that ease of access to green areas can reduce obesity and stress.[74] Altinpark is located in an easily accessible area, allowing citizens to access the park by vehicle, public transportation, or on foot. While the park provides a good environment for recreation, it falls short in terms of entertainment options. Although there is a debate about balancing recreational versus entertainment uses in urban parks,[75] larger parks such as Altinpark could potentially accommodate both without disturbing those who use them primarily for recreation. In terms of "social quality," it can be stated that Altinpark is in good condition.

The inspection revealed that the park is clean, well-maintained, and suitable for children, the elderly, and the disabled. However, as found in similar studies,[57,76,77] the park is mostly used by young and middle-aged healthy individuals. It was observed that the senior citizens' club within the park encourages elderly usage. Similar regulations could facilitate park usage by individuals from all segments of society and age groups, including those with physical disabilities, thereby enhancing its sustainability. In the model, the factor with the most design elements was "esthetics and furnishing quality." With the increase in urban development and the desire for a good life, urban parks have begun to play important roles in meeting the esthetic desires and recreational needs of urban residents.[78,79] Urban parks play crucial roles in meeting esthetic demands and providing restorative environments against the psycho-physiological effects of living in the city.[80] To achieve these expected benefits, the parks' soft and hard landscaping, furniture, walking and jogging paths, and other elements must be designed holistically. The elements should harmonize through color, form, and texture; in other words, their esthetic quality must be high. Research indicates that citizens associate parks with feelings of comfort, peace, and serenity.[23,57] In general, it has been observed that Altinpark enables citizens to experience visual pleasure while supporting mental and physical health through the furniture and usage areas that meet the needs of the citizens.

In the model, environmental factors such as water and energy conservation, waste management, and biodiversity are grouped under the "environmental quality" factor. Urban parks serve crucial roles in stabilizing microclimate, filtering noise and wind, and purifying air and water.[81] However, to fulfill these functions effectively, parks must be environmentally sustainable.[82] For this purpose, measures should focus on economical water use – especially for irrigation, energy conservation practices should be implemented, and a waste management system for the whole park should be established. Although efforts are being made in these areas at Altinpark, there is still significant

room for improvement. Implementing gray water and rainwater collection systems, smart irrigation systems, water-permeable landscaping materials, green roofs, water-saving plants, photovoltaic panels, sensor lighting systems, and furniture made from recycled materials can enhance environmental sustainability. These practices will also transform the park into an outdoor educational space where visitors can experience sustainability.

The final factor of the model addresses "activity quality," which includes design elements related to promoting active lifestyles within parks. Although special paths have not been designed for bicycles in Altinpark, no negative opinions were encountered during the evaluation. However, research emphasizes the importance of parks for cycling activities and the necessity of establishing bicycle paths for safety.[83] While kiosks or similar facilities are needed to meet users' basic needs such as food and drink, excessive commercialization – such as in Altínpark – can detract from a park's core functions.[57,60] The last design element under this factor is organizing events in the parks. Research emphasizes the importance of organizing events in urban areas and citizens' expectations regarding such events.[57,84] Unfortunately, Altinpark falls short; aside from poorly attended fairs, few events are held there compared to its early years,[60] leading to reduced interest among citizens. Hosting artistic, cultural, and scientific events in the park could increase its vitality.

6. Conclusion and recommendations

Urban parks offer important opportunities to increase the well-being of citizens struggling with physiological and psychological challenges in increasingly urbanized environments. As such, they are important urban areas that can contribute to environmental, social, and economic sustainability. The sustainable design of parks will maximize this contribution and set a good example for society as sustainable areas. This study developed an urban park model unique in the literature. The model is simple, with six factors and 30 design elements under these factors. This model can guide stakeholders, including local administrators, designers, contractors, and citizens when designing new urban parks or renovating existing parks. It facilitates concrete discussions about which needs should be prioritized to maximize the potential of parks.

The evaluations conducted on Altinpark within the framework of the model revealed significant sustainability shortcomings, such as lack of citizen participation in park management, excessive commercial enterprises being opened in the park, which detracts from its intended function, 110 out of 180 plant species are exotic species, 67% of the plants being moderate and/or high water consuming plants despite being located in an arid region, almost no use of renewable energy sources, and few events beyond fairs are organized which leads to decreased usage. More concerning is the park's regression compared to its original design. Many activity areas in the park have been closed or rented to commercial enterprises over time. These issues prevent the effective use of parks and hinder their potential contribution to urban sustainability.

Based on the evaluation conducted on Altinpark, it is possible to make the following general recommendations to stakeholders.

(i) For parks to be used effectively, citizen participation in park management should be ensured.
(ii) Parks should be easily accessible, meet the needs of residents of all ages, and be organized and managed according to changing and developing needs to increase the quality of life of city residents.
(iii) Park security, maintenance, and cleanliness should be handled with consideration.
(iv) Improve the park's esthetic appeal and the suitability of its furnishings.
(v) Focus on reducing energy and water use, using renewable energy sources, and developing a waste management system.
(vi) Different activities should be organized to increase park usage.

7. Limitations of the study and future studies

The study focused on citizens living in Ankara, and the case study was conducted on only one park, Altinpark. The model can be validated by repeating the research with more participants. The model was examined in Altinpark, located in a large area with a good design. Comparative studies on different urban parks can contribute significantly to the literature. In the future, it is also possible to create a sustainable park evaluation system by determining concrete indicators for the criteria and developing a scoring system for assessing urban parks.

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Author contributions

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Formal analysis: All authors
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ORIGINAL RESEARCH ARTICLE

Conservation, recreation, or both? The National Trust for Scotland's exploitation of UK country park policy, 1967 – 1992

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Abstract

Britain's two National Trusts are charitable bodies, primarily known for conserving historic buildings, but also ensuring public access to those properties and their surroundings, and to important or historic landscape areas. With that remit in mind, it is curious to find the National Trust for Scotland (NTS) engaging closely in the creation of country parks, intended by the UK Government as dedicated (and somewhat expendable) recreational spaces. This paper uses five separate and distinct case studies to compare the approaches taken by the NTS in its Scottish country park projects. Very little academic work has been done on the NTS, and this paper fills an important gap in exploring the organisation's approach with recreational land under its control. It shows the organisation addressing restrictive donor conditions contradicting a published ethos of open access, showing itself willing to bend, and even to subvert, the rules set by legislators, to use funding in innovative ways, and to promote 'passive' recreation – walking, picnicking, relaxing – as an approach less likely to compromise the scenic aspects of the landscape that visitors are seeking to enjoy. This analysis is important to present-day understandings of the balance between landscape conservation and public access, a dilemma that continues to trouble organisations concerned with conservation but dependent on public support and desirous of opening up access.

Keywords: Conservation; Access; Country parks; Charitable bodies; Public funding; Recreation

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1. Introduction

The National Trust (NT) for Places of Historic Interest or Natural Beauty, generally known as the NT, is the largest voluntary organisation in the United Kingdom, and also the largest private landowner.[1] Founded in 1895, it has been described as 'the most important and successful voluntary society in modern Britain,'[2] evolving from a largely patrician organisation led by aristocratic and property-owning interests into a more democratic body with a stronger voice for its members. Focused initially on the conservation of significant buildings and landscapes, it also has increasingly provided public access and promotes a wider understanding of heritage,[3] a responsibility that has become controversial, notably in highlighting the origins of several of its properties in wealth gained through the slave trade.[4] It is an important body in the UK with the ear

of government and of policy-makers, not only on heritage but on a much wider range of conservation and cultural issues.[5] However, its remit is limited to England, Wales and Northern Ireland; a similar, but autonomous, body exercises a comparable role in Scotland and is similarly influential with the Scottish devolved government.

The NT for Scotland (NTS) was established in 1931, much later than its English counterpart. It emerged in response to the possibility that a particular Scottish property might be acquired by the NT, a prospect that alarmed a group of influential Scots, led by Sir John Stirling-Maxwell of Pollok, who thought that Scotland should manage its own heritage and should establish a body to do this.[6] The government statute empowering the NTS confirmed its purpose as 'promoting the permanent preservation for the benefit of the nation of lands and buildings in Scotland of historic or national interest or natural beauty.'[7] Like its counterpart, it holds land (including wild land), heritage buildings and their contents, and planned gardens, whether associated with country estates or created separately. The NTS manages these to ensure they are protected, but also available to access by the public; and provides extensive interpretation of its portfolio to inform visitors as to their significance.

Both the NT and the NTS are registered charities, independent of government, and funded by a combination of charitable donations, public funding, and private endowment funds provided by property owners seeking to transfer their property (and its ongoing costs) to one of the Trusts. They have been granted important legal powers, including the right to own land and property and to declare it inalienable, thereby protecting the property against compulsory purchase, and preventing it from disposal – an important security for those making donations. The trusts also have the power to create restrictive covenants over land owned by others (with cooperation, naturally), giving them a measure of control over any adverse intentions on the part of future heirs.[8]

This paper explores the relationship between the NTS and the country park initiative, which emerged through the Countryside (Scotland) Act of 1967, legislation which also established the Countryside Commission for Scotland (CCS) as the body responsible for promoting the country park as a recreational concept. During CCS' lifetime, up to 1992 when it was merged into Scottish Natural Heritage (now NatureScot), a total of 36 country parks were designated in Scotland. The NTS had a close association both with the idea of the country park in a Scottish context, and with its practical implementation, and by 1992 owned and managed two of the 36 Scottish parks, was closely involved with two others, and had also engaged strongly with a fifth site that became a country park toward the end of this period. Given the strong recreational focus of the country park initiative, it is curious to see a conservation body like the NTS taking so close an interest in it, and this merits further exploration.

The paper also notes attempts made by NTS to access the National Land Fund (NLF). This had been established in 1946, to the tune of £50 million (nearly £3 billion in 2024 equivalent terms) by the post-war Attlee government with the intention of funding property of significant heritage value as a memorial to lives lost during the Second World War. The NT benefitted significantly from this fund, acquiring several properties, and also contents, left to the nation while the value of the taxes levied on these properties on the death of their owner was transferred from the NLF to the Treasury. However, the fund never achieved its early aspirations and was wound up in 1980, replaced by the National Heritage Memorial Fund with a vastly smaller budget.[9]

The NTS has been largely by-passed by academic research. Studies focus on the much larger NT in England and Wales (NT), and although there are parallels between the two bodies, they are separate entities with different contexts to their work. Several histories of the NT exist, mainly written by staff and therefore well-informed but variable in their objectivity, and also in the extent to which they recognise the NTS. Fedden includes a short chapter on the Scottish body, acknowledging that this is merely a brief overview,[10] but Gaze only notes the NTS in passing,[11] while Newby's contributors barely mention the NTS at all.[12] Waterson's centenary history of the NT also mentions the NTS only in passing,[13] although an NTS property features prominently in his more recent work.[14] Beyond these insider perspectives, Lowe and Goyder's exploration of the role of the voluntary sector in environmental politics analyses the influence of the NT, but again only mentions the NTS briefly in the context of a specific campaign it shared with the NT.[15]

Even in literature more closely focused on Scotland, the NTS is marginalised: Linklater and Denniston's analysis of 'how Scotland works' mentions it only as part of a wider network of influence,[16] and the NTS is also only a passing thought in Mackay's analysis of Scotland's rural land management, where the NTS' important role surely deserves greater attention.[17] Histories of the NTS largely focus on its acquisition record and offer only limited analysis of policy-making; Ryan is an example, with little to offer the historian beyond a description of its origins.[18] Two smaller, undated publications from the early 1970s, both celebrating the NTS, are of more interest: in one, Prentice echoes Linklater and Denniston by noting the

importance of NTS' networks of influence, cultivated in particular by Jamie Stormonth Darling during his tenure as NTS Secretary, and the prominence of partnership as a means to achieving the desired outcome.[19] The second booklet also emphasises partnership, alongside the need to educate visitors, sustaining and stimulating interest in the disciplines the Trust seeks to showcase.[20] The most effective treatment of NTS history is that of Bremner, who explores this chronologically, identifying different themes and priorities – funding, partnership, voluntarism, for example – as each gained prominence. The book achieves its probable objective of celebrating the Trust's work over a 70-year period but lacks a more penetrative and critical analysis.[21]

It is therefore helpful to find Calder giving attention to the context in which the NTS works, an approach that allows her to discuss more freely the difficulties and tensions the NTS had to grapple with. An important example of this is her treatment of 'Unna's rules,' conditions set by the celebrated mountaineer Percy Unna, who generously donated to NTS for the acquisition of several iconic Scottish wild areas – under stringent conditions.[22] These 'rules' included restricted public access to protect the land's wilderness quality, and banning field sports, signage, or access improvements, conditions readily accepted by the NTS at the time.[23] However, these 'rules' did not anticipate later growth in enthusiasm for public exploration of wild land, a trend the NTS has found difficult to resist, which has, in turn, led to accusations of failing to honour the donor's original intentions.[24]

This illustrates one of the great tensions affecting the NTS' work: the need to maintain a balance between conservation on the one hand, and public enjoyment on the other. This problem was by no means confined to Scotland: the NT's chairman asserted in 1966 that 'The trust's job is not to involve itself in the entertainment industry;'[25] responding to a growing enthusiasm, described in detail by Tinniswood, whereby country house owners in England developed 'attractions' to draw visitors in, ranging from safari-park animals to naturist conventions.[26] The NTS may have balked at ideas of this type, but always recognised the importance of attracting visitors and keeping their interest; Stirling-Maxwell was committed to this view from the outset, describing the NTS in 1936 as 'a cabinet … where [valuable things] will be perfectly safe,… and where they are open to be seen and enjoyed by everyone.'[27] This balance has proved delicate, however, because increasing visitor numbers, while generating welcome revenue, has also presented problems of facilities provision, visitor management, and pressures on-site quality.

It was this same tension between conservation and recreational access that lay behind the creation of the country park in the late 1960s. The idea's roots lay in a burgeoning desire for access to the countryside that began in the first half of the 20th century, accelerated by a massive expansion in car ownership during the 1950s and 1960s; by 1966, 45% of British households owned a car,[28] and much larger numbers of newly mobile people now wished to enjoy leisure time in countryside settings. Their numbers, and their sometimes inappropriate behaviour, attracted strong criticism from rural interests, and several commentators noted the paradox of large numbers of visitors damaging the very scenic quality and tranquillity they wished to enjoy. Perhaps the most influential argument came in a 1965 article by Michael Dower, in which he not only described the present 'battalions of cars…pour[ing] out of the city,' but also forecast an apocalyptic millennium in 2000 if the problem were allowed to grow unchecked.[29]

Dower suggested setting aside countryside specifically for recreation, an idea taken up in a Government announcement introducing the country park as a new landscape designation, leading to the Countryside (Scotland) Act of 1967,[30] which gave Scottish local authorities powers to create country parks and offered grant support of up to 75% to assist with this. The parks would provide a wider choice of countryside destinations for motorists, thus reducing congestion at scenic sites, and spaces where insensitive behaviour would be less problematic. The parks would not need to be especially attractive in themselves but would have to look the part and provide for motorists' essential needs, including parking, toilets and litter disposal.[31] The underlying idea was separation, removing vehicles and disruptive activities into less sensitive spaces, and leaving scenic beauty to those better able to appreciate it. This was a perspective shared, at least initially, by the NT, whose Annual Report in 1968 noted the importance of distinguishing the needs of those wanting 'a happy day in pleasant rural surroundings' from those wanting 'a special experience…of tranquil beauty or rugged grandeur.'[32] It is not difficult to discern an underlying elitism in this approach, with the masses encouraged to use more expendable countryside while beauty was reserved for a more cultured and appreciative audience.

On the face of it, country parks would therefore seem to have little connection to the work of the NTS. They were not expected to be the places of natural beauty that were the NTS' focus, but rather landscapes of expediency, acting as magnets for motorists for whom any countryside would suffice and thus protecting scenic and heritage properties from being overrun. However, the NTS took a very active interest in country parks, and it is interesting

to explore the nature of its involvement with the concept more closely, and to understand their enthusiasm for the idea. Jan Woudstra and I have suggested that site-specific case studies would help to address questions about country park development; such an approach might include studies of proprietorship and rationale, as in this paper, which considers five examples where the NTS engaged – in different ways that reflect distinct contextual influences – with the country park agenda (Figure 1).[33]

2. Methodology

The NTS engaged with the country park initiative in five separate instances. Each of these is presented as a case study, showing in detail how the organisation worked to secure or failed to secure, the outcome it sought. This approach allows not only an understanding of the background to each of the five cases but also enables exploration of the similarities and contrasts in the approach taken across the country park era, which lasted from 1967 to around 1992 when CCS lost its

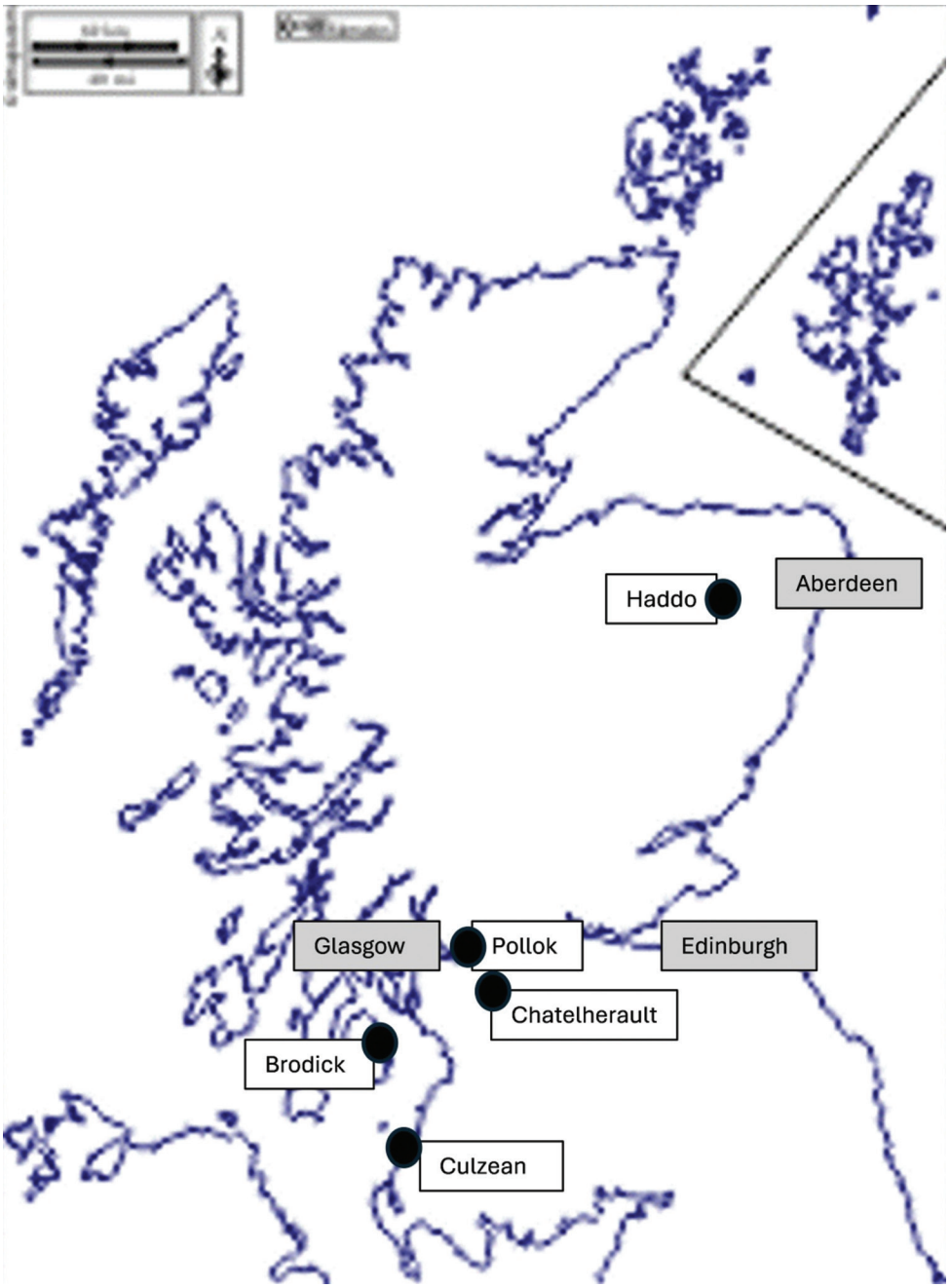

Figure 1. Map showing locations of case studies within Scotland

identity and the country park designation lost its precision of meaning. Each case study has been explored in depth using primary archive sources, including the NTS' own archives, Scottish Development Department (SDD) papers (the SDD had control of government funding for country parks), the papers of other statutory and non-statutory bodies, and local archives. These original materials have been supplemented by personal visits and exploration of each of the parks concerned. A small number of secondary sources have been consulted; these are primarily histories of the organisations involved, supplemented by analyses of countryside policy in Scotland in this period, and are all referenced in the Introduction section.

3. Case studies

3.1. Culzean[1]

In 1945, the NTS was still a relatively young organisation, but it had developed from cautious beginnings to a more confident position, managing more than 20 historic properties, and a large acreage of the heritage landscape.[34] However, this confidence was tested severely when in that year Lord Ailsa offered the NTS the gift of Culzean Castle, an A-listed[2] historic building with extensive gardens set in a 230 ha estate on the Ayrshire coast. Culzean had suffered badly from neglect, and was being offered without the financial endowment the Trust would normally expect, to finance immediate repairs and ongoing maintenance.[35] The offer of such an iconic property was irresistible, however; after acceptance of the gift an appeal was launched, but Culzean nevertheless caused persistent deficits in the NTS finances, to the point where in 1948 it 'almost sank the Trust's ship for good.'[36] Deficits on Culzean's revenue account continued to be reported into the late 1960s; with a further appeal launched in 1968 and Culzean's finances continued to be a major concern for the Trust as it approached the 1970s.[37]

It was against this backdrop that the NTS's Secretary, Jamie Stormonth Darling, began in 1968 to think in terms of utilising the funding available under the Countryside (Scotland) Act to mitigate this problem. He needed support from a variety of sources: these included CCS, the agency managing the country park programme; the SDD, who held the funding for it; the local authority, required by the Act to assess the need for a country park in their district;[38] and the UK Government's Scottish Office, and the Treasury, which held positions of authority over all these bodies. Securing this support would not necessarily be difficult; there was a strong and urgent desire on the part of both CCS and the SDD to produce a country park, to validate the concept as relevant to Scotland.[39] Stormonth Darling quickly secured Scottish Office support for the proposition,[40] receiving considerable help from the SDD, who wrote to HM Treasury in very positive terms as to what country park funding might achieve at Culzean.[41] He also successfully lobbied not only the immediate local authority, Ayrshire County Council, but also the two Burgh Councils of Ayr and Kilmarnock, suggesting (incorrectly) that they now had a statutory duty to provide a country park.[42]

There were nevertheless several complications that Stormonth Darling had to tackle. Match-funding was one of these; the CCS grant would meet 75% of the costs of providing a country park, but Stormonth Darling needed to find the balance elsewhere, without compromising NTS resources. Cost sharing with the three councils was the solution,[43] and was agreed at an early stage, subject to confirmation of the sums involved.[44]

A further complication was the eligibility implicit in the country park legislation. Although no formal policy existed at this stage, it was clear that country parks were expected to be close to population centres, with a presumption in favour of more active recreation than Culzean was likely to offer.[45] CCS' own feasibility study noted the relative remoteness of Culzean from major population centres, something which might have disqualified it from becoming a country park.[46] Even the SDD's letter of support seems written partly to defuse the possibility of rejection on the grounds of ineligibility.[41] Nevertheless, the application was encouraged enthusiastically by both CCS and SDD. Culzean's transition into a country park can therefore be seen as subverting the very policy it was pioneering and implementing.[47]

Stormonth Darling also had to convince his own Executive Committee that the NTS' interests and statutory obligations would not be compromised through a partnership with external bodies and funders, and to reassure both his own committee and external interests that an increase in visitor numbers would not damage the essential character of Culzean, something all parties – including the donor himself – felt strongly about.[42]

These concerns were addressed in a formal agreement between the NTS and the three local authorities concluded in March 1970.[48] This set up a joint management committee of the three councils while giving the NTS day-to-day responsibility for managing the country park within an agreed budget and policy, effectively allowing the NTS to spend the country park funding as it saw fit, within agreed parameters which also expressly guaranteed 'the character and atmosphere of Culzean.'[49]

1 Culzean is pronounced 'Cullane'.

2 A-listing is the highest level of listed building status in Scotland, indicating a building of national or international significance.

Culzean was formally designated on 19 December 1969, becoming Scotland's first country park. A private exchange of correspondence between Stormonth Darling and his English counterpart, John Winnifrith, reveals the underlying rationale. The key priority was financial: Securing capital to develop facilities, allowing NTS funds to be transferred to building repairs, and increasing visitor revenue to offset the annual deficits. Stormonth Darling also claimed that the partnership with local authorities gave democratic legitimacy to the project and helped dispel any notion of elitism.[50] He later described this agreement as 'a fantastic coup.'[51]

The issue of visitor management was dealt with separately. The NTS had discovered the landscape architect Elisabeth Beazley in 1967, through an article in which she discussed the threats countryside motorists posed to site character and ambience, an issue clearly pertinent at Culzean.[52] Stormonth Darling invited her to visit Culzean and later credited her with the initial idea of seeking country park designation.[53] Beazley ended up advising NTS at Culzean on visitor management and related matters for 14 years from 1970, visiting around 80 times.[54] She was very much in tune with Stormonth Darling's thinking on reconciling increased visitor numbers with conservation objectives and saw the importance not only of the acquisition but also of the financial dimension.[55]

Stormonth Darling was also clear from the outset that an increase in visitor numbers was something to be welcomed, rather than feared. His business case for the country park reasserted the founders' principle that the NTS should make its assets accessible to the widest possible audience, reminding his Executive Committee of the NTS's commitment to public enjoyment and recreation as an essential part of its remit.[56] As a country park, Culzean would continue to offer visitors a chance to experience the historic castle, enjoy its gardens, and explore its wider countryside, without compromising its essential quality as a landscape of peace and tranquillity. While he recognised the innate inconsistency in the Culzean project as being 'a country park of a very different nature to that conceived by those who thought up… the Countryside (Scotland) Act,'[57] he nevertheless also saw it as a prototype, an example to be followed by others.[57]

3.2. Brodick

It was, however, a further ten years before the Culzean model resurfaced, this time at the NTS property at Brodick, on the Isle of Arran off the Ayrshire coast. Brodick Castle and its surrounding 292-ha estate, including magnificent planned gardens, had been acquired by the NTS in 1958, and was supplemented by the gift (again by Percy Unna) of the adjacent mountain of Goat Fell and other wild land amounting to a further 3,042 ha.[58]

Brodick had many similarities to Culzean. It too consisted of an A-listed castle, with extensive formal gardens, and a wider estate that might qualify under the legislation. Like Culzean, it was a property of considerable importance in terms of both heritage and natural beauty, and its benefactor (Lady Jane Fforde, heir of the Duchess of Montrose) was similarly concerned to preserve its essential character and tranquillity.[59] Moreover, as Culzean had been, it was a drain on NTS's financial resources; although it had come with an endowment, this had been seriously eroded by inflation.[60] By 1975, the custodians at Brodick were pressing the NTS for an £80,000 injection of funds (equivalent to around £1 million in 2024) to enable them to carry out necessary repairs and capital works,[61] while the annual revenue deficit had reached £14,000 by 1976 – 1977 (around £200,000 in 2024), in spite of support from the local council and other sources.[62]

There were, however, two contextual differences that affected Brodick's country park application. One was the reorganisation of local government in 1975, which abolished the county and burgh councils that had funded Culzean and replaced them with a regional strategic authority (the enormous Strathclyde Regional Council [SRC]), and a district authority, Cunninghame District Council, covering north Ayrshire and Arran. The second change came about in CCS's policy as regards eligibility for funding. Whereas Culzean had benefitted from a total absence of ground rules on country park funding, CCS had since established criteria for designation that might have excluded Brodick as too remote and inaccessible – factors actually emphasised by CCS's officer when assessing the project's suitability.[63] The site was a long way from any population centre (breaching what was now a formal requirement), and reachable from the mainland only by ferry. It was however an important destination for holiday visitors to the island, around 40% of whom visited the castle every year,[64] and the NTS's view was that 'the property is eminently suitable for a country park based on the Culzean formula.'[65]

CCS was also aware that it had not been as successful as its English counterpart in stimulating the creation of country parks, and wanted to add to its portfolio to avoid drawing attention to this failure. There was therefore a considerable imperative by 1980 to accept applications, and during the course of that year, no fewer than 11 parks were designated.[66] Despite the eligibility question-mark, CCS found it could accept Brodick as a country park, a decision undoubtedly motivated by its need to increase its portfolio, but which was nevertheless clearly inconsistent

with, and even contradictory to, CCS's more developed criteria for acceptance.[67]

Stormonth Darling stated that he wanted a similar arrangement to that at Culzean, and envisaged a partnership (and funding, naturally) with both new local authorities, alongside other statutory bodies.[68] Strathclyde proved uncooperative, seeing Brodick as an essentially local facility,[69] but Cunninghame DC was supportive, in spite of the need for an increased (and ultimately unsustainable) level of grant,[70] and an agreement was drawn up along Culzean lines but with important differences. It emphasised the importance to both parties of preserving the character and atmosphere of Brodick, and set up a Joint Committee with powers to set a budget and general policy, while delegating day-to-day management to the NTS, as at Culzean.[71] However, in Brodick's case, the NTS and the Council were equally represented on the Joint Committee, suggesting that the NTS was learning from experience and wanted a greater say than it had allowed itself at Culzean.[72]

Brodick was duly designated a country park on 10 April 1980. However, its narrative makes it clear that this was a product of expediency rather than genuine recreational need. The designation made little difference to its appeal to visitors, which fluctuated according to the appeal of Arran as a holiday destination rather than anything else.[73] CCS agreed to designation against its own advice (and clearly against the spirit behind the legislation) because it needed to expand its portfolio or face accusations of failure. Stormonth Darling was quite clear in his internal discussions that the purpose of the project – as at Culzean a decade earlier – was to reduce overall costs to the NTS and to allow it to focus its own resources on the castle.[74] Brodick was a further subversion of the country park idea, highly questionable in policy terms, but a solution to the partners' differing, but complementary, needs and aspirations.

3.3. Pollok

Like Brodick, Pollok also became a country park in 1980, but the NTS's interest in it goes back to a much earlier date. Its A-listed centrepiece house was the home of one of the NTS's founders, Sir John Stirling-Maxwell, and was where the decision to establish the NTS was taken in 1931.[75] The Pollok estate constitutes what remains of a once extensive countryside landholding, much of it sold off for development, leaving a 146-ha park and other green space as an island of the countryside on Glasgow's south side. Since 1983, the country park has also housed the Burrell Collection, an enormous, eclectic accumulation of artefacts and artworks bequeathed to Glasgow in 1944.

Pollok was opened up for everyday public access in 1911, under an agreement between Stirling-Maxwell and Glasgow Corporation, long before the NTS came into being. It was first offered to the NTS in 1938, as an attempt to protect the land from future development, but negotiations failed due to the lack of an endowment and the financial weakness of the then fledgling NTS.[76] Legislation in 1938[77] opened up an alternative possibility to secure the future of the estate, and in 1939 a Restrictive Agreement was concluded between the estate owner and NTS, giving the NTS a right to veto any development on the site or any other action that might detract from its amenity value. The agreement provided that the land should remain 'as open spaces or woodlands for the enhancement of the beauty of the neighbourhood and… for the benefit of the citizens of Glasgow,'[78] and perpetuated the owner's wish not only to prevent development during his lifetime but also to bind his heirs to this commitment. It was successfully used, for example, to block a Council plan to build housing on part of the estate in 1964.[79]

Three further attempts were made to gift Pollok to the NTS, all of them unsuccessful. An offer in 1956 was again declined because of the lack of endowment, and the prospect of significant financial losses accruing to NTS if Pollok were accepted;[80] similar considerations scuppered further approaches in 1962 and 1963.[81] The capital sum needed by the NTS was estimated at £300,000 (around £8.4 million in 2024),[82] but the Restrictive Agreement closed off the possibility of selling off part of the property to finance this. Stormonth Darling explored several ideas, some quite radical; one was to sell the house's art collection to the NLF while keeping it on display at Pollok, a proposal that was carefully considered by the Government (the NLF was significantly underspent at this time) but eventually dismissed as possibly illegal because the money would go to NTS rather than to the Treasury.[83] He failed to secure a solution; the upshot was that in 1966 the family gifted the park outright to Glasgow Corporation.[84] On the face of it, this looks like a dangerous move – it was only two years since the city had tried to develop the land – but the conditions attached to the gift protected against development, and the Restrictive Agreement with NTS remained in force as a further barrier to encroachment.[84]

The gift was complicated by the city council's decision to provide space within the park for the Burrell Collection, an astoundingly eclectic collection of artefacts collected by the shipping magnate Sir William Burrell over decades and gifted to Glasgow in 1944 – but still without a permanent home, as the conditions attached to the gift had never been met.[85] This decision required NTS approval under the Restrictive Agreement, and an agreement in principle was secured which included the setting up of a Pollok Advisory Committee (PAC), to be chaired by NTS and giving them

a more proactive role in managing the land for the future.[84]

In 1972, Glasgow City Council explored the designation of Pollok as a country park, but an application was turned down by CCS on the entirely reasonable grounds that Pollok was an urban open space, not a countryside one.[86] In 1979, however, the idea was revived by CCS, who were anxious to secure new designations, partly to improve their disappointing record in this respect, but also perhaps with one eye on the Thatcher government's intention to rein in public spending in Scotland.[87] The family was nervous about this proposal, which they thought might encourage increased visiting, but Stormonth Darling was more concerned to secure the increased resources he associated with designation, and to strengthen the PAC by bringing in CCS expertise.[88]

The comparative weakness of the Restrictive Agreement, as opposed to outright NTS ownership and its associated inalienability, was exposed twice during the past two decades of the 20th century. The first challenge came through traffic management for the Burrell, which caused a very serious disruption of the relationship between the NTS and the city when the latter approved the Burrell architect's plan without consulting the PAC, breaching the Restrictive Agreement.[89] The NTS took strong exception but eventually had to accept this apparently inadvertent *fait accompli* for the sake of the Burrell project as a whole.[90]

A further test arose in 1971, when a proposal was mooted to extend the M77 motorway southward toward Ayr, a project that would require taking land from the western side of the estate.[91] Although Stormonth Darling deprecated what he described as a 'most serious intrusion,'[92] he was advised that defeat was inevitable – the forces promoting the motorway were too strong to resist, and the best the NTS could hope for was mitigation.[93] The NTS contracted landscape architect Sylvia Crowe to advise on suitable measures;[94] her suggestions were accepted by the proponents of the project, and the NTS waived its right to object in 1974.[95]

Nevertheless, the wider discussion on the motorway dragged on for a decade, and ended up at a Public Inquiry in 1988, with formal approval late in 1989; work only commenced on site in 1992.[96] The project provoked widespread opposition from 1972 onward, culminating in the 'Pollok Free State' in 1994–96, a widely-publicised eco-protest employing direct action with protesters occupying trees scheduled for felling, chaining themselves to diggers, and the construction of a 'car henge,' a monument made by burying cars vertically in the land scheduled for the motorway.[97] The NTS was accused of neglecting its responsibilities under the 1939 Agreement and 'selling out' to the motorway interests,[98] but this was a battle it could never win against a government-backed multi-million-pound scheme; mitigation was probably the least bad option available.

In 1998, the city council set up a lease arrangement with the NTS whereby the city retains ownership of the land but the NTS now manages and maintains it; Pollok House is thus now part of the NTS portfolio of properties, although still owned by the city council.[99] This arrangement appears to be working well, with the park winning the Best Park in Britain award in 2007, and the Best Park in Europe award the following year.[100] The Restrictive Agreement remains in force, so the NTS continues to have veto powers over any plan to develop or sell off the land, but the M77 extension project demonstrates that these powers are vulnerable to *force majeure*, whereas the inalienable status derived from outright ownership offers a much stronger level of protection.

In the case of Pollok, the country park designation seems to have been completely incidental to the NTS's relationship with the site. The only advantages gained from country park status were to the city council, as a possible recipient of countryside funding, rather than to NTS directly, although the facilities enabled by this have improved a site the NTS now manages. Even then, the designation was never a pre-requisite for funding (although this was implied by CCS) and Glasgow could have sought CCS's financial help without making Pollok a country park. The other benefit identified from designation was the participation of CCS in the PAC, but Stormonth Darling found this consistently disappointing in practice.

3.4. Haddo

Haddo is a country house in Aberdeenshire, around eight miles from the nearest small town (Ellon) and 20 miles north of the nearest large centre, Aberdeen. Designed by William Adam, built in the 1730s, and set in around 75 ha of grounds, Haddo is an A-listed building, with extensive formal gardens, and was formerly owned by the Earls of Aberdeen (one of whom was Prime Minister of the UK). The landscape includes open parkland, a large memorial to a family member who died at Waterloo, a deer park, and woodland managed by the Forestry Commission. By the second half of the 20th century, it had an established reputation as an arts venue, with an active choral society, and an annual concert attracting some of the biggest names in classical music.[101]

In 1973, the earl opened discussions with Aberdeen County Council on possible new uses for the property; he was especially interested in creating a residential arts centre, building on the house's reputation for musical excellence. The council was wary; however, and the idea was shelved. Nevertheless, potential new uses for Haddo

re-emerged after the earl's death in 1974, and the Secretary of State for Scotland was approached by his widow concerning possible acquisition of Haddo in lieu of death duties.[102] Three separate parties would be involved in these negotiations: the NTS, the local authority (by this time Grampian Regional Council [GRC]), and the Haddo estate trustees.

A generous endowment accompanied the offer,[103] and the NTS was unsurprisingly very interested in acquisition. They hoped to establish a country park, with Culzean cited as an illustration of their intent; they sought a Brodick-type arrangement whereby they would take ownership of both house and grounds, managed by a Joint Committee alongside the local authority. However, Capt. Farquharson, the estate's factor, doubted that GRC would accept such an arrangement: 'I think [the Council] very much wish to go it alone here.'[104] He was right; the council wrote to NTS stating unequivocally their insistence on having legal title to any land placed under their control, a position which they claimed had the Secretary of State's support.[105] This would not preclude working together on issues of shared interest, but would mean that 'the NT (*sic*) would have to be satisfied with the terrace and the lawns.'[104] Interestingly, although they would clearly have preferred a different approach,[106] NTS did not challenge this position with any vigour, and negotiations over the country park part of the transaction continued between GRC and the estate with only limited NTS involvement.

The transition to a country park was, however, by no means straightforward. There was a significant difference of opinion over the price the Secretary of State should pay, with the family valuing the property at £32,000 (£300,000 at 2024 equivalent) while the District Valuer set a figure of £15,000.[107] There was disagreement over the land to be included in the deal, with the estate insisting on restricting access to large parts of the grounds, including the monument and the deer park, an approach which severely reduced the potential of the park in the council's eyes: 'we are left with enormous expenditure…and no real opportunity of opening up the area's potential…[we would gain] a very second-rate park without large public areas.'[108] The estate also wanted to retain grazing rights, without which, it argued, its farm operations would become unviable.[109] Despite Lady Aberdeen's strong desire to retain the peace and tranquillity of the grounds,[102] estate trustees and others periodically put forward ideas that would have threatened this.[110] There was also an ongoing dispute over the retention of shooting rights over part of the land.[111] The impression given in the correspondence that ensued is that the estate was willing to take the money, but only if it retained all its existing rights and usage of the land, a completely unrealistic proposition. In the circumstances, it is perhaps unsurprising that the estate's solicitor described the negotiations as 'by far the most complicated deal of its kind to pass through [my] hands.'[112]

What could have become a very protracted discussion was fortuitously hastened to a conclusion by the Scotland and Wales Bill, then passing through Parliament and raising a real possibility of Scottish independence. The NTS suspected that the financially constrained National Heritage Memorial Fund (NHMF), which had now superseded the NLF, would not be devolved to an independent Scotland; this would put the whole transaction in jeopardy.[113] This focused minds dramatically; an acquisition price of £28,000 was agreed with Lady Aberdeen in 1978, and a further £18,000 (£145,000 in 2024) allocation was made for essential works, both to come from the NHMF.[114] Under the final arrangements, issued in May 1980, GRC would acquire the country park, with public access to much of the disputed area, while the NTS would accept the house, gardens and lawns. The two bodies undertook to share the costs of improved access and car parking; a 75% grant from CCS would greatly help with these costs.[115] A Joint Committee was also established in the end, including NTS, GRC and the residual estate.[116] Moreover, Farquharson was eventually, albeit reluctantly, persuaded that allowing shooting in an area frequented by the general public was really not a good idea.[117] Haddo was designated as a country park on 9 December 1980.

The NTS had become quite peripheral to the negotiations over the country park, and much less involved than it was in its other 1980 designations, at Brodick and Pollok. However, this more liminal engagement was perhaps inevitable, given that the problems caused by the estate related to GRC's part of the arrangement; there was no controversy over the house or gardens. Once it was determined that these were going to the NTS, and once the endowment and the repair fund were agreed, there was little for the NTS to be especially concerned about at Haddo, and it was able to access CCS funding for infrastructure improvements such as the car park. It may also have drawn comfort from the fact that visitors to the country park could well also be customers of the NTS's gift shop and catering facilities associated with the house.

It is also interesting that Stormonth Darling, who was so closely involved with negotiations at both Brodick and Pollok, took very little part in the discussions over Haddo. Even the negotiations with the aristocracy, very much Stormonth Darling's preserve elsewhere, was at Haddo assigned to his deputy. Stormonth Darling might have been able to find a way through the complex negotiations over the country park and confronted more authoritatively the

unrealistic expectations of the estate, but GRC's insistence on ownership meant that he was effectively excluded from the discussions, other than to draw attention to the potential in the NHMF.

3.5. Chatelherault

The last country park possibility to interest the NTS was Chatelherault, a large estate of grassland and wooded glen south of Hamilton, dominated by an 18th-century hunting lodge. Chatelherault itself is an A-listed building designed by William Adam, which originally formed part of the extensive Hamilton Palace landholding; it has an associated parterre and other gardens but these are limited in scale, reflecting the building's original subsidiarity to the Palace itself. The wider Chatelherault estate includes a historic ruined castle, several ancient trees and the famous Cadzow wild white cattle.[118] The land north of the hunting lodge had been extensively mined, first for coal, later for sand, from the early 19th century, leading to the demolition of Hamilton Palace itself in the 1920s; by the 1960s the encroachment of continuing sand extraction was threatening the stability of Chatelherault as well. A planning application to extend the extraction was submitted in 1964; although it did not say so specifically, it was evident this would involve the demolition of Chatelherault, and it opened a new chapter in the property's history, bringing both its importance and its increasingly lamentable condition to a wider audience.[119]

The local planning authority, Lanark County Council (LCC) sought support for preservation, and the NTS was among those invited to join them in this campaign.[120] An NTS assessment confirmed that Chatelherault was 'a very fine work of architecture' but thought it unlikely to attract significant popular interest, thus ruling out an appeal to the public for funding. As there was no endowment, and the prospect of considerable expense to rehabilitate the building, NTS acquisition was not at all attractive, but this did not prevent NTS's active and supportive interest in Chatelherault's preservation.[121] The Royal Fine Arts Commission for Scotland (RFACS) also supported preservation, but lacked powers to finance a rescue, as did other interested parties.[122] While the RFACS advocated unrealistic propositions such as relocating the building to Pollok, Stormonth Darling was looking to build a partnership to put pressure on the estate, and exploring restoration *in situ* with the SDD.[123]

The planning application ended up at a Public Inquiry in 1966, where several expert witnesses testified as to the building's architectural significance. This was accepted by the Secretary of State, who ruled against the estate company, suggesting that saving Chatelherault was 'not yet beyond hope,' and urging someone to come forward with a proposal for rescuing it.[124]

This encouraging result, however, came to little. The issue was bandied around indecisively for 3 years, with several bodies expressing concern, but all were either unable to act themselves or sought to transfer the responsibility elsewhere. A further planning application, intended to take advantage of this impasse, was again unsuccessful, but the stasis continued, and Chatelherault continued to deteriorate to the point where it was considered 'in the last stages of decay;'[125] vandalism and pagan sacrifice were reported, though the latter turned out to be nothing more than an occasional orgy.[126] The NTS remained the body most committed to finding a solution, with its Chair, Lord Bute, planning to discuss the issue directly with Lord Hamilton, who owned the property through a Trust arrangement.[127] Ideas for resolving the issue surfaced and died across several years, falling at hurdles of finance or practicality, but one that lasted longer than most others was that of making Chatelherault the focal point of a country park.

One history of Chatelherault credits the genesis of this idea to Jean Balfour, then Chief Executive of CCS, in 1977.[128] However, Stormonth Darling had been thinking along these lines since at least 1972, when he raised the possibility with the Duchess of Hamilton.[129] He tried to get the local authorities interested, but made little headway, and even CCS, who had previously hinted at the possibility of funding, turned their back on the idea.[130] Negotiations with the family, however, proved more fruitful; the Duke offered in 1978 to put Chatelherault into guardianship as an Ancient Monument, and to gift its surroundings as a public park,[131] an approach supported within the Scottish Office.[132] The NTS's influence here – particularly that of Lord Bute – seems to have been critically important to this proposal.[133] However, the Duke of Hamilton died before this arrangement could be realised, and the estate trustees were horrified to discover the plan, evidently negotiated by the Duke without their knowledge; they immediately repudiated it.[134]

The Duke's demise, however, opened up the new possibility of a gift in lieu of death duties, something Stormonth Darling was alert to, observing that the NLF was seriously underspent in the present financial year.[135] An offer in lieu was duly made, but the value of the estate was considerably greater than the duty owed, and there was no legal provision to allow reimbursement of the excess. The trustees were unable to accept this, so this opening also failed to materialise.[136]

Nevertheless, the country park idea remained alive, and LCC asked Stormonth Darling to expand further on it in 1974. He pointed out that 'architectural merit' on its own was clearly not going to save Chatelherault, but that 'a large

measure of public enjoyment,' linked to its location close to New Towns at East Kilbride and Stonehouse,[3] and its visibility from the M74, then being promoted as a gateway to Clydeside, would help; these were exactly the types of argument he had used at Culzean.[137] He also emphasised the importance of not just saving the building, but also identifying uses for it thereafter, using the repurposing of buildings at Culzean into a visitor centre for illustration.[135] Local government reorganisation also came into play after 1975; the new regional authority, Strathclyde, declined to become involved, but the newly-formed Hamilton District Council engaged actively with the idea of preservation, agreeing in principle to taking ownership (and ongoing responsibility) for Chatelherault.[138] The NTS offered on at least two occasions to act as an intermediary to broker a scheme agreeable to all concerned.[139] However, a solution was still some way off.

The impasse was eventually resolved in 1978 by the estate selling off the property in three lots, one of which included the hunting lodge, gardens, and much of the natural countryside; the Secretary of State agreeing to buy this portion, and to use the NLF to fund the restoration; and Hamilton District Council undertaking to manage the site thereafter as a recreation area for residents and visitors.[140] An advisory group was established that included the NTS, and also CCS, who offered funding toward a ranger service, parking and interpretation – all facets of a typical country park[141] – and a funding package was assembled including European resources recently opened up to the UK applicants.[142] The restoration took 8 years, and was not without its own problems, both bureaucratic and financial, but the site was duly designated as a country park in 1987.[143] It was described as 'a park …designed for passive recreation… we want to see lots of people enjoying the countryside.'[144] The ambition behind the project attracted praise, but also criticism: one commentator described it as 'a gamble on increased leisure'[145] – which indeed it was, since without the associated country park the restoration would never have happened.

Why, then did the NTS not offer to take ownership at any stage in this story? The answer is partly financial; even after the Scottish Office approved the costs of restoration of the building; there was no prospect of ongoing help with revenue costs other than from Hamilton District Council. Although it might have been possible to establish an agreement on the Brodick model, there is no evidence that such an approach was ever considered; Hamilton was allowed to take the project forward and to do the work of developing the country park and its facilities without NTS support. It seems likely that the uncertainty over costs proved to be a strong disincentive to closer engagement on NTS's part; but it is also arguable that the building offered fewer possibilities for use as an NTS property and would not therefore be an attractive proposition for revenue generation. Interestingly, though, Hamilton was content to proceed with a project implying significant cost at a time when Council revenue budgets were coming under serious pressure from the Thatcher administration's policy toward Scottish local government.[146]

4. Discussion

Five different projects are identified here, all of which resulted in the creation of country parks, but with different outcomes in terms of the NTS's role. At Culzean and Brodick, the NTS was able to establish a partnership arrangement that gave them day-to-day responsibility for managing the whole of the property, both house and parkland, but also provided local authority funding alongside that offered by CCS. At Haddo, the local authority declined such an arrangement, preferring to manage the park themselves; the partnership here was much looser, and the division between the park, free of entry charges, and the house, where a charge is levied, is more obvious to the visitor. At Pollok, the NTS never came into ownership of the land, although it was given the opportunity to do so on several occasions; instead, it was given powers under a legally-binding Restrictive Agreement that proved effective on occasion in preventing an ambitious city council from developing the land for housing, but which put it in a difficult position as regards the Burrell and even more so the motorway extension, leading to accusations of 'selling out.' At Chatelherault, the NTS acquisition was never considered, and instead, the organisation sought to act as an intermediary in the protracted negotiations between the parties connected with the property.

Yet, for all these differences, there are a number of similarities here. All the resulting country parks were focused on passive recreation, the enjoyment of natural beauty, rather than on the more active, noisy and disruptive recreation that had prompted the UK Government to promote the country park idea in the first place. Stormonth Darling was correct in identifying Culzean as different from what the legislators had intended; the major difference was the provision of quiet and scenically beautiful countryside to be enjoyed, rather than the expendable, noisy landscapes envisaged by the legislators, and the same outcome can be identified at the other four sites, with every donor requiring a commitment to tranquil, passive recreation. In this sense at least, Culzean did indeed act as a prototype.

[3] Stonehouse was ultimately discarded as a New Town, but was still a live proposal at this point.

Moreover, all five cases involved the preservation of an A-listed building. The Countryside Act funding had of course to be used for the park, not the building, but it allowed other finance, whether from the owners' own resources or elsewhere, to be redirected from grounds maintenance into caring for the property. This was a significant part of Stormonth Darling's purpose at Culzean and Brodick, and it also operated in favour of the owners of Pollok and Chatelherault, with the park becoming an essential condition of the restoration of the latter. At Haddo, much of the countryside funding went to GRC, but this relieved the NTS of the financial burden of managing the associated parkland and allowed the endowment to be focused on the buildings.

This is part of the reason for NTS's unexpected interest in country parks. The legislation provided an opportunity to open up existing sites to greater numbers of visitors, and increased revenue, while allowing the diversion of existing limited resources away from grounds maintenance and into building conservation. Country Park funding also provided for important enhanced facilities in the form of visitor information, car parking, toilets, and catering, which in turn supported and encouraged higher levels of visiting and on-site spending, and allowed the sites to align more closely with growing visitor expectations.

5. Conclusion

Thus, in the end, NTS's engagement in the country park initiative was essentially driven by finance; the means may have varied but the endgame was the same. The NTS approach was a pragmatic one that took account of the specific situation it, and other prospective partners, faced at each site. It benefitted from, but also contributed to, the similarly pragmatic approach adopted by the funding bodies – the local authorities, NLF/NHMF, CCS, and (to a lesser extent) the government. It meant bending the rules, or at least interpreting them in the most favourable way possible, and persuading others of the validity of this position, something at which Stormonth Darling emerges as a master, persuading the funders to accept Culzean, Haddo and especially Brodick in spite of their remoteness, and securing NHMF support for Haddo and Chatelherault. His approach to central government funding for Pollok was similarly radical, although unsuccessful; and his insight into saving the building at Chatelherault through the country park mechanism was fundamental to the rescue package. The five country parks identified here are only a small part of his overall legacy as Secretary of the NTS, but they are nevertheless a testament to his approach and his conception of what might be possible, given a partnership based on pragmatism and problem-solving, and awareness of external funders' priorities.

Because although the Countryside (Scotland) Act was intended to provide alternative destinations for countryside motoring, and so relieve pressure on scenic locations and congestion on the roads leading to them, this was never really a serious problem in Scotland. There were issues associated with Loch Lomond, where noisy picnickers and powerboaters disturbed more peace-loving visitors, but these were only occasional and geographically confined, as were (at this time, at least) alleged problems of erosion in the Cairngorms and other remote locations.[147] Meanwhile, CCS in particular was under pressure to spend its allocated resources, country parks were understood as offering vicarious protection to vulnerable sites, and Stormonth Darling was able to exploit this situation very effectively, while his awareness of NLF/NHMF priorities was also very helpful.

Although the NTS's interpretation meant vastly increased visitor numbers, the sites in question were not vulnerable, could handle the greater numbers, and might deflect visitors away from wilderness sites – at least, that was an expectation to be exploited. In reality, the pressures in Scotland were minimal and isolated, and opportunities to measure the demand for recreation, and the effectiveness of the policy, were missed or ignored. Moreover, the recreation being offered was essentially passive in nature, and protection for the 'essential character' of the landscapes was built into the arrangements. An organisation focused on conservation might not have been expected to devote so much attention to funding intended to promote recreational opportunity. However, the NTS has always had a strong emphasis on public access; an approach expressed at its foundation, and echoed throughout its lifetime, so there is no inconsistency between the NTS's role in seeking to conserve the five historic properties noted here and the opening up of their landscapes to large-scale recreation. That is entirely in keeping with the essential premise on which the NTS was founded, and there is no record of significant opposition to this approach at any of the five parks in which NTS took an interest. Unna's rules were thus never tested by the NTS' approach to country parks; this would come later as access pressures on wilder NTS land mounted.

Striking a balance between recreation and conservation priorities is not merely a historical issue; much landscape conservation around the world is predicated on rights of access as well as preservation priorities, and much is dependent on the funding that visitors, and visitor centres, generate. The NTS's pragmatic, site-specific approach is thus instructive; each site has its own dynamics and an inflexible, one-size-fits-all approach would have been less likely to achieve the balance needed. The arrangements that succeeded at Culzean could be modified for Brodick, but proved undeliverable at Haddo; a new approach had to be

deployed there with a different sharing of responsibilities and finance. Financial limitations forced a different approach at both Pollok and Chatelherault; a less flexible organisation would have failed in both cases.

The NTS country parks also illustrate the importance of understanding not only recreation in the round but also the fact that other interested parties may not be able to see the wider picture. An extreme in this respect can be seen at Haddo, where the factor had to be convinced that recreational shooting might be incompatible with public access. The legislators' thinking was to provide expendable spaces for active and noisy recreation; the NTS rethought this and instead offered places for quiet enjoyment of the countryside, picnics, and appreciation of the natural world, modifying the recreational expectation to ensure the balance was struck with conservation, and ensuring this by building into the agreements the preservation of the essential character of these places.

Finally, we also see here the possibilities of negotiated solutions between providers and funders. The country parks the NTS provided (or enabled) were not what the legislators intended, but nevertheless allowed them to demonstrate successful delivery. The agreements reached, and the funding secured, enabled not only the provision of recreational facilities but also the diversion of those funds originally applied to recreation toward other purposes, including the preservation of heritage properties. Stormonth Darling's approach, recognising not only his own organisation's needs but also those of the funders, produced five different, but successful, outcomes, and was also replicated successfully at some non-NTS country park sites. The approach was opportunistic, and involved rule-bending, but it succeeded, and it may still offer possibilities for solving the recreation/conservation equation today; it is, after all, possible to have both.

The focus on the NTS has limited this study to just five sites. Many more locations and facilities have faced the challenge of balancing these two variables, and it would be interesting to explore how jurisdictions with much stronger access obligations secure conservation priorities in vulnerable landscapes, and how those bodies that rely on visitors to sustain their conservation work ensure that the visitors do not damage the very thing they come to see. Increased environmental tourism, for instance to polar regions, can be a double-edged sword, raising awareness and financial support, but also demanding visitor facilities and careful management to limit disturbance and erosion. History and past practice can help with this continuing dilemma.

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Conflict of interest

The author declares no conflicts of interest, other than his status as an ordinary member of the National Trust for Scotland.

Author contributions

This is a single-authored article.

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Availability of data

Data used in the study can be obtained from one or more of the libraries and archives cited in the reference section.

Further disclosure

The research behind the Chatelherault section of the study has been presented, in a different form and context, to a small audience at Gladstone's Land, Edinburgh, and to a student history society at Glasgow University, and is scheduled to be published, in different textual form, in an article in *Scottish Local History*, Spring 2025. The research was also used in my book, *The Origins of Scotland's Country Parks* (York: Navitie Press, 2020).

The research behind the Culzean section of the study was published, in an extended form and using different text, in Woudstra, J and Back, P. 'Culzean Country Park – how an iconic Scottish landscape used the designation to secure a sustainable future,' *Landscape Research* 45(8), August 2020, 1032-1046.

The Pollok section of the study was published, in an extended form and with different text, in *Scottish Local History*, Autumn 2022.

The Brodick and Haddo sections of the study have never been published before, nor has the historiography of the National Trust for Scotland.

The five case studies presented here have never been brought together and analysed side by side as they are in this article, which uses the underlying research but addresses and explores a completely different question.

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Complete electrothermal and lifetime model of 18650 nickel manganese cobalt cell based on artificial neural network

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Abstract

This study presents a comprehensive electrothermal and lifetime model for cylindrical 3 ampere-hours (Ah) lithium-ion cells using artificial neural networks (ANNs) to estimate the cell's lifespan. The model combines an electrothermal component with an ANN-based lifetime prediction approach, offering a holistic representation of cell behavior over its lifetime by incorporating key parameters, including the state of charge, temperature, current, and cycle life. The ANN is trained offline using extensive experimental data collected from Sony cylindrical 3 Ah cells under various operating conditions. The electrothermal component employs a second-order Thévenin equivalent circuit model topology, enhanced with extended versions of characterization and parameterization procedures. Validation of the coupled model is performed using laboratory tests at different stages of the cells' life (500, 1000, and 1500 cycles), demonstrating its ability to estimate cell electrical and thermal performance across a broad lifespan range. Results indicate a maximum error of 1% in voltage readings and 3% in temperature evolution during discharge with the complete model. This comprehensive approach not only enhances the understanding of long-term Sony 3 Ah cell dynamics but also provides a computationally efficient tool for battery management systems and control strategies. The model's capability to predict both electrical and thermal performance simultaneously at different stages of the cell's lifetime makes it particularly valuable for optimizing battery performance and lifespan in various applications.

Keywords: Lifetime modeling; Lithium; Artificial neural networks; Temperature; State of charge; Nickel manganese cobalt; Electrothermal modeling

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1. Introduction

Lithium-ion batteries (LiBs) have become essential components in modern technology, powering a wide range of devices from portable electronics to electric vehicles (EVs).[1] As the demand for high-performance energy storage solutions continues to grow,[2] understanding and predicting the behavior of batteries over their lifetime have become increasingly crucial.[3-6] Modeling and simulation play a vital role in this process, serving as essential tools for evaluating novel concepts and optimizing battery system design.[7-9]

The development of accurate and efficient battery models is crucial for optimizing the performance and longevity of LiBs.[10-13] Traditional approaches to battery modeling

often face a trade-off between computational speed and accuracy.[14,15] Low-level lifetime models, while fast to set up and execute, often rely on mathematical equations with many coefficients and may struggle to capture intricate electrochemical degradation mechanisms.[16-19] Conversely, high-fidelity models offer detailed analysis but are time-consuming in both model setup and simulation.[20-23]

To bridge this gap, there is a growing need for medium-fidelity lifetime models that balance accuracy and computational efficiency. Data-driven methodologies, particularly artificial neural networks (ANNs), have demonstrated promise in significantly improving modeling accuracy while maintaining reasonable computational demands.[24-26] ANNs have demonstrated high accuracy in various battery estimation tasks.[27-31] Severson *et al.*[32] demonstrated the potential of machine learning in predicting battery life cycles, achieving high accuracy using early-cycle data. Building on this, Attia *et al.*[33] developed a closed-loop optimization system that combined machine learning with Bayesian optimization to optimize fast-charging protocols for LiBs efficiently. In the realm of electrothermal modeling, Dai *et al.*[34] proposed a coupled electrothermal-mechanical model that provided insights into the multi-physics behavior of LiBs. Their work highlighted the importance of considering multiple physical domains in battery modeling. Similarly, Guo *et al.*[35] developed a multiscale model that integrated electrochemical, thermal, and aging effects, offering a comprehensive approach to battery performance prediction. The integration of data-driven methods with physics-based models has also gained traction. Wu *et al.*[36] combined a physics-based model with machine learning to improve the accuracy of state-of-health estimation. Their hybrid approach demonstrated superior performance compared to traditional methods. In a related study, Li *et al.*[37] utilized a deep learning framework to enhance the prediction of remaining battery lifespan, incorporating both static and dynamic features of battery degradation. Despite these advancements, the specific combination of semi-empirical electrothermal modeling with ANN-based lifetime estimation for 18650-type cells remains relatively unexplored.

Therefore, this study presents a comprehensive electrothermal and lifetime model for Sony 3 ampere-hours (Ah) 18650 nickel manganese cobalt lithium-ion cells, leveraging ANNs to predict the lifespan of these cells effectively. The proposed model integrates an electrothermal component with an ANN-based lifetime prediction approach, providing a holistic representation of cell behavior throughout its operational life. Key parameters, such as state of charge (SoC), temperature, current, and cycle life, are incorporated into the model, which is trained using extensive experimental data collected under various operating conditions. The electrothermal component employs a second-order Thévenin equivalent circuit model (ECM), enhanced by advanced characterization and parameterization procedures.

Validation of the coupled model demonstrates its effectiveness in estimating both electrical and thermal performance across different stages of the cell's lifespan. The results revealed remarkable accuracy, with a maximum error of just 2% in voltage readings and 3% in temperature predictions during discharge. This comprehensive modeling approach not only enhanced our understanding of the long-term dynamics of Sony 3 Ah cells but also served as a computationally efficient tool for battery management systems and control strategies.

2. Methods

2.1. Battery feature

The batteries tested were cylindrical Sony 18650-type lithium-ion cells (LiBs) with a capacity of 3 Ah (Sony, China). These cells feature a $Li(NiMnCo)_{1}/_{3}O_{2}$ cathode and a graphite anode (G), with an average mass recorded at 46.6 g. Their nominal capacity and voltage were 3 Ah and 3.7 V, respectively. In this paper, the C-rate (C) is defined as 1C = 3 A.

A Neware CT-4008 system (Neware, China) was employed to cycle the batteries, offering a voltage range of 25 mV – 5 V and a current range of 0.5 mA – 6 A. This system was computer-controlled, and the charging/discharging current was set based on the manufacturer's specifications.[38] To monitor the temperature of the batteries, a type-K thermocouple was affixed to the cells. Figure 1 illustrates the experimental setup for characterization.

2.2. Electrothermal characterization

To parameterize the electrothermal model, several characterization tests were conducted: (i) capacity test; (ii) hybrid pulse power capability (HPPC);[39,40] (iii) open-circuit voltage (OCV) (please send out + upload in GD) test;[41,42] (iv) thermal pulse test;[43,44] and high-current test.[45] These tests were derived from international battery standards[46,47] and were conducted at various temperatures, with a rest period of 3 – 4 h used to precondition the cells to the desired temperature (−10, 10, 25, 35, 45, or 60°C).

The capacity test involves performing full charge and discharge cycles at varying discharge C-rates (C/5, C/4, C/3, C/2, 1C, and 2C) and temperatures (−10, 10, 25, 35, 45, and 60°C) to capture the data needed for modeling battery capacity. During the test, the charging C-rate was

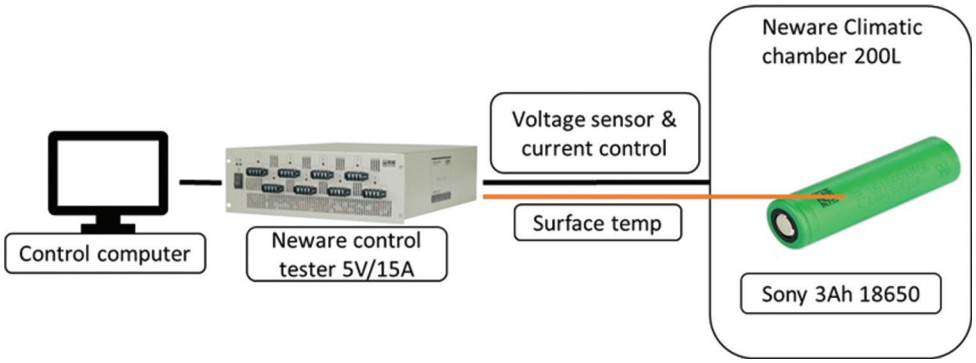

Figure 1. Schematic of the experimental setup used for testing the Sony 3 Ah nickel manganese cobalt/G
Abbreviations: Ah: Ampere-hours.

maintained at C/2 (1.5 A), while the discharge C-rate was adjusted accordingly.

The HPPC test measures the internal resistance (IR) of the battery by using a profile with both discharge and charge pulses. This test helps determine the IR of the cell as a function of the SoC and temperature. The same C-rates (C/5, C/4, C/3, C/2, 1C, and 2C) were applied for a 10 s pulse.

An essential electrical test is the OCV test, which provides the OCV values of the cell across different SoC levels. The OCV is critical for the electrical model, and in this study, the OCV curve is derived for both charging and discharging conditions across a range of temperatures (−10, 10, 25, 35, 45, and 60°C).

The thermal pulse test is designed to bring the cell to a steady-state temperature by applying pulses at a fixed SoC of 50%. The profile used to assess the specific heat capacity (C_p) consists of charging and discharging pulses, referred to as micro-pulses, applied at the manufacturer's recommended maximum rates and at a fixed SoC of 50%. The primary objective of this profile is to inject and extract the same amount of Ah from the cell, eliminating any dependency on SoC that could influence electrical and thermal parameters, such as cell resistance. The secondary aim is to rapidly reach a steady-state temperature, at which the cell loses heat at the same rate it gains heat. At this point, thermal parameters, such as convective heat transfer, can be measured. For C_p assessment, the period during which the surface temperature is increasing (transient state) is considered for comparison with the model. The test profile is then repeated at various temperatures to observe the behavior of the parameters against thermal gradients.

The high-current test is performed using a high C-rate (6C or 18 A in this case) to apply a continuous elevated current. This test helps assess the thermal behavior of the battery, which can later be compared to the thermal model for validation purposes.

Finally, a total of 12 samples were used for characterization (Table 1). The samples were distributed as follows: three for low-temperature testing (−10 and 10°C), three for ambient-moderate temperature environment testing (25 and 35°C), and three for high-temperature testing (45 and 60°C). This distribution ensured the cells remained in optimal condition for each temperature range. In addition, due to the demanding nature of the high current test, only three separate samples were included for this test to ensure that the cells were in optimal condition before testing commenced.

2.3. Lifetime characterization

The lifetime data were obtained from in-house cycling tests. A comprehensive test matrix was designed, covering various combinations of cycling temperatures, rest times, and charge/discharge current rates. Each test condition was applied to at least three cells. Table 2 provides an overview of this test matrix, with the numbers representing the number of cells tested under each condition. The cells underwent 100 full equivalent cycles (FECs), where one FEC is defined as the point at which the total charged or discharged capacity equals the nominal capacity. After each cycling phase of 100 cycles, capacity and resistance measurements were conducted at 25°C to evaluate the aging state of the cells by measuring capacity and impedance evolution. For this purpose, a reference performance test (RPT) was performed on a regular interval and at a constant temperature, typically involving a full capacity test at C/2 (or 1.5 A) and a short HPPC test at 50% SoC and one pulse of C/5 (or 0.6 A).

During each cycling phase, the cells followed a load profile outlined in Table 2, which served as the reference profile: charging at C/2 (1.5 A) and discharging at 1C (3 A). To quantify the effects of different stress factors (cycling temperature, rest times, and charge/discharge rates), modifications were made to the reference profile, isolating one stress factor at a time. For instance, to assess

Table 1. Number of samples per characterization test

Test	Number of samples at different temperatures		
	−10 and 10°C	25 and 35°C	45 and 60°C
Capacity	3	3	3
HPPC			
OCV			
Thermal pulse			
Electrical and thermal model validation			
High-current		3	

Abbreviations: HPPC: Hybrid pulse power capability; OCV: Open-circuit voltage.

Table 2. Lifetime testing matrix

Condition	Number of samples	Temperature (°C)	C-rate		Rest time (min)	Depth of discharge (%)
			Discharge	Charge		
I	3	25	1	0.5	60	100
II	3	25	1	0.5	15	100
III	3	25	1	4	60	100
IV	3	25	4	0.5	60	100
V	3	45	1	0.5	60	100
VI	3	25	Dynamic profile for validation			
VII	3	10	1	0.5	60	100

the impact of the charging rate, the charging current was increased from 0.5C (3 A) to 4C (12 A), while other factors remained unchanged.

Moreover, a dynamic discharging profile, instead of a constant one, was applied to validate the lifetime model. Finally, the end-of-life of the cell was fixed at 60% of the initial capacity.

2.4. Electrothermal model development

A comprehensive battery model was developed by integrating and validating specialized sub-models into a unified modeling framework. This framework incorporates electrical, thermal, and lifetime models (Figure 2). The entire model was created using the MATLAB/Simulink® 2024 platform. The electrothermal component simulates both the electrical and thermal behaviors of the battery cell, capturing key parameters, such as voltage, SoC, and temperature. Meanwhile, the aging model is designed to estimate the degradation of the cell over time and to update the cell's capacity and IR using results from both the electrical and thermal models.

2.5. Lifetime model development

ANNs have demonstrated high accuracy in battery estimation tasks.[27-31] Among these, feed-forward neural networks (FNNs) stand out as a particularly effective approach for dynamic systems, making them suitable for modeling battery degradation. FNNs excel in predicting a single output, such as capacity degradation, which aligns with the requirements of this study. Therefore, a FNN architecture was employed to build the lifetime model. Figure 3 illustrates a typical two-layer FNN configuration, with the corresponding mathematical expressions presented below:[48]

$$y_i = \sigma\left(\sum_{l=1}^{L} \omega_{ij}\sigma\left(\sum_{j=1}^{L} v_{lj}x_j + v_{lj}\right) + w_{i0}\right) i = 1,2,\ldots,m \quad \text{(I)}$$

where V and W represent the weight matrices, while v_{i0} and w_{j0} denote the firing thresholds. The function σ(.) serves as the mapping function. The inputs to the network are the n signals x_1, x_2..., x_n, and the outputs are y_1, y_2..., y_m. After initializing the network's weights and biases, it is ready for training. Within this framework, the FNN was trained using three input parameters: temperature, current, and cycle number, alongside the lifetime characterization data (Section 3.2). The network utilized 10 hidden neurons, and the dataset was divided accordingly, with 75% used for training and 25% for validation and testing. All these processes—training, validation, and testing—were conducted in the MATLAB/Simulink® 2024 environment to ensure compatibility with the electrothermal model.

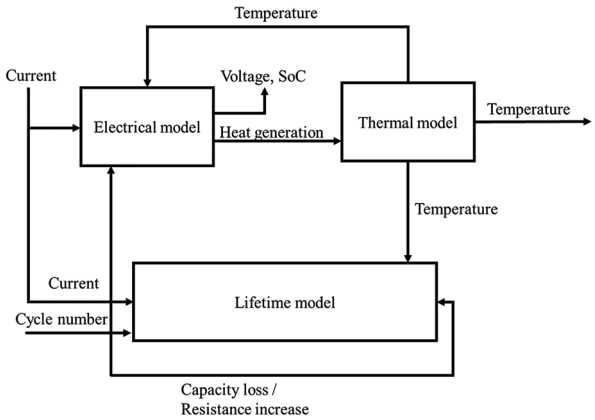

Figure 2. Schematics of the electrothermal and aging model
Abbreviation: SoC: State of charge.

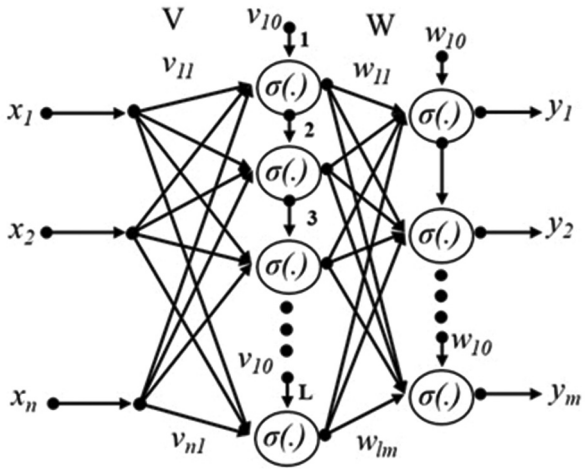

Figure 3. The architecture of the feed-forward neural network model

3. Results and discussion

3.1. Electrothermal characterization results

Figure 4A displays the IR values at various charge and discharge rates across different SoCs. The data reveal a noticeable increase in IR at both low and high SoC levels, with a decline observed between 30% and 70% SoC. The resistance values are similar at higher temperatures for both charging and discharging resistances. However, at 60°C, the resistance is higher compared to 45°C, likely due to aging effects caused by prolonged exposure to extreme temperatures. In contrast, at lower temperatures, the resistance is elevated in both charging and discharging, which is likely a result of slowed electrochemical reactions in colder environments, hindering Li-ion transfer and increasing resistance. The HPPC test data are used to extract the electrical parameters for the electrothermal model.

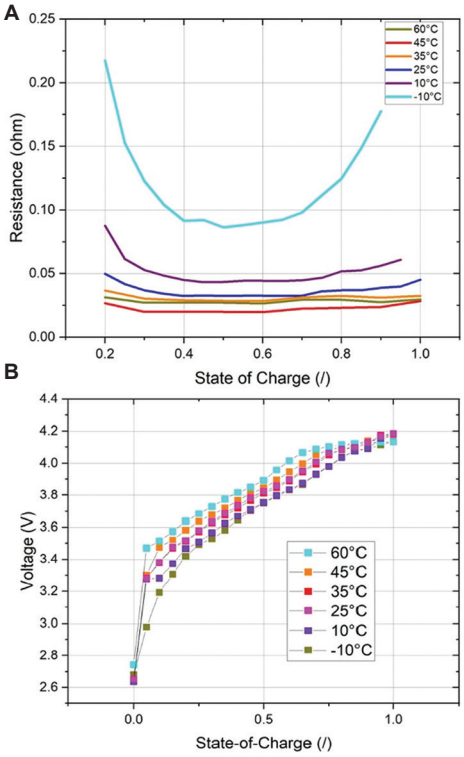

Figure 4. Electrothermal characterization results of the Sony 3 Ah nickel manganese cobalt (NMC)/G. (A) The internal resistance versus state of charge (SoC) at different temperatures for C/5 (0.6A). (B) open-circuit voltage versus SoC of the Sony 3Ah NMC/G at different temperatures.

Furthermore, Figure 4B displays the OCV curves at different temperatures, illustrating the voltage versus SoC at different temperatures. As observed, the temperature has minimal impact on the OCV behavior of the Sony 3 Ah cell.

Table 3 provides the capacity values across all C-rates and temperatures. A general trend of decreasing capacity with increasing C-rate is observed, which is expected. Interestingly, capacity increases with rising temperatures, while decreasing at lower temperatures.

Lastly, Table 4 presents the specific heat capacities derived from the thermal pulse test. The data indicate a slight positive correlation between the cell-specific heat capacity of the Sony 3 Ah and temperature.

3.2. Lifetime results

The results of the lifetime characterization tests are displayed in Figure 5A. The capacity retention trend under normal operating conditions (conditions I and II) demonstrates a consistent degradation pattern, with 70% capacity remaining after 1200 cycles. Notably, rest time does not appear to influence the cell's lifespan.

Table 3. Capacity of Sony 3 Ah at different C-rates and temperatures

C-rate	Capacity at different temperatures (Ah)					
	−10°C	10°C	25°C	35°C	45°C	60°C
C/5	2.46	2.74	2.96	3.04	3.09	3.11
C/4	2.46	2.73	2.94	3.03	3.08	3.10
C/3	2.43	2.72	2.93	3.02	3.07	3.09
C/2	2.42	2.72	2.90	3.01	3.06	3.08
1C	2.50	2.71	2.88	2.99	3.05	3.07
2C	2.52	2.70	2.86	2.99	3.04	3.06

Table 4. Specific heat capacity of Sony 3 Ah at different temperatures

Temperature (°C)	Specific heat capacity (J/kg°C)
−10	1275
10	1258
25	1280
35	1269
45	1274
60	1282

In contrast, under more severe operating conditions (conditions III, IV, V, and VI), capacity retention decreases more rapidly. Among these conditions, the charge and discharge C-rate appears to have a greater impact than the high-temperature environment (45°C), with capacity dropping to 40% after 1300 FECs in condition V, and 35% after 1100 FECs in condition VI.

For condition VI, which follows a dynamic profile, capacity retention exhibits a similar decline to that observed under severe conditions, with 85% capacity remaining after just 200 cycles. This indicates that dynamic cycling profiles significantly affect the battery's lifespan, even more so than standard operating conditions.

In addition, low-temperature cycling has a substantial effect on the cell's longevity, displaying a sharp decline in performance, with 12% capacity remaining after 190 FECs. This suggests that cycling the Sony 3 Ah at low temperatures accelerates aging considerably.

Regarding the IR (Figure 5B), the results largely corroborate the conclusions drawn from the capacity retention evolution. Under normal operating conditions (conditions I and II), the IR exhibits a consistent degradation pattern, increasing to 4 – 5 times its initial value after 1500 FECs. Notably, rest time does not appear to significantly influence the cell's lifespan.

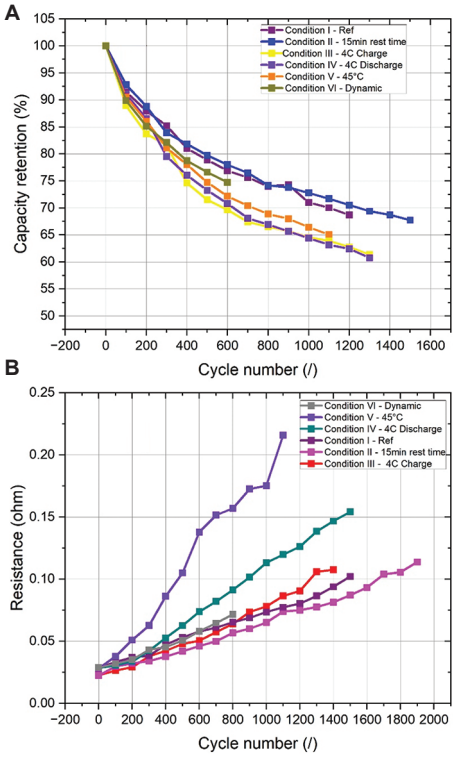

Figure 5. (A) Capacity retention results of the Sony 3 Ah for all tested conditions obtained at C/2. (B) Internal resistance evolution obtained at 50% state of charge and C/5.
Abbreviations: Ref: Reference.

In contrast, more severe operating conditions (conditions III, IV, V, and VII) lead to a more rapid increase in resistance. Among these, the high-temperature environment (45°C) seems to have a greater impact than the C-rate. When cycling at 45°C, the resistance increases up to 10 times its initial value after nearly 1000 FECs.

Concerning the influence of charge and discharge C-rates, the trend in resistance increase suggests that the discharge rate has a more pronounced effect than the charging rate. In condition IV, the resistance rises to 6 times its initial value after 1400 FECs. Conversely, for condition III (4C charge), the resistance evolution closely resembles that of conditions I and II, indicating that the charging rate is not significantly more detrimental to resistance than normal operating conditions.

For condition VI, which follows a dynamic profile, the resistance increase displays a similar trend to that observed under normal conditions, reaching 2.5 – 3 times its initial value after 700 cycles.

Finally, the influence of low-temperature cycling on resistance could not be assessed due to an error in the RPT HPPC test.

3.3. Electrothermal model

3.3.1. Principle of the electrothermal model

This study employed a one-dimensional electrothermal model, utilizing a semi-empirical approach within the MATLAB/Simulink® 2024 platform. The model is designed to simulate the electrical and thermal behavior of the battery cell through two main modules: the electrical and thermal components. The electrical module determines the SoC by analyzing electrical parameters, while the thermal module estimates the cell's temperature using heat generation equations.

The electrical model (Figure 6) is based on the second-order Thevenin model,[49,50] consisting of a voltage source in series with two parallel RC networks and an ohmic resistor. According to the ECM, the output voltage of the Li-ion battery cell is calculated as the voltage drop across the OCV, the ohmic resistance (R_0), the concentration polarization resistance (R_1C_1 circuit), and the activation polarization resistance (R_2C_2 circuit). The resulting output voltage is then computed using the following equation:[7,13]

$$V_{cell} = OCV - R_1I_1 - R_2I_2 - R_0I_{batt} \quad \text{(II)}$$

where I_{batt} is the flowing current in the battery (A). Thereafter, the SoC is determined by the Coulomb-counting method and is defined in:[51,52]

$$SoC = SoC_0 - \frac{1}{C_{init}}\int I_{batt}dt \quad \text{(III)}$$

where SoC_0 represents the initial SoC of the cell. C_{init} is defined as the initial capacity (Ah), which is assumed to be dependent on temperature and influenced by the applied current and degradation. In Equation II, the OCV was directly obtained from the OCV test, as outlined in Section 2.2. The resistances, which vary with temperature, SoC, and aging, were determined using a parameter extraction algorithm. Based on the HPPC test results, a fitting algorithm within Batalyse was employed to match simulation data with experimental results, allowing for the extraction of individual parameters. These extracted parameters were then mapped into lookup tables within the MATLAB/Simulink® environment.

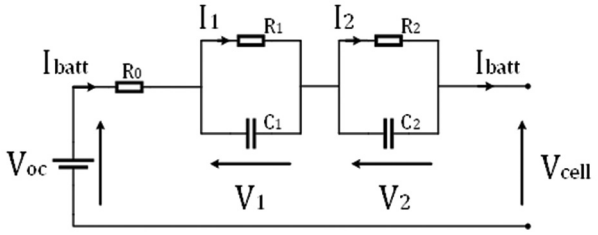

Figure 6. The schematic of the second-order Thévenin model[55]

The thermal aspect of the model incorporates thermodynamic equations specific to cylindrical cells. It assumes a single temperature point, where heat is generated at a particular location on the cell's surface, defined by its specific heat capacity and mass. Heat is then dissipated from the cell's surface to the surrounding environment. A heat balance equation at the cell surface is applied to model the thermal exchange between the cell and the ambient environment, as described by the following thermodynamic equations:[53]

$$\left\{\begin{array}{c} \frac{dU_{cell}}{dt} = Q_{gen}(t) - Q_{loss}(t) = m.Cp.\frac{dT}{dt} \\ Q_{gen} = R_{int}.(I_{batt})^2 \\ Q_{loss} = Q_{conv} = h_{conv}.S_{area}.(T_{cell} - T_{amb}) \end{array}\right\} \quad \text{(IV)}$$

where U_{cell}, the internal energy, is the total energy contained by a thermodynamic system (J); Q_{gen} is the generating heating rate (W) in the corresponding element; and Q_{loss} is the heat losses of the corresponding element (W). C_p is the specific heat of the cell (kJ/kg.K) and m is the mass of the cell (kg). The thermal model operates under the following assumptions:

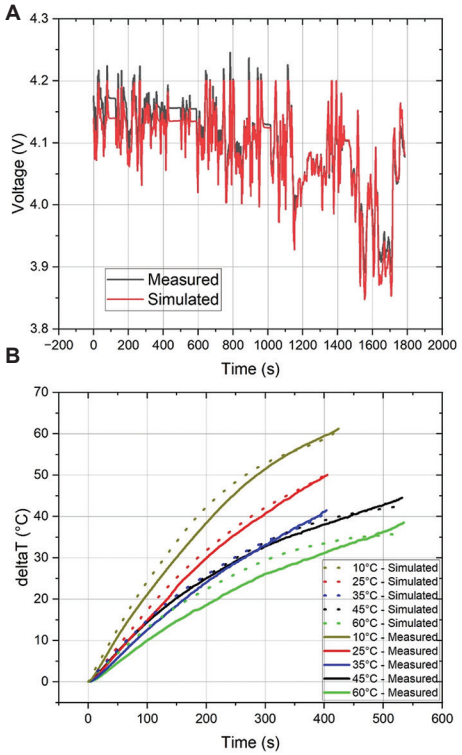

Figure 7. (A) Electrical validation using the WLTC. (B) Thermal validation using the high-current test.
Abbreviation: WLTC: Worldwide harmonized light vehicles test cycle.

(i) The cell's surface temperature, T_{cell}, is assumed to be uniformly distributed across the entire surface, representing the overall temperature of the battery
(ii) Joule heating is used for estimating the heat generation
(iii) Natural convective heat transfer is considered, with parameters such as ambient temperature (T_{amb}, °C), surface area of heat exchange (S_{area}, m^2), and convective heat transfer coefficient (h_{conv}, $W/m^2.K$)
(iv) The specific heat capacity was obtained from the thermal pulse test (Section 2.2) and the surface area was calculated directly based on the cell dimensions (S_{area} = 0.004327 m^2). In addition, a natural convection coefficient of h_{conv} = 15 $W/m^2.K$ was applied.[54]

3.3.2. Validation of the electrothermal model

To ensure the accurate validation of the electrothermal model, additional validation tests were conducted. For electrical validation, a dynamic profile was applied to the battery, cycling between 90% and 10% SoC. This dynamic profile was derived from the Worldwide Harmonized light vehicles test cycle (WLTC),[56] and the results obtained at 25°C are illustrated in Figure 7A. For other temperatures (35, 45, 60, 10, and −10°C), the errors are detailed in Table 5. The model's accuracy was assessed using the root-mean-square error (RMSE), which measures the deviation of the simulation results from the experimental data. The table highlights that the model has an average error of around 2%, demonstrating the strong accuracy of the electrical modeling and parameter estimation.

For thermal validation, the test involved discharging the battery from 100% to 0% SoC at a high current (Section 2.2). Figure 7B compares the simulated delta T (temperature differences) from the thermal model with the actual measured temperature. The estimated temperature closely aligns with the measured values, with a deviation of <2°C. Furthermore, the RMSE values for thermal validation across all tested temperatures are provided in

Table 5. Root-mean-square error (RMSE) of electro-thermal model validation

Temperature (°C)	RMSE (%)	
	Electrical	Thermal
-10	1.98	1.92
10	1.87	1.75
25	1.3	1.1
35	0.5	1.1
45	0.4	2
60	0.3	1.6

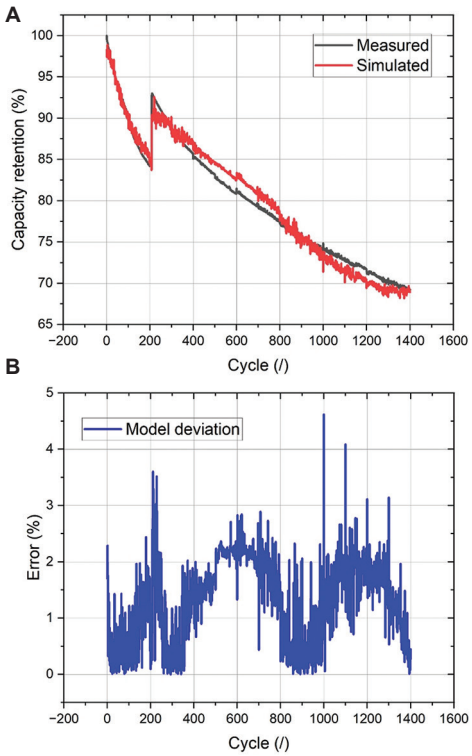

Figure 8. Feed-forward neural network model validation using the (A) static behavior profile (condition II) and (B) corresponding error deviation.

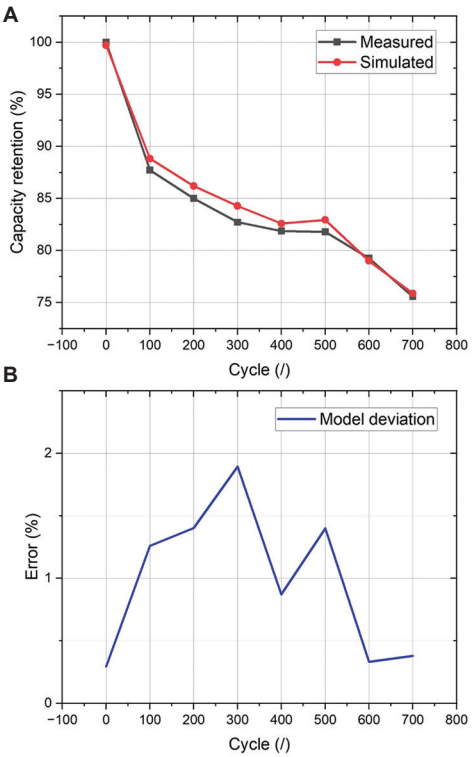

Figure 9. Feed-forward neural network model validation using the dynamic discharge behavior profile. (A) Capacity retention comparison between simulated and measured data. (B) Corresponding model deviation.

Table 5, with an average error of approximately 2%. This confirms the reliability of the thermal model, which uses only Joule heating to predict temperature changes.

In summary, the electrothermal model accurately captures the electrical and thermal performance of the Sony 3 Ah cell under dynamic load conditions, making it a reliable tool for optimization algorithm development.

3.4. Lifetime model

The validation of an aging model typically involves comparing its lifetime predictions against a set of previously unknown inputs and long-term cycling data.[28,55,57] In this study, both static and dynamic profiles were used to validate our lifetime model.

3.4.1. Static profile validation

For the static profile validation, an independent dataset not included in the ANN training process was employed. These data were obtained from condition II (25°C; 1C discharge/0.5C charge, 100% depth of discharge [DoD]; Table 2).

Figure 8A presents a comparison between the measured and simulated capacity retention over 1400 FECs. An

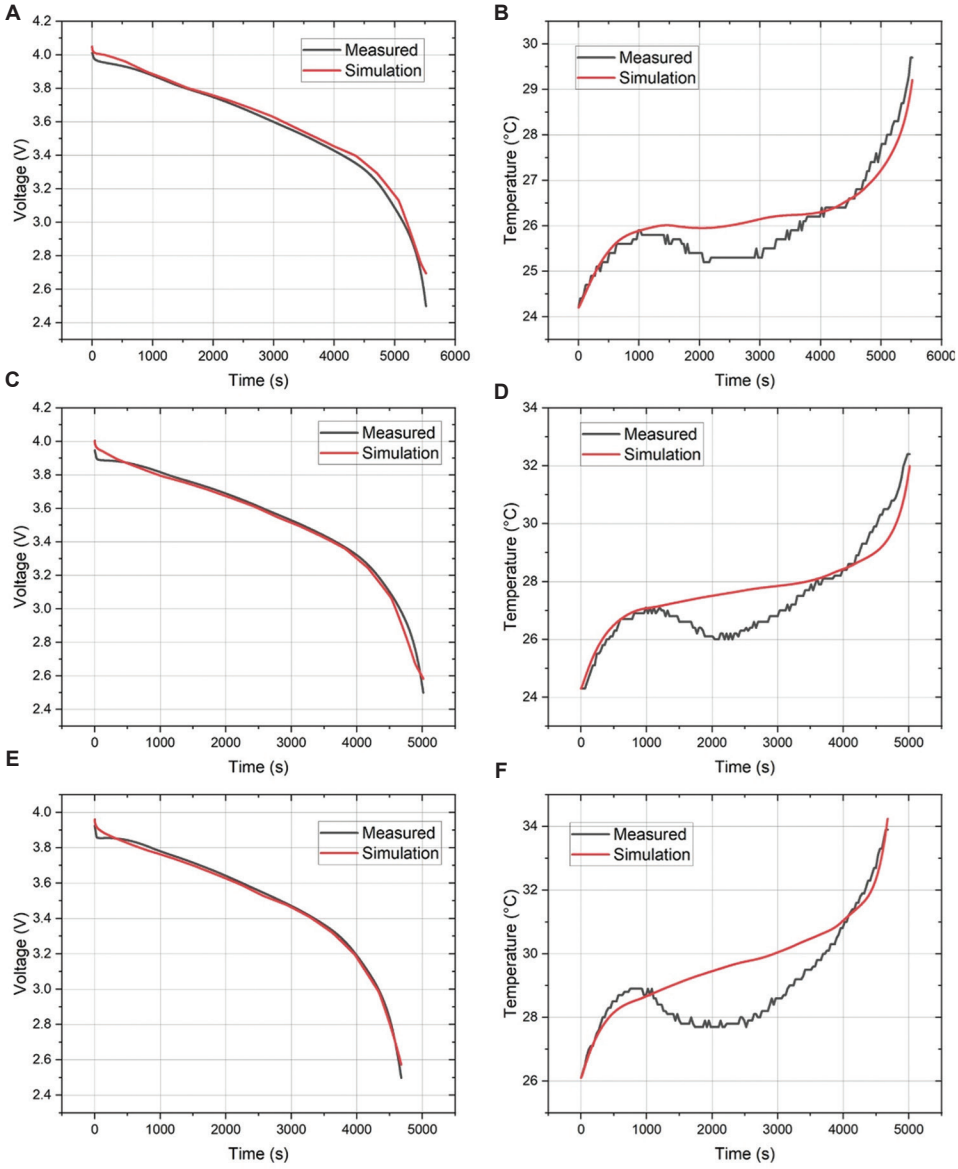

Figure 10. Validation of the coupled electrothermal lifetime model for condition II: (A) voltage comparison of 500 FECs; (B) temperature comparison of 500 cycles; (C) voltage comparison of 1000 FECs; (D) temperature comparison of 1000 cycles; (E) voltage comparison of 1500 FECs; (F) temperature comparison of 1500 FECs.
Abbreviation: FECs: Full equivalent cycles.

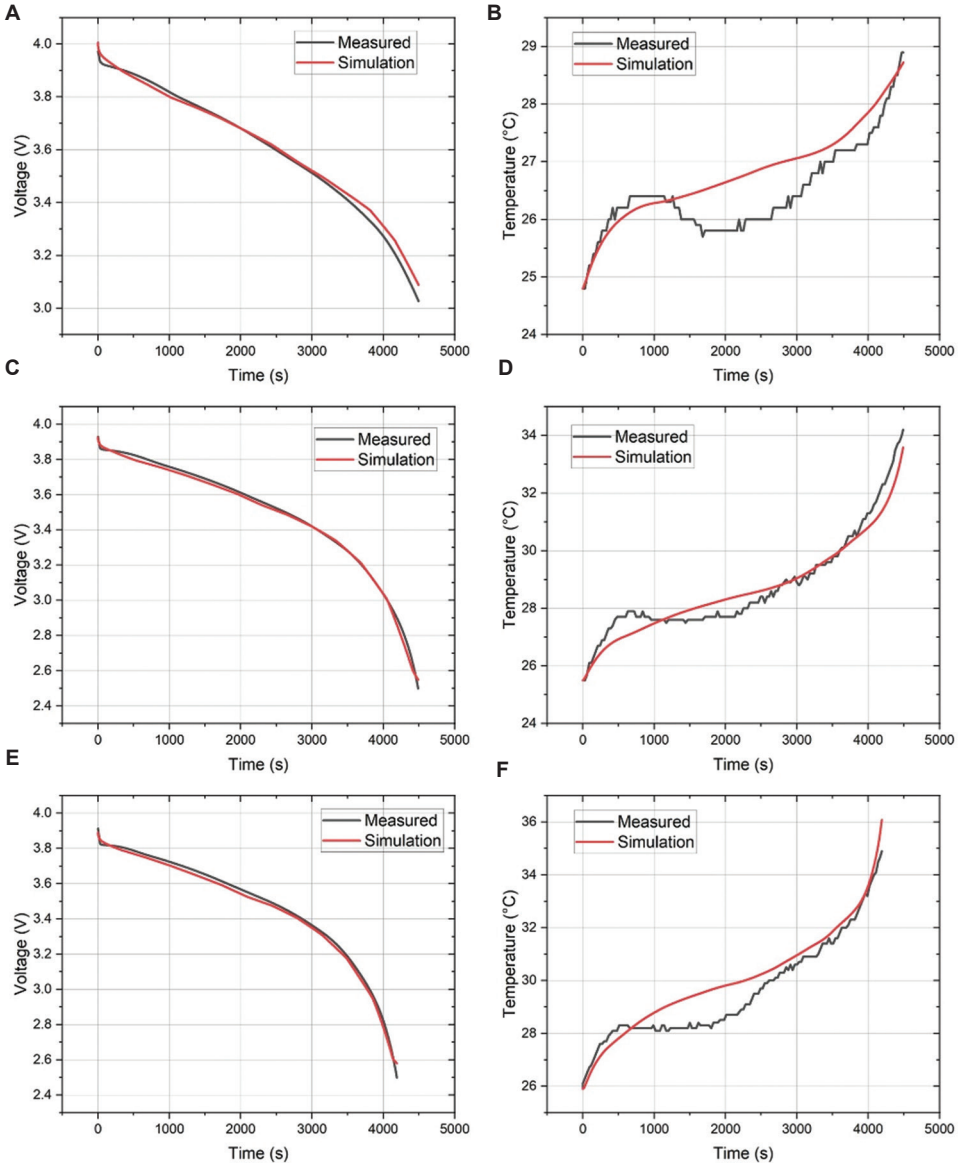

Figure 11. Validation of the coupled electrothermal lifetime model for condition IV: (A) voltage comparison of 500 FECs; (B) temperature comparison of 500 cycles; (C) voltage comparison of 1000 FECs; (D) temperature comparison of 1000 cycles; (E) voltage comparison of 1500 FECs; (F) temperature comparison of 1500 FECs. Abbreviation: FECs: Full equivalent cycles.

Table 6. Root-mean-square error of the model validation for conditions II and IV

RMSE	Condition II			Condition IV		
	500 FECs	1000 FECs	1500 FECs	500 FECs	1000 FECs	1500 FECs
Electrical (%)	0.8	0.81	0.74	0.78	0.81	0.76
Thermal (%)	2.4	2.1	2.3	2.2	2.05	2.2

Abbreviation: RMSE: Root-mean-square error; FECs: Full equivalent cycles.

unexpected increase in measured capacity retention at 200 FECs was observed, likely due to a data acquisition system error.

Despite this anomaly, the FNN accurately captured the overall capacity retention trend, including the slight rise at 200 FECs. The error metric, calculated as the absolute difference

Table 7. Comparison of the proposed model with related work

Study	Model type	Prediction accuracy (%)
This work	ANN-based electrothermal model	Voltage: <2 error Temperature: <3 error
Tu *et al.*[58]	A physics-based model with machine learning	Voltage: 3 error Temperature: 4 error
Pour[59]	Empirical thermal model	Temperature: 2.5 error
Zhang *et al.*[60]	Data-driven electrical model	Voltage: 1.5 error

Abbreviation: ANN: Artificial neural network.

between actual and simulated data, remained below 3%, indicating satisfactory accuracy in estimating cell lifetime under static conditions (Figure 8B). While static profile validation provides valuable insights, a more comprehensive validation approach involves using dynamic profiles that differ significantly from the training data and utilizing a dynamic discharge current pattern, further demonstrating the model's robustness and predictive capabilities.

3.4.2. Dynamic profile validation

Ideally, validation requires using a completely independent set of long-term aging data, which differs from the training data in key variables (temperature, current, etc.) or behavior. Therefore, to complete the lifetime model validation, a separate testing condition was employed for model validation, involving a dynamic discharge current pattern rather than the constant current used in the other conditions (Table 2). Specifically, the cycling profile, in this case, includes: charge at C/2 (or 1.5A); a 1 h rest period; dynamic discharge using the WLTC until the cell is depleted; and repeats for 100 cycles.

Three cells were tested under these validation conditions, as previously described in the experimental section, with only the best-performing sample being utilized for validation. The remaining test conditions were used to build and train the FNN model, Figure 9A illustrates a comparison between the measured data and the simulated lifespan, plotting capacity retention (%) against the number of cycles for 700 FECs. The FNN model's estimates closely align with the experimental results. Despite some minor deviations at the 200 and 300 FEC marks, the FNN accurately captures the capacity retention trend across the full 700 cycles. In addition, the error metric—calculated as the absolute difference between real and simulated data—is presented in Figure 9B. The deviation remains below 2%, indicating that the model can simulate the accelerated profile with satisfactory accuracy. This highlights the FNN model's robustness in predicting the cell's lifespan, making it a reliable tool for optimization algorithm development.

3.5. Coupled electrothermal aging model

The primary objective of this study is to present a complete cell-level electrothermal model coupled with an ANN-lifetime model. This approach offers two significant advantages: it uses a simple neural network to estimate the cell's lifetime, providing a fast-response solution to the computational complexity challenge typically associated with mathematical models, and it can predict cell voltage and temperature based on the cell's cycle life. To validate the complete model's voltage and temperature estimations, experimental data from the discharging phase (C/2) of RPTs at different cycle points (500, 1000, and 1500 FECs) were used for two conditions: (i) condition II involved a 1C discharge, 0.5C charge, 100% DoD, and 15 min of rest time, and (ii) condition IV included a 4C discharge, 0.5C charge, 100% DoD, and 60 min of rest time. The results (Figures 10 and 11) demonstrate highly accurate voltage predictions with a maximum RMSE of <1% (Table 6). Temperature estimations exhibit minor deviations, particularly in the middle of the discharge phase, but the overall error remains below 3%. The combination of a semi-empirical approach with ANN offers a powerful method for predicting battery performance and lifetime. This hybrid approach leverages the strengths of both model-based and data-driven techniques, potentially providing more accurate and efficient predictions for battery management systems.

4. Conclusion

In this study, a complete cell-level electrothermal model coupled with an ANN-lifetime model was proposed for Sony 3 Ah 18650-type lithium-ion cells. First, a comprehensive study of the cells was performed, providing valuable insights into their electrothermal characteristics and aging behavior but also the necessary model parameters for the development of the model.

The electrothermal characterization revealed important trends in IR, OCV, and capacity across different

temperatures and states of charge. Notably, the IR exhibited increases at both low and high SoC levels, with temperature significantly impacting resistance values. The capacity tests demonstrated a clear relationship between discharge rates, temperature, and cell capacity, with higher temperatures generally yielding increased capacity. Lifetime characterization tests uncovered critical factors affecting battery longevity. While normal operating conditions displayed consistent degradation patterns, severe conditions, such as high C-rates and extreme temperatures, accelerated capacity loss and resistance growth significantly. Interestingly, rest time appeared to have minimal impact on cell lifespan, whereas dynamic cycling profiles proved particularly detrimental to battery capacity.

The coupled ANN electrothermal model, derived from characterization data, offers several advantages for battery performance estimation. A key benefit of this model is its ability to predict both thermal and electrical performances simultaneously at different stages of the cell's lifetime. The model demonstrates high accuracy in its predictions, with voltage predictions showing a maximum error of <2%. Temperature estimations exhibit minor deviations, particularly in the middle of the discharge phase, but maintain an overall error below 3%. These results confirm the model's reliability in predicting battery performance under various conditions.

To highlight the novelty and advantages of our approach, a comparison of the work with related studies is reported in Table 7.

This study contributes valuable data and modeling techniques to the field of battery electrothermal lifetime modeling, offering insights that can inform the design and optimization of battery models and battery management systems. The findings have significant implications for improving battery performance prediction and management, particularly in EV applications. Future work should focus on enhancing the model's capabilities through several avenues. Integration of more sophisticated algorithms and expansion of the training dataset could further improve prediction accuracy. In addition, validation across a wider range of operational conditions, including extreme environments and diverse battery chemistries, would provide valuable insights into the model's robustness and applicability in various scenarios. Developing advanced *in situ* diagnostic techniques and real-time health monitoring algorithms could enhance the model's practical utility. These future directions aim to develop a more comprehensive and widely applicable battery modeling framework, contributing both to academic knowledge and practical advancements in energy storage system design and management across various industries.

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The authors have no conflicts of interest to declare.

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Data are available on request from the authors.

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ACCSCIENCE PUBLISHING

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ORIGINAL RESEARCH ARTICLE

The influence of the carbon neutrality goal on tourists' low-carbon tourism behavior intention in space tourism

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Abstract

China's carbon neutrality goals and the emergence of the space tourism industry have raised increasing environmental concerns. Fostering the awareness of low-carbon practices is vital for industry sustainability and enhanced competitiveness. The existing literature underscores how state policies, such as the dual carbon goal, which aims to peak carbon dioxide emissions by 2030 and achieve carbon neutrality before 2060, drive motivations to go green, shaping public intentions toward low-carbon travel. The contemporary focus is on various dual carbon factors influencing low-carbon tourism, although research on motivations, awareness, and behavioral intentions in space remains limited. To address this gap, this study aims to evaluate how the carbon neutrality goal impacts low-carbon tourism motivation, awareness, and behavioral intentions based on the event system theory. The study employed quantitative methods and examined the constructs and causality of low-carbon tourism. After performing a literature review, we constructed a research model to explore the relationship between low-carbon space tourism and behavioral intentions with mediation constructs of carbon neutrality goal, motivation, and awareness. Statistical Package for the Social Sciences (SPSS) and MPLUS were employed in data analysis. The data were analyzed using SPSS and MPLUS software, and various mathematical and statistical methods such as reliability analysis, validity analysis, factor analysis, correlation analysis, common method variance analysis, and structural equation modeling were used to analyze the survey data. Findings suggest positive effects of the carbon neutrality goal, low-carbon travel motivation (LCM), and low-carbon tourism awareness (LCA) among tourists. The present study affirms the influential role of the carbon neutrality goal in space tourism and the mediating effects of LCM and LCA in positively affecting sustainable space tourism intention. This study also suggests that cooperation among governmental entities, tourism authorities, businesses, and tourists is vital to advancing sustainable space tourism practices.

Keywords: Space tourism; Carbon neutrality goal; Motivation; Awareness; Behavioral intention

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1. Introduction

Space tourism is "the movement of people for leisure purposes beyond the Earth's atmosphere."[1,2] This form of tourism encompasses various segments, including terrestrial

space tourism, focusing on activities bound to Earth and supplemented by cyberspace tourism, as well as atmospheric and low-Earth-orbit tourism. In addition, it extends to astrotourism, which ventures into experiences beyond Earth's orbit, such as lunar and Mars expeditions.[3,4] At present, there is a competitive space race underway among various commercial space tourism enterprises such as Virgin Galactic, Blue Origin, and SpaceX. The thriving commercial space flights conducted by these space tourism companies in 2021 have showcased the viability of space tourism. However, space tourism should pay more attention to the potential environmental pollution not only from the supply side but also from consumers, with the latter depending on the awareness of low-carbon space tourism.

Researchers have long been interested in the link between space tourism and environmental pollution.[1,5] Similarly, there is a well-documented positive relationship regarding motivation, awareness, and behavioral intention for low-carbon tourism. As a form of adventure travel, space tourism could dramatically change global atmospheric circulation, ozone distribution, and temperature patterns with 1,000 new suborbital launches using hybrid rocket motors.[6] In China, the carbon neutrality goal is an important initiative formulated by the state to mitigate severe climate changes in the long term. In September 2020, General Secretary Xi solemnly declared that China has set the time for achieving carbon neutrality before 2060.[7]

With the increasingly prominent issue of global warming and the increasingly severe deterioration of the world's climate, the frequent occurrence of extreme weather in various countries has seriously endangered human health, safety, and living environment. The Intergovernmental Panel on Climate Change of the United Nations stated in its Third Assessment Report that the warming effect of many greenhouse gases, such as carbon dioxide, nitrous oxide, and methane emitted from human activities in recent years, is the main reason for global warming. Therefore, there has been a paradigm shift in the concept toward a low-carbon economy, which has become a consensus among countries worldwide. As a type of green tourism with low energy consumption and low pollution, low-carbon tourism has also become a focus of attention in the world tourism industry and a hot research topic in academia.

Centered on carbon neutrality, this study adopts a questionnaire approach to investigate factors that shape tourists' behavioral intentions toward low-carbon space tourism. The primary focus is examining tourists' awareness and motivations regarding this concept in Zhuhai City, Guangdong Province, and the Macao Special Administrative Region. The objective is to ascertain tourists' willingness to contribute financially to low-carbon space tourism in the future and to evaluate the influence of diverse factors on their behavioral intentions. By analyzing tourists' comprehension and intentions regarding low-carbon space tourism, this study aims to formulate recommendations grounded in the collected data. Clarifying these aspects can pave the way for effectively promoting low-carbon tourism among space tourists, ultimately enabling governments and businesses to devise sustainable strategies for space tourism. Therefore, the outcomes of this research hold substantial practical implications.

To achieve these goals, this article employs event system theory (EST) as a theoretical framework to address the following research questions through field and online questionnaires:

(i) To what extent does the concept of carbon neutrality influence tourists' motivations for low-carbon space tourism and their awareness of it?
(ii) How do tourists' motivations for low-carbon space tourism and their awareness of it impact their behavioral intentions toward such tourism?
(iii) What is the correlation between carbon neutrality, motivation, awareness, and behavioral intention toward low-carbon space tourism?

This study endeavors to develop a conceptual model grounded in the EST, specifically examining the relationship between the perceived intensity of the "Carbon Neutral Goal" concept and its implications for low-carbon space tourism motivation, awareness, and behavioral intention. The study's objectives, tailored to the context of space tourism, are as follows:

(i) To investigate the influence of the perceived intensity of the "Carbon Neutral Goal" concept on tourists' motivation for low-carbon travel;
(ii) To analyze the impact of the perceived intensity of the "Carbon Neutral Goal"' concept on tourists' awareness of low-carbon tourism;
(iii) To examine the effect of low-carbon travel motivation (LCM) on tourists' awareness of low-carbon tourism;
(iv) To explore how LCM and awareness jointly influence tourists' behavioral intention toward low-carbon space tourism;
(v) To investigate the mediating role of LCM in shaping tourists' behavioral intentions;
(vi) To assess the mediating function of low-carbon tourism awareness (LCA) in influencing tourists' behavioral intention.

2. Model construction

Based on the EST, this study constructed a research model to investigate the influence of the carbon neutrality goal

on sustainable space tourism intention, considering the mediating effects of low-carbon motivation and awareness. EST mainly focuses on and explains the dynamic impact of the essential attributes of events (time, space, and intensity) on entities based on the interaction between system levels.[8] EST divides the event of the carbon neutrality goal into active and passive influences on the relationship of consumers' motivation, awareness, and intention of sustainable space tourism.[9-11]

2.1. Carbon neutrality

Carbon neutrality aims to offset carbon dioxide emissions through various measures, achieving zero net emissions.[12-14] Current research focuses mainly on societal and industry-wide perspectives,[15-17] with agriculture, forestry, and industry as the critical industries.[18-20] However, tourism-specific research, especially in space tourism, is limited. Existing tourism studies focus on carbon footprint measurement in destinations,[21-23] neglecting the space tourism field. Commercial space tourism companies must address the carbon footprint in space tourism in light of the global environmental crisis we are facing.[2,24] Some scholars argue that travel policy will be a crucial source of travel information for tourists.[25,26] Governments formulate policies to intervene, coordinate, and motivate tourists' activities, which play a practical guiding role.[27,28] Studies suggest that residents' participation and satisfaction with low-carbon policies positively influence their low-carbon behavioral intentions.[29] Thus, three hypotheses are proposed as follows:

H_1: Perceived carbon neutrality positively impacts low-carbon motivation in space tourism;

H_2: Perceived carbon neutrality positively impacts low-carbon awareness in space tourism;

H_3: Perceived carbon neutrality positively impacts low-carbon travel intention in space tourism.

2.2. LCM

Travel motivation is the internal force that drives people to tourism activities,[30] with proper activation, orientation, maintenance, and adjustment of these tourism activities helping to move the tourism industry toward the sustainability goal.[31] LCM is an internal driver that pushes tourists to reduce carbon emissions throughout their tourism activities. The literature suggests that understanding tourists' low-carbon motivation helps us identify the factors that drive tourists to participate in low-carbon tourism.[32] Thus, the following hypotheses are proposed:

H_4: Tourists' low-carbon motivation positively impacts low-carbon awareness in space tourism;

H_5: Tourists' low-carbon motivation positively impacts low-carbon behavioral intention in space tourism;

2.3. LCA

The scholarly definition of tourism awareness draws on the conceptual explanation of awareness in psychology. Holt[33] pointed out that a broad phenomenon of cognitive processes includes perception, judgment, learning, and concept formation. Anderson[34] stated, from a psychological perspective, that awareness is people's knowledge and understanding of something through a series of psychological processes such as perception, memory, and processing. Low-carbon awareness is the basis for forming low-carbon attitudes and behaviors. A higher level of low-carbon awareness can easily promote a correct low-carbon attitude and then transform into positive low-carbon behaviors.[35,36] Therefore, identifying tourists' low-carbon awareness levels can help guide their low-carbon behavior. Thus, the following hypothesis is proposed:

H_6: Tourists' low-carbon awareness positively impacts low-carbon behavioral intention in space tourism.

2.4. Low-carbon tourism behavioral intention

Regarding behavioral intention, Smith[37] posited that it encapsulates the likelihood of an individual enacting a specific behavior toward an object, encompassing actual behavior. Gollwitzer and Bargh[38] further elaborated that behavioral intention comprises goal and execution intentions. The former pertains to planning, where individuals consider their behavioral goals, whereas the latter relates to execution, determining when, where, and how to implement the plans.[38] Scholars have studied the antecedent influencing variables of tourists' behavioral intention from different perspectives, including destination management and service aspects.[39] Low-carbon behaviors specifically refer to ensuring the ecosystem's sustainability while maintaining normal economic development.[40]

2.5. The mediating effect of LCM

This study aimed to explore the motivation for low-carbon space tourism. Drawing from the literature, we hypothesize that variations in awareness trigger subsequent motivational processes, ultimately activating behavioral motivation. Policies, in particular, can stimulate consumer awareness and diverse motivations. Government tourism policies play a practical guiding role, intervening in and coordinating tourists' activities while stimulating specific travel motivations.[28,30] Analogically, space tourists influenced by carbon neutrality concepts are likely to develop low-carbon tourism motivations.

Further research reveals that COVID-19 positive information awareness positively impacts students' travel intentions, mediated by perceived behavioral control, travel attitude, and travel motivation, forming

a "COVID-19 positive information awareness-travel motivation-behavioral intention" pathway.[41] This literature underscores the mediating factor of tourism motivation. Therefore, we posit that tourism motivation, specifically low-carbon tourism motivation, serves as a mediating variable, and the emerging concept of low-carbon space tourism motivation merits inclusion in this discussion. Therefore, the hypothesis is drawn:

H_7: Tourists' low-carbon motivation has a mediating effect between the perceived carbon neutrality goal and low-carbon tourism behavioral intention in space tourism.

2.6. The mediating effect between low-carbon awareness and behavioral intention

Integrating the "dual carbon" strategy into low-carbon tourism requires public recognition of carbon neutrality. In the framework of "Awareness-Willingness-Behavior," awareness serves as the foundation, willingness as the prerequisite, and behavior as the outcome.[42,43] Domestic research also indicates that low-carbon awareness mediates the link between "dual carbon" strategies and low-carbon willingness.[44] As protective policies aimed at environmental conservation and tourism's low-carbon development, the "dual carbon" strategy and carbon neutrality goal complement well with each other. Guided by supply-side policies, awareness precedes willingness, leading to the proposed hypothesis of the "policy event-awareness-behavioral intention" pathway. Therefore, the following hypothesis is drawn:

H_8: Tourists' LCA mediates between the perceived carbon neutrality goal and the behavioral intention of low-carbon space tourism.

The research framework is presented in Figure 1.

3. Research design and methodology

3.1. Measurements

A multi-item measurement used a survey questionnaire, which was screened from the literature, and the question items were revised to tailor to the investigation of space tourism behavior.[45,46] In this study, the survey instrument comprises six constructs and 24 items, including questions on LCM (five items),[29,32,47] low-carbon space tourism awareness (five items),[22,48,49] low-carbon space tourism behavioral intention (three items),[50-52] and perceived intensity of the "carbon neutrality" in space tourism (11 items).[8] Reliability and validity tests were conducted to confirm a qualified measurement tool utilizing a seven-point Likert scale ranging from 1 denoting strongly disagree to 7 indicating strongly agree[45]; (Appendix).

3.2. Data collection

As few tourists have traveled to space, and the costs entailed are exorbitant, the interviewees surveyed were all potential tourists willing to travel to space, mainly students from Macao and Zhuhai.

Data were collected from November to December 2023 through online platforms (Xiaohongshu, WeChat, and QQ groups) after performing convenience and snowballing sampling. Individuals aged 18 years or older and interested in participating in space tourism were invited to participate. Five hundred and fifty subjects were invited, and 550 panel members completed the survey with valid responses. After the respondents who took <1 min to finish the questionnaire were excluded, the data and questionnaire responses of the remaining 416 potential space tourists were subjected to analysis using Statistical Package for the Social Sciences and Mplus software, and various mathematical and statistical methods such as reliability analysis, validity analysis, factor analysis, correlation analysis, common method variance (CMV) analysis, and structural equation modeling (SEM) were used to analyze the survey data.

4. Data analysis

4.1. Descriptive statistical analysis

A descriptive analysis of 416 respondents' demographic data revealed a balanced gender ratio (43.3% male and 56.7% female). Age-wise, young adults (18 – 30) constituted the majority of the respondents (77.3%) due to the novelty of space tourism and the limited travel frequency among

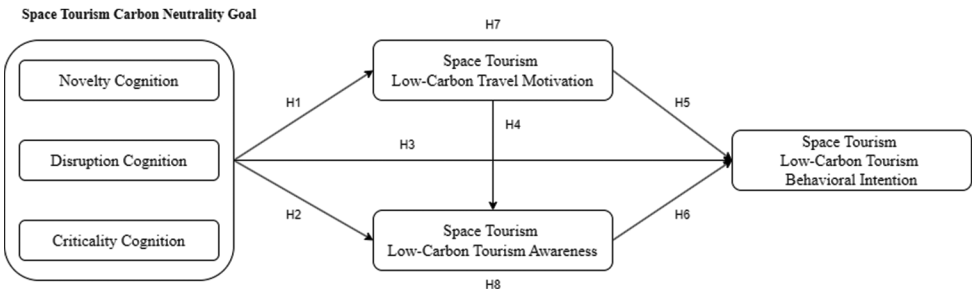

Figure 1. Research framework

the elderly because of risk perception. Over 80% had a bachelor's degree or higher, indicating a high educational level of the respondents. In terms of occupation, slightly more than half of the respondents (51%) were students. Geographically, 76.4% of the respondents expressing a strong interest in low-carbon space tourism hailed from mainland China. Monthly income analysis showed that 45.4% earned RMB 3,000 or less, reflecting the student-heavy sample, as shown in Table 1.

4.2. Normality test

Skewness and kurtosis of data are the two primary data distribution measures used to assess the distribution and spread of data in most statistical analyses. In general, skewness refers to the symmetry of a distribution, where symmetric datasets mirror each side of the center. Data with high kurtosis exhibit thicker tails or more outliers, whereas low kurtosis datasets have shallower tails or fewer outliers. The data follows certain expected patterns in a standard distribution: 95% of the sample falls within the mean ± 1.96 standard deviations, whereas 99% falls within the mean ± 2.58 standard deviations.[53] In Table 2, the mean values for each behavioral intention indicator are between 5.10 and 5.22, signifying strong intent from respondents. Regarding skewness and kurtosis, coefficients for the indicators ranged from −1 to 0, indicating a close-to-normal distribution. The skewness coefficients ranged from −1 to 0, whereas kurtosis coefficients ranged from −1 to 1, suggesting normality across the variables, suitable for conducting the multivariate analysis.

4.3. CMV analysis

As indicated in Table 3, the analysis identified six common factors, with the first factor explaining 35.117% of the variance, which is below the 40% critical threshold commonly accepted in literature.[54] This suggests that no single factor dominates the variance, indicating the current research scale is not significantly impacted by common method bias, as shown in Table 3.

Table 1. Demographic characteristics of the survey sample (*n*=416)

Measurement	Items	Frequency (*n*)	Percentage (%)
Gender	Male	180	43.3
	Female	236	56.7
Age	18 – 25	242	58.1
	26 – 30	80	19.2
	31 – 50	69	16.7
	50 and above	25	6.0
Degree/diploma	Junior high school and below	30	7.2
	High school/Secondary school	46	11.0
	Specialized/Bachelor's degree	272	65.4
	Postgraduate and above	68	16.4
Occupation	Student	212	51.0
	Company staff	107	25.7
	Freelance work	53	12.7
	Party and government personnel	23	5.5
	Resigned/retired	9	2.0
	Other	12	2.8
Location	Areas within Guangdong province	143	34.3
	Areas outside Guangdong province	175	42.1
	Hong Kong, Macao, and Taiwan	44	10.6
	Others	54	13.0
Income (monthly)	3,000 yuan and below	189	45.4
	3,001 – 6,000 yuan	101	24.3
	6,001 – 12,000 yuan	95	22.8
	12,001 – 20,000 yuan	20	4.8
	20,001 yuan and above	11	2.7

Table 2. Normality test

Items	Minimum statistic	Maximum statistic	Mean	Std. deviation	Skewness		Kurtosis	
				Statistic	Statistic	Standard error	Statistic	Standard error
NC1	1	7	5.12	1.292	−0.597	0.120	0.157	0.239
NC2	1	7	4.95	1.350	−0.463	0.120	0.022	0.239
NC3	1	7	5.14	1.231	−0.677	0.120	0.602	0.239
NC4	1	7	5.13	1.237	−0.293	0.120	−0.381	0.239
DC1	1	7	5.02	1.288	−0.527	0.120	0.225	0.239
DC2	1	7	5.03	1.358	−0.508	0.120	−0.105	0.239
DC3	1	7	5.01	1.213	−0.381	0.120	0.010	0.239
DC4	1	7	5.14	1.305	−0.435	0.120	−0.216	0.239
CC1	1	7	5.21	1.375	−0.549	0.120	−0.194	0.239
CC2	1	7	5.05	1.332	−0.514	0.120	0.020	0.239
CC3	1	7	5.21	1.333	−0.642	0.120	0.253	0.239
LCM1	1	7	5.04	1.281	−0.431	0.120	0.081	0.239
LCM2	1	7	5.12	1.343	−0.554	0.120	0.100	0.239
LCM3	1	7	5.19	1.379	−0.536	0.120	−0.079	0.239
LCM4	1	7	5.12	1.265	−0.371	0.120	−0.186	0.239
LCM5	1	7	5.21	1.374	−0.754	0.120	0.345	0.239
LCA1	1	7	5.28	1.374	−0.715	0.120	0.267	0.239
LCA2	1	7	5.29	1.367	−0.533	0.120	−0.111	0.239
LCA3	1	7	5.05	1.256	−0.349	0.120	0.075	0.239
LCA4	1	7	5.10	1.404	−0.459	0.120	−0.249	0.239
LCA5	1	7	5.09	1.252	−0.371	0.120	−0.127	0.239
LCB1	1	7	5.22	1.411	−0.738	0.120	0.343	0.239
LCB2	1	7	5.10	1.375	−0.494	0.120	−0.208	0.239
LCB3	1	7	5.20	1.397	−0.632	0.120	−0.096	0.239

Abbreviations: CC: Criticality cognition; DC: Disruption cognition; LCA: Low-carbon tourism awareness; LCB: Low-carbon behavior intention; LCM: Low-carbon travel motivation; NC: Novelty cognition.

Table 3. Harman's one-factor test results

Component	Initial eigenvalues			Extraction sums of squared loadings		
	Total	% of variance	Cumulative %	Total	% of variance	Cumulative %
1	8.428	35.117	35.117	8.428	35.117	35.117
2	2.267	9.445	44.562	2.267	9.445	44.562
3	1.996	8.316	52.877	1.996	8.316	52.877
4	1.471	6.131	59.008	1.471	6.131	59.008
5	1.315	5.478	64.487	1.315	5.478	64.487
6	1.023	4.261	68.748	1.023	4.261	68.748
7	0.685	2.853	71.601			
8	0.599	2.498	74.098			

Extraction method: Principal component analysis.

4.4. Reliability analysis

The reliability analysis revealed that Cronbach's α coefficients for latent variables exceeded the 0.7 thresholds set by George and Mallery.[55] The corrected item-total correlations also surpassed the preferred 0.5 level, indicating good internal consistency of questions. Moreover, Cronbach's

α values post-item deletion remained below the latent variable's coefficients, further affirming the soundness of the questionnaire (Table 4).

4.5. Validity analysis

The validity test was conducted through factor analysis, and principal component analysis with varimax rotation was employed independently for each construct. Before this, "Bartlett's Test of Sphericity" (BTS) was used to assess the presence of correlations, and the "Kaiser's Measure of Sampling Adequacy" (KMO) test was conducted to ensure adequate sampling. Results indicated a KMO value above 0.50 and a BTS value being significantly different from 0, which are the prerequisites for performing factor analysis (Hair *et al*., 2006). Extraction was based on Eigenvalue criteria, retaining factors with Eigenvalues above one and explaining at least 50% cumulative variance. Separate factor analyses were performed on six scales, revealing convergence under six factors: Novelty cognition (NC), disruption cognition (DC), criticality cognition (CC), LCM, LCA, and low-carbon behavior intention (LCB) for space tourism. These factors accounted for approximately 68% of the variation, with Eigenvalues greater than 1 for all (Table 5).

Table 4. Reliability analysis of all variables

Measurement	Items	CITC	Cronbach's α if item deleted	Cronbach's α
NC	NC1	0.601	0.757	0.801
	NC2	0.617	0.750	
	NC3	0.598	0.759	
	NC4	0.643	0.737	
DC	DC1	0.700	0.794	0.844
	DC2	0.664	0.810	
	DC3	0.645	0.817	
	DC4	0.713	0.788	
CC	CC1	0.695	0.807	0.847
	CC2	0.699	0.803	
	CC3	0.753	0.751	
LCM	LCM1	0.711	0.862	0.884
	LCM2	0.713	0.861	
	LCM3	0.703	0.864	
	LCM4	0.758	0.852	
	LCM5	0.724	0.859	
LCA	LCA1	0.727	0.823	0.863
	LCA2	0.731	0.822	
	LCA3	0.624	0.849	
	LCA4	0.611	0.854	
	LCA5	0.728	0.824	
LCB	LCB1	0.591	0.748	0.786
	LCB2	0.653	0.681	
	LCB3	0.635	0.701	

Abbreviations: CC: Criticality cognition; CITC: Corrected item-total correlation; DC: Disruption cognition; LCA: Low-carbon tourism awareness; LCB: Low-carbon behavior intention; LCM: Low-carbon travel motivation; NC: Novelty cognition.

Confirmatory factor analysis was used as a confirmatory test to assess the measurement tool, testing how well-measured variables represent a smaller number of constructs.

The data analysis revealed that all 24 questions on each variable scale had factor loadings exceeding 0.6, with significance at 0.001. All six constructs' combination reliability surpassed the 0.6 criterion, indicating internal consistency. Furthermore, the Squared multiple correlation (SMC) values for these questions were 0.454 or higher, exceeding 0.3 and indicating strong linear relationships.[56] This validates the measurement model and questions, effectively capturing the study's contents through latent variables (Table 6).

According to earlier research, discriminant validity between variables is established when evaluating the discriminant validity of numerous variables if the minimum value of Average variance extracted (AVE) is higher than the maximum value of the square of the correlation coefficient.[57] The maximum value of the correlation coefficient between awareness and behavioral intention of low-carbon space tourism among all latent variables is 0.685, which is smaller than the minimum value of the square root of AVE, 0.709, indicating that the partition validity of the current research model has good discriminant validity (Table 7).

4.6. SEM

The SEM, illustrated in Figure 2, includes variables such as perceived intensity of carbon neutrality goals for space tourism (NGC), LCM, LCA, LCB, NC, DC, and CC. NGC is perceived as driven by NC.

Based on the analyzed data, the overall confirmatory factor analysis results show that each inspection index meets the standards. This indicates that the measurement model has good fit indices, as shown in Table 8. Based on the data analysis results, the findings from the comprehensive confirmatory factor analysis conducted in this research (Table 8) indicate that the overall fit index of the measurement model is as follows: χ^2/df (chi-square degrees of freedom) stands at 1.535, within the 1 – 3 range, reaching the desired standardized value, suggesting a favorable level of fitness for the

Table 5. Overall exploratory factor analysis results

Construct	Items	Component						Communalities	KMO
		1	2	3	4	5	6		
NC	NC1	0.076	0.219	0.131	**0.756**	0.056	0.076	0.652	0.877
	NC2	0.161	0.058	0.261	**0.688**	0.153	0.190	0.630	
	NC3	0.197	0.064	0.139	**0.725**	0.188	0.018	0.624	
	NC4	0.129	0.131	0.210	**0.743**	0.136	0.080	0.655	
DC	DC1	0.125	0.174	**0.788**	0.148	0.079	0.148	0.717	
	DC2	0.110	0.089	**0.772**	0.146	0.136	0.123	0.672	
	DC3	0.062	0.050	**0.741**	0.250	0.159	0.082	0.649	
	DC4	0.151	0.166	**0.775**	0.172	0.131	0.132	0.715	
CC	CC1	0.188	0.168	0.138	0.156	**0.792**	0.086	0.741	
	CC2	0.122	0.125	0.156	0.191	**0.805**	0.121	0.755	
	CC3	0.102	0.192	0.186	0.146	**0.831**	0.114	0.807	
LCM	LCM1	**0.777**	0.156	0.092	0.109	0.066	0.145	0.674	0.878
	LCM2	**0.774**	0.101	0.096	0.159	0.108	0.133	0.674	
	LCM3	**0.787**	0.137	0.091	0.087	0.075	0.093	0.668	
	LCM4	**0.814**	0.126	0.115	0.116	0.104	0.110	0.728	
	LCM5	**0.774**	0.173	0.085	0.115	0.124	0.126	0.680	
LCA	LCA1	0.138	**0.728**	0.150	0.039	0.141	0.327	0.701	0.829
	LCA2	0.156	**0.813**	0.087	0.101	0.140	0.131	0.740	
	LCA3	0.232	**0.738**	0.070	0.209	0.094	−0.019	0.656	
	LCA4	0.096	**0.612**	0.118	0.116	0.100	0.374	0.561	
	LCA5	0.142	**0.793**	0.140	0.101	0.126	0.145	0.716	
LCB	LCB1	0.328	0.250	0.155	0.126	0.049	**0.643**	0.625	0.700
	LCB2	0.169	0.168	0.131	0.133	0.157	**0.803**	0.761	
	LCB3	0.158	0.290	0.219	0.075	0.123	**0.723**	0.701	
Rotation sums of squared loadings	Total	3.573	3.235	2.797	2.529	2.278	2.086		
	% of variance	14.889	13.480	11.654	10.538	9.493	8.693		
	Cumulative %	14.889	28.370	40.023	50.561	60.054	**68.748**		

Note: Value in boldface indicates factor loadings.
Abbreviations: CC: Criticality cognition; DC: Disruption cognition; KMO: Kaiser's measure of sampling adequacy; LCA: Low-carbon tourism awareness; LCB: Low-carbon behavior intention; LCM: Low-carbon travel motivation; NC: Novelty cognition.

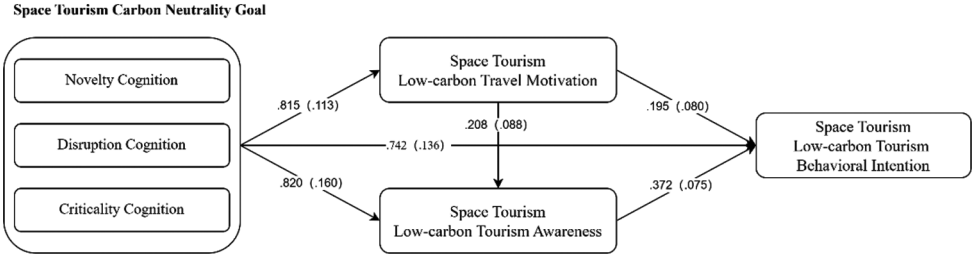

Figure 2. Structural equation modeling diagram of measurement model

model as a whole. The standardized residual mean square is calculated at 0.035, and the root mean square error of approximation at 0.036 – both values are below the standard thresholds of 0.05 and 0.08, respectively. Furthermore, the comparative fit index = 0.973, and the Tucker–Lewis index = 0.969, surpassing the

Table 6. Results of confirmatory factor analysis

Dimension	Items	Estimate	SE	SMC	CR	AVE
NC	NV1	0.678	0.033	0.454	0.802	0.503
	NV2	0.736	0.030	0.542		
	NV3	0.677	0.033	0.462		
	NV4	0.743	0.029	0.552		
DC	DC1	0.780	0.025	0.608	0.845	0.578
	DC2	0.735	0.028	0.540		
	DC3	0.717	0.029	0.517		
	DC4	0.805	0.023	0.645		
CC	CC1	0.778	0.025	0.607	0.849	0.652
	CC2	0.787	0.025	0.618		
	CC3	0.856	0.021	0.734		
LCM	LCM1	0.772	0.024	0.596	0.885	0.607
	LCM2	0.765	0.024	0.587		
	LCM3	0.752	0.025	0.566		
	LCM4	0.819	0.020	0.669		
	LCM5	0.785	0.023	0.616		
LCA	LCA1	0.795	0.023	0.632	0.866	0.566
	LCA2	0.804	0.022	0.648		
	LCA3	0.683	0.030	0.466		
	LCA4	0.678	0.031	0.458		
	LCA5	0.790	0.023	0.623		
LCB	LCB1	0.720	0.031	0.517	0.788	0.553
	LCB2	0.749	0.029	0.555		
	LCB3	0.762	0.029	0.587		

Abbreviations: AVE: Average variance extracted; CC: Criticality cognition; CR: Combination reliability; DC: Disruption cognition; LCA: Low-carbon tourism awareness; LCB: Low-carbon behavior intention; LCM: Low-carbon travel motivation; NC: Novelty cognition; SE: Standard error; SMC: Squared multiple correlation.

recommended level of 0.9 by Xia and Yang,[58] indicating strong model fitness and data consistency for this study. These results illustrate a high fitness level for the measurement model and the quality of data aggregation in this study.

Every fit index value considered in this study has met the expected criteria, thus indicating a suitable fit for the research model. All eight underlying assumptions were verified through an in-depth analysis of the correlation between each potential variable using route coefficients, as indicated in Table 9. The detailed analysis in Table 9 and 10 reveals that all path coefficients are positively significant. These results affirm the successful testing of all research hypotheses, consistent with the study outcomes. The model conforms to the specified standards, and no modifications are necessary for the research model in this study.

Table 7. Correlation coefficient and AVE

	NC	DC	CC	LCM	LCA	LCB
NC	0.709					
DC	0.612**	0.760				
CC	0.528**	0.490**	0.807			
LCM	0.460**	0.387**	0.397**	0.779		
LCA	0.447**	0.444**	0.484**	0.473**	0.752	
LCB	0.470**	0.546**	0.466**	0.556**	0.685**	0.744

Notes: The diagonal numbers are the square root of the AVE, and the numbers below the diagonal are the correlation coefficients between the latent variables. **At 0.01 significance level (two-tailed), the correlation is significant.
Abbreviations: CC: Criticality cognition; DC: Disruption cognition; LCA: Low-carbon tourism awareness; LCB: Low-carbon behavior intention; LCM: Low-carbon travel motivation; NC: Novelty cognition.

Table 8. Indicators of structural validity and criteria thereof

Fitness indicators	Measurement standards	Measurement results
χ^2/df	<3	1.535
SRMR	<0.05	0.035
RMSEA	<0.05	0.036
CFI	>0.90	0.973
TLI	>0.90	0.969

Abbreviations: CFI: Comparative fit index; RMSEA: Root mean square error of approximation; SRMR: Standardized residual mean square; TLI: Tucker–Lewis index.

Through utilizing Mplus software and the Bootstrap program, the significance of the mediating effect within the research model was specifically examined. A significant mediating effect is indicated when the product of the regression coefficients from the independent variable to the mediating variable and from the mediating variable to the dependent variable is unequivocally non-zero. In addition, the mediating effect is confirmed as noteworthy when the confidence interval (CI) between the upper and lower bounds does not encompass 0.

Initially, 1,000 bootstrap samples encompassing the complete original sample data set (n = 416) were obtained using a sampling technique. The regression coefficients originating from the mediating variable toward the dependent variable and from the independent variable toward the mediating variable were calculated based on these bootstrap samples. Subsequently, the estimates of the product of the total regression coefficients were ordered numerically from the smallest to the largest, forming a 95% CI between the 2.5 and 97.5 percentiles. The presence of mediating effects is affirmed when these regression coefficients' 95% CI does not encompass 0, as indicated in Table 10.

Table 9. Path analysis standardized estimates and significance data

Hypothesis path	Standardization estimates	SE	Est/SE	*P*	Hypothesis testing
H1: NGC→LCM	0.560	0.064	8.803	***	Supported
H2: NGC→LCA	0.510	0.082	6.253	***	Supported
H3: NGC→LCB	0.316	0.085	3.698	***	Supported
H4: LCM→LCA	0.188	0.079	2.382	*	Supported
H5: LCM→LCB	0.190	0.073	2.624	***	Supported
H6: LCA→LCB	0.400	0.075	5.350	***	Supported

Note: *P<0.05, ** P<0.01, ***P<0.001.
Abbreviations: Est/SE: Estimated value; LCA: Low-carbon tourism awareness; LCB: Low-carbon behavior intention; LCM: Low-carbon travel motivation; NGC: Perceived intensity of carbon neutrality goals for space tourism; SE: Standard error.

Table 10. Mediating effect analysis

Mediating effect path	Indirect effect			Total effect			Proportion of indirect effects			Hypothesis testing
	Effect size	95% CI	*P*	Effect size	95% CI	*P*	Effect size	95% CI	*P*	
NGC→LCM→LCB	0.159 (0.107)	0.036, 0.201	0	0.999 (0.668)	0.546, 0.766	0	0.159 (0.160)	0.040, 0.260	0	Supported
NGC→LCA→LCB	0.305 (0.204)	0.132, 0.316	0				0.305 (0.457)	0.158, 0.431		Supported

Abbreviations: 95% CI: 95% confidence interval; LCA: Low-carbon tourism awareness; LCB: Low-carbon behavior intention; LCM: Low-carbon travel motivation; NGC: Perceived intensity of carbon neutrality goals for space tourism.

5. Discussion and conclusion

The present study identified six factors: NC, DC, CC, space tourism LCM, space tourism LCA, and space tourism LCB, which have been empirically validated with the help of confirmatory factor analysis.

Concerning the relationship between the constructs, SEM results revealed that NGC, LCM, and LCA have positive and significant effects on LCB. The study showed that the perceived intensity of the "carbon neutrality for space tourism" concept was vital to potential tourists getting into space low-carbon tourism to acquire knowledge about the destination. Tourists were also motivated by low-carbon tourism motivation and awareness of themselves, which affected their behavior intention.

The SEM result also indicated that low carbon awareness positively affected tourists' behavior intention toward space. The study provides evidence that a higher level of tourist's low-carbon awareness will raise behavior intention.

Regarding indirect relationships, motivation, and awareness mediate the relationship between the perceived intensity of the "carbon neutrality for space tourism" and tourists' behavior intention. It suggests that low-carbon motivation and awareness of tourists visiting space leads to a better understanding of "carbon neutrality for space tourism" and their behavior intention. This positive behavior intention, in turn, leads to forming a positive knowledge of carbon neutrality.

5.1. Empirical and theoretical contributions

5.1.1. Pioneering the integration of EST in space tourism research

This study makes a significant contribution to tourism research by being one of the first to apply the EST to the context of space tourism. Typically used in the analysis of consumer behavior in conventional tourism, integrating this theory into the space tourism context provides a novel and insightful framework for understanding tourists' intentions for low-carbon behavior. This integration extends the applicability of the EST and opens up new avenues for research in the tourism industry, particularly in the emerging field of space tourism.

5.1.2. Examining the impact of carbon neutrality goals on tourists' behavioral intentions

This research fills a gap in the existing literature by focusing on the influence of space tourism carbon neutrality goals on tourists' intentions to engage in low-carbon tourism behavior. The findings of this study contribute to our understanding of how the pursuit of carbon neutrality in space tourism can shape tourists' behavior intentions. It provides empirical evidence of the potential influence of sustainability goals on consumer behavior in the context of space tourism, which can inform future research and industry practices.

5.1.3. Examining the behavioral intentions in the context of space tourism

This study focuses on tourists' intentions to engage in low-carbon tourism behavior in the context of space tourism,

providing valuable insights into the psychological factors that influence consumers' decision-making processes regarding sustainable tourism practices. By examining these intentions, this research contributes to the understanding of consumers' attitudes toward environmental sustainability in the context of space tourism, which can inform future research and industry practices aimed at promoting more sustainable tourism options.

5.2. Practical implications

5.2.1. Raising public awareness of low-carbon space tourism

Tourism authorities should fully interpret the development requirements of the "carbon neutrality" industry, establish a high-quality, low-carbon space tourism environment through carbon regulation of space tourism enterprises and carbon constraints in the tourism market, and strengthen the publicity and popularization of peak carbon and carbon neutrality.

5.2.2. Entrusting relevant tourism stakeholders with corporate responsibilities

Space tourism enterprises have strengthened investment in technological elements, reduced energy consumption in space tourism supply, implemented low-carbon concepts, provided low-carbon products, and emphasized the low-carbon concept pertaining to space tourism through marketing and publicity. The image of the space tourism market is shaped to conform to the psychology of mass consumption. Thus, encouraging the modernization of low-carbon space tourism services and the industry's sustainable development are crucial.

5.2.3. Adjusting the rational balance between supply and demand for space tourism

Enterprises and the government can create a favorable environment for low-carbon space tourism through a reasonable balance of tourism supply and demand. Having a general awareness of tourism is key to uniting the industry, bringing out the advantages of low-carbon space tourism products, and promoting the development of space tourism. It is essential to increase public awareness of carbon emissions, absorption, and sinks related to tourism and encourage their participation in the process. In addition, "carbon neutrality" must be interpreted with a realistic and objective material basis. The supply side of space tourism can be refined and fed back by monitoring tourists' motivations and cognitive processes. On the other hand, tourists' attitudes and perceptions of the effects of tourism development are important elements and assessment bases for ensuring the sustainable development of the tourism industry and realizing a virtuous cycle of tourism supply and demand under the "carbon neutrality" conditions.

5.3. Limitations and future research

Every precaution was taken to ensure the objectivity, reliability, and validity of the present study, but some limitations were identified. These limitations can be overcome in future studies. First of all, college students constituted a large portion of the current sample, which was not diverse and representative in terms of the actual populations; therefore, the sampling range and sample size should be expanded in further studies. Secondly, this study is a cross-sectional study; thus, different study designs should be attempted for future studies. Thirdly, this study used purposive sampling and included only 1st-time visitors. In the future, a comparative analysis of the motivations of 1st-time and repeat visitors and their impact on visitors' perspectives and attitudes of the travel destinations could be conducted. Fourth, future studies should consider other variables in similar contexts. Finally, our study was geographically limited to China's context, warranting an expansion of the research context to other regions.

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Conflict of interest

The authors declare they have no competing interests.

Author contributions

Conceptualization: All authors
Formal analysis: Linghui Liang
Investigation: Linghui Liang
Methodology: All authors
Writing – original draft: Linghui Liang
Writing – review & editing: All authors

Ethics approval and consent to participate

Not applicable.

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Availability of data

Data is available from the corresponding author upon reasonable request.

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Appendix

Note: The present questionnaire presented herein is a translated English version. The questionnaire was originally prepared in Chinese, and can be obtained from the corresponding author.

Questionnaire for space low-carbon tourism tourists

Questionnaire number

Dear Respondent:

Hello! This is an academic questionnaire aimed at understanding the impact of carbon neutrality policies on space tourism tourists' low-carbon travel behavioral intentions. You do not need to be named when filling out this questionnaire. Your personal privacy is not involved, and there is no right or wrong answer. The information obtained is for academic research purposes only. Your assistance will have an important impact on the conclusions of this research. We kindly ask you to spend your precious time and fill out this questionnaire based on your true personal feelings. Thank you very much for your support!

Background sharing

Carbon neutrality refers to the total amount of carbon dioxide emissions directly or indirectly produced by a country, enterprise, product, activity, or individual within a certain period of time, using low-carbon energy to replace fossil fuels, planting trees, energy conservation and emission reduction, etc. to offset itself. The generated carbon dioxide emissions are offset by positive and negative offsets, achieving relatively "zero emissions."

There are generally two ways to achieve carbon neutrality:

1. Through the carbon compensation mechanism, the carbon emissions generated are equal to the carbon emissions reduced elsewhere. For example: planting trees and purchasing renewable energy certificates
2. Use low-carbon or zero-carbon emission technologies (see low-carbon economy). For example, using renewable energy (such as wind and solar) to avoid emitting carbon dioxide into the atmosphere from burning fossil fuels; the ultimate goal is to transition entirely to low-carbon energy sources, replacing fossil fuels, so that the carbon emitted into the atmosphere is fully offset by the carbon absorbed back into the Earth, maintaining a balance without any net increase.

Part 1: Questionnaire Part

The following are questions about your feelings about the impact of carbon neutrality policies on space tourism. Please rate according to your true feelings.

Please choose the number after the following question to represent your level of agreement with the question, and put a "√" on the corresponding score. Among them, "1" means strongly disagree, "4" means average, as the number increases, the degree of agreement increases, and "7" means strongly agree.

1. Please select your level of agreement based on your understanding of carbon neutrality policy and space tourism? (This question is a single choice, please tick "√" according to the actual situation)

Question item	Strongly agree	Aagree	Agree somewhat	Nor disagree neither agreeb	Somewhat disagree	Disagree	Strongly disagree
The approach to implementing the carbon neutrality goal is clear.	7	6	5	4	3	2	1
The "carbon neutrality" goal is implemented with easy-to-understand procedural measures.	7	6	5	4	3	2	1
The implementation of the "carbon neutrality" goal can refer to similar incidents in the past to formulate response measures.	7	6	5	4	3	2	1
There are rules, procedures, or guidelines to follow up on the implementation of the "carbon neutrality" goal	7	6	5	4	3	2	1
The implementation of the "carbon neutrality" goal requires the development of space tourism to stop and think	7	6	5	4	3	2	1

Question item	Strongly agree	Aagree	Agree somewhat	Nor disagree neither agreeb	Somewhat disagree	Disagree	Strongly disagree
The implementation of the "carbon neutrality" goal has changed the thinking of space tourism development	7	6	5	4	3	2	1
The implementation of the "carbon neutrality" goal has changed the usual approach to space tourism development	7	6	5	4	3	2	1
The implementation of the "carbon neutrality" goal requires changes in the previous way of developing space tourism	7	6	5	4	3	2	1
The implementation of "carbon neutrality" goals is important to the success of space tourism	7	6	5	4	3	2	1
The implementation of the "carbon neutrality" goal is the primary event in the development of space tourism	7	6	5	4	3	2	1
The implementation of the "carbon neutrality" goal is an important event in the development of space tourism	7	6	5	4	3	2	1

2. What is your motivation for low-carbon space tourism? Please rate your feelings according to your personal point of view. (This question is a single choice, please tick "√" according to the actual situation)

Question item	Strongly agree	Aagree	Agree somewhat	Nor disagree neither agreeb	Somewhat disagree	Disagree	Strongly disagree
I identify the concept of ESCR.	7	6	5	4	3	2	1
It reduces the impact on the tourism environment.	7	6	5	4	3	2	1
It can reduce resource waste.	7	6	5	4	3	2	1
I am interested in energy saving and carbon reduction.	7	6	5	4	3	2	1
I am responsible for the environment.	7	6	5	4	3	2	1

3. Do you usually live a low-carbon life? Correspondingly, how do you feel about your own awareness of low-carbon tourism? Please select your level of agreement? (This question is a single choice, please tick "√" according to the actual situation)

Question item	Strongly agree	Aagree	Agree somewhat	Nor disagree neither agreeb	Somewhat disagree	Disagree	Strongly disagree
Energy conservation and emission reduction are everyone's social responsibility.	7	6	5	4	3	2	1
Energy conservation and emission reduction are beneficial to the sustainable development of space tourism.	7	6	5	4	3	2	1
I know the knowledge and skills of low-carbon consumption.	7	6	5	4	3	2	1
The public's evaluation will encourage you to carry out low-carbon tourism.	7	6	5	4	3	2	1
Before embarking on low-carbon space tourism, you can collect a wealth of relevant information.	7	6	5	4	3	2	1

4. After understanding the content of carbon neutrality policies and the significance of sustainable space tourism, what thoughts and actions do you have? Please rate based on the actual situation. (This question is a single choice, please tick "√" according to the actual situation)

Question item	Strongly agree	Agree	Agree somewhat	Nor disagree neither agreeb	Somewhat disagree	Disagree	Strongly disagree
I'm willing to actively adhere to low-carbon tourism in space travel.	7	6	5	4	3	2	1
In the future, I will have the intention of low carbon tourism in space tourism.	7	6	5	4	3	2	1
I'd like to persuade my friends and family to stick to low-carbon travel when participating in space tourism.	7	6	5	4	3	2	1

Part 2: Personal Information Section

1. Gender	□ Male	□ Female		
2. Age				
□ 18~25	□ 26~35	□ 36~45	□ 46~55	□ 56 or above
3. Education Level				
□ Junior high school and below	□ High school	□ Undergraduate	□ Master degree and above	
4. Profession				
□ Student	□ Staff	□ Government staff		□ Freelancer
□ Retirees	□ Other			
5. Where are you from				
□ Areas within Guangdong Province	□ Areas outside Guangdong Province	□ Hong Kong, Macao and Taiwan regions		□ Other ___
6. Monthly Income (RMB)				
□ 2,000 yuan and below	□ 2,001~5,000 yuan	□ 5,001~10,000 yuan		□ 10,001~15,000 yuan
□ 15,001 yuan and above				
7. The number of trips you take per year is approximately:				
□ Within half a day	□ 1 Day	□ 2 Day		□ 3 Days and above
8. Most of your travel purposes are (multiple choices available)				
□ Leisure	□ Visit friends	□ Business trip		□ Other___
9. Travel mode:	□ Tour group	□ Free travel		□ Other___

This questionnaire ends here, thank you very much for your assistance!

ACCSCIENCE PUBLISHING

Explora: Environment and Resource

ORIGINAL RESEARCH ARTICLE

Integrating organic manure and natural phosphate for sustainable long bean (*Vigna sinensis* L.) cultivation on marginal soils

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Abstract

Long bean (Vigna sinensis L.) is a legume widely cultivated for its high nutritional value and economic importance. However, marginal podzolic soils in regions such as Riau, Indonesia, pose challenges for sustainable agriculture due to low nutrient availability and high acidity. This study evaluates the integration of quail manure and natural phosphate fertilizers as a sustainable soil management strategy to enhance soil health and crop productivity. A factorial randomized complete block design was implemented with three levels of quail manure (0, 1.5, and 3 kg/plot) and natural phosphate (0, 12.5, and 25 g/plant) across 27 experimental plots. The effects of these amendments on soil properties, plant growth, and yield components were assessed using analysis of variance and Duncan's multiple range test. Results demonstrated that the combined application of quail manure and natural phosphate significantly improved plant growth parameters and soil fertility. The findings suggest that integrating organic and natural fertilizers enhances crop productivity while reducing dependence on synthetic inputs, offering a promising approach for sustainable agriculture on degraded soils.

Keywords: Sustainable agriculture; Quail manure; Natural phosphate; Marginal soils; Long bean

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1. Introduction

Long bean (*Vigna sinensis* L.) is an essential legume crop widely cultivated for its nutritional value and economic importance, particularly in tropical and subtropical regions. It is a significant source of protein, vitamins (A, B, C), minerals (iron, potassium, magnesium), and antioxidants, contributing to food security and dietary diversity.[1,2] However, despite its adaptability, long bean cultivation is often constrained by soil degradation, particularly in marginal podzolic soils. These soils, characterized by low organic matter content, high acidity, and limited phosphorus availability due to fixation by aluminum (Al) and iron (Fe), pose a critical challenge to achieving sustainable agricultural productivity.[3] Soil degradation is a global issue, affecting over 33% of the

world's arable land, and is exacerbated by unsustainable farming practices, climate change, and deforestation.[4] Addressing soil fertility in such degraded ecosystems is crucial for ensuring food security, especially in regions where agriculture is the primary livelihood.[5]

Efforts to address soil fertility issues in marginal soils have traditionally relied on synthetic fertilizers. While effective in boosting yields, the overuse of synthetic fertilizers has led to significant environmental issues, including nutrient runoff, water pollution, and increased greenhouse gas emissions.[6,7] The environmental costs of synthetic fertilizers are substantial, with nitrogen-based fertilizers alone contributing to approximately 2.4% of global greenhouse gas emissions.[8] Recognizing these limitations, there is growing interest in exploring sustainable alternatives that improve soil fertility while minimizing environmental impacts.[9] Organic amendments, such as manure and compost, have gained attention for their ability to enhance soil structure, increase microbial activity, and provide essential nutrients in a slow-release manner.[10] Among these, quail manure stands out as a rich source of organic carbon, nitrogen, and phosphorus, which are critical for soil fertility.[11] Recent studies have demonstrated that quail manure not only improves soil health but also enhances crop resilience to environmental stressors, making it a promising option for sustainable agriculture.[12]

The potential of organic fertilizer to improve crop yields and soil health has been highlighted in recent reports. For instance, Ma *et al.*[13] demonstrated that organic manure application significantly increased soil organic carbon and microbial activity, resulting in better nutrient cycling. Similarly, Manono *et al.*[14] found that the application of organic amendments significantly reduced soil bulk density, which in turn improved water infiltration, retention, and aeration, thereby promoting root development and nutrient uptake. However, organic amendments alone may not address phosphorus deficiencies prevalent in acidic podzolic soils.[15] Natural phosphate fertilizers, derived from sedimentary rocks, offer a sustainable alternative by providing a slow-release source of phosphorus, which is essential for root and shoot development.[16] Studies by Timofeeva *et al.*[17] and Mardamootoo *et al.*[18] have demonstrated that natural phosphates are particularly effective in acidic soils, where their dissolution is enhanced, ensuring sustained phosphorus availability to crops. In addition, the integration of organic and inorganic amendments has reportedly improved the efficiency of phosphorus use, reducing the need for synthetic inputs.[19]

While the benefits of organic and natural phosphate fertilizers are well-documented, research integrating these amendments for marginal soil improvement, specifically for long bean cultivation, remains limited. Most studies focus either on organic or chemical fertilizers, with few exploring the synergistic effects of combining organic manure with natural phosphates. For example, Zhen *et al.*[10] evaluated organic amendments on sandy soils but did not consider their interaction with natural phosphate fertilizers. Similarly, Talboys *et al.*[20] examined phosphorus management in acidic soils but overlooked the potential of combining organic amendments to further enhance nutrient availability. Recent research by Cen *et al.*[21] demonstrated that combining organic and inorganic fertilizers significantly improved soil health and crop yields in temperate regions, suggesting a similar potential for tropical marginal soils.

This research aims to address these gaps by investigating the combined application of quail manure and natural phosphate fertilizers for long bean cultivation on podzolic soils. The study evaluates their effects on key agronomic parameters, including plant growth, pod production, and soil health. By integrating these sustainable fertilization strategies, this study contributes to the broader discourse on sustainable agriculture, particularly for regions with degraded soils. The findings aim to provide actionable insights for optimizing land use while promoting environmental resilience, aligning with global efforts to achieve the United Nations Sustainable Development Goals (SDGs), particularly SDG 2 (Zero Hunger), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action).[22]

2. Methods

2.1. Study location

The study was conducted in a controlled greenhouse environment at the Faculty of Agriculture, Universitas Lancang Kuning, Riau, Indonesia (0°34'37.2"N 101°25'30.3"E). The greenhouse conditions were regulated to simulate the tropical climate of the region, with temperatures maintained at 28 – 32°C, relative humidity at 70 – 80%, and a photoperiod of 12 h of light per day. These conditions were chosen to mimic the natural growing environment of long beans in tropical regions. The soil used for the experiment was podzolic, representative of marginal soils in tropical regions, characterized by low fertility, high acidity (pH 5.2), and poor phosphorus availability due to Al and Fe fixation,[3] as displayed in Figure 1.

2.2. Experimental design

A factorial randomized complete block design was employed to assess two factors: quail manure (P) and natural phosphate fertilizer (R). Quail manure was tested

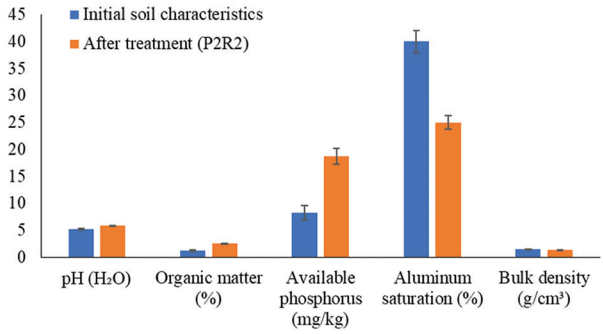

Figure 1. Changes in soil properties following application of quail manure and natural phosphate (P2R2 treatment; $n = 3$)

at three levels: no application (P0), 1.5 kg/plot (P1), and 3.0 kg/plot (P2). Natural phosphate was tested at three levels: no application (R0), 12.5 g/plant (R1), and 25 g/plant (R2). Each treatment combination was replicated 3 times, resulting in 27 experimental units, each containing four plants. This design ensured robust statistical analysis of the main and interaction effects of the treatments.[23] The experiment was conducted over a period of 7 weeks, from seed germination to final harvest, to capture the full growth cycle of long beans.

2.3. Plant materials and soil preparation

The experiment utilized *V. sinensis* L. (variety Parade Tavi), which is well-suited to tropical climates. Soil samples were collected from agricultural fields in Riau at a depth of 0 – 20 cm, homogenized, and sieved through a 2-mm mesh to remove debris and large particles. The soil was classified as podzolic with an initial pH of 5.2, low organic matter (1.25%), and high aluminum saturation (40%). These characteristics necessitate amendments to improve fertility.[3,24] Before planting, the soil was air-dried and thoroughly mixed to ensure uniformity across all experimental units.

2.4. Fertilizer application

Quail manure was air-dried, pulverized, and applied as a basal amendment 1 week before planting. The manure composition included 1.8% nitrogen, 0.4% phosphorus, and 0.6% potassium, consistent with previous studies on organic amendments.[6] Natural phosphate, containing 32% P_2O_5, was sourced locally and applied 3 days before planting to the soil surface, then thoroughly mixed with the top 15 cm of soil to ensure even distribution. This timing was selected to allow for the gradual release of nutrients and improve phosphorus availability at the time of seedling establishment. Long bean seeds were sown in planting holes of 3 cm depth, ensuring uniform germination and optimal root development. The combination of these amendments provided an integrated approach to enhancing soil fertility while minimizing synthetic inputs.[10,11,25] The fertilizer application rates were predetermined according to the experimental treatments.

2.5. Plant cultivation

Pre-germinated seeds of V. sinensis L. were transplanted into the prepared soil at a spacing of 40 × 60 cm, with each plot containing four plants. Transplantation was conducted simultaneously across all experimental units to ensure uniform growth conditions. Plants were monitored for 1 week post-transplantation to assess seedling establishment and minimize transplant shock before further data collection. Irrigation was provided daily to maintain field capacity, and pest control was achieved using mancozeb fungicides (Dithane® M-45; Corteva. Indonesia) and deltamethrin insecticides (Decis® 25 EC; Bayer, Indonesia) as required. Weed management was performed manually to ensure no competition for nutrients or space. The plants were monitored daily for growth and any signs of stress or disease.

2.6. Measured parameters

The study assessed the impact of quail manure and natural phosphate fertilizers on the growth and yield of long beans through a series of agronomic measurements, chosen to reflect both vegetative growth and reproductive performance. All parameters were measured from three sample plants per experimental unit to ensure statistical reliability.

Flowering is a critical phenological stage in plant development, and the days to flowering were recorded as the number of days from planting until the first flower appeared. This parameter provides insights into the plant's response to nutrient availability and its ability to reach reproductive maturity under the applied treatments.[26,27] The stem diameter, measured 1 week before harvest using a digital caliper at 5 cm above the soil surface, served as an indicator of the plant's structural robustness. Stem diameter is directly associated with the plant's ability to transport water and nutrients efficiently, a key determinant of overall plant health.[28]

To evaluate reproductive performance, the number of pods per plant was counted at the end of the harvest period. This metric reflects the reproductive success of the plant, which is influenced by the nutrient supply and soil conditions.[29] In addition, pod length was measured for the longest pod harvested from each plant using a measuring tape. Pod length is a vital yield component that indicates the effectiveness of the treatments in promoting pod development.[30]

Finally, the pod weight per plant was determined by weighing all harvested pods from each sample plant using a digital balance. Harvesting was conducted 7 weeks after transplantation when the pods reached full maturity. Pod weight, expressed in grams (g), represents the culmination of the plant's growth and reproductive processes, offering a comprehensive indicator of yield potential.[30] By analyzing these parameters, the study aimed to capture the full spectrum of plant responses to the integrated application of quail manure and natural phosphate fertilizers, providing robust evidence for the effectiveness of these sustainable soil amendments.

2.7. Data analysis

The collected data were analyzed using analysis of variance (ANOVA) to determine the significance of the main and interaction effects of quail manure and natural phosphate fertilizers. ANOVA was chosen because it allows for the simultaneous comparison of multiple treatment groups and their interactions. Treatments with significant effects ($P < 0.05$) were further analyzed using Duncan's New Multiple Range Test (DNMRT) at a 5% significance level to identify specific differences between treatment means. DNMRT was selected for its ability to control type I errors while providing a clear comparison of treatment effects. Statistical analyses were performed using the Statistical Package for the Social Sciences software (version 25.0; IBM Corp., USA).[31]

2.8. Environmental and soil analysis

Soil samples were collected before treatment application (week 0) and after harvesting (week 7) to assess the initial fertility status and the effects of the amendments. For each experimental plot, three subsamples were taken at a depth of 0 – 20 cm and then composited into one representative sample per plot. This approach ensured a homogenous representation of soil conditions across treatments. Soil pH was measured in a 1:2.5 soil-water suspension using a pH meter (HI98128; Hanna Instruments, Romania). Organic matter content was determined using the Walkley-Black method, while phosphorus availability was quantified using the Bray-1 extraction method and a spectrophotometer (Shimadzu ultraviolet-1800; Shimadzu Corp., Japan). Aluminum saturation was determined using the 1 M KCl extraction method, and total nitrogen was measured using the Kjeldahl method. These analyses provided baseline and post-treatment soil characteristics essential for evaluating the amendments' efficacy.[31] Soil bulk density was measured using the core method at a depth of 0 – 10 cm and 10 – 20 cm to assess changes in soil structure and porosity. Measurements were taken before treatment application (week 0) and after harvesting (week 7) to evaluate the effects of the amendments on soil compaction and aeration.

3. Results and discussion

3.1. Soil characteristics and their transformation

The podzolic soils used in this study were initially characterized by low fertility and high acidity, conditions that pose significant challenges to sustainable crop production. These soils exhibited a pH of 5.2, low organic matter content (1.25%), and high aluminum saturation (40%), which limits the availability of essential nutrients such as phosphorus.[1] These properties are typical of tropical marginal soils and are often associated with poor agricultural productivity due to their compact structure and low capacity for nutrient retention.[3,24,32]

The application of quail manure significantly improved soil characteristics by increasing organic matter content ($P < 0.01$), as illustrated in Figure 1, which displays notable enhancements in organic matter percentage ($P < 0.01$), phosphorus availability ($P < 0.01$), and reduced aluminum saturation ($P < 0.05$). Organic matter plays a crucial role in improving soil aggregation, enhancing water infiltration, and creating a more favorable environment for root growth. In addition, as organic material decomposes, microbial activity is stimulated, leading to the mineralization of nitrogen into plant-available forms (NH_4^+ and NO_3^-).[33] This process not only increases nitrogen availability but also enhances soil microbial diversity, accelerating the breakdown of organic residues and further improving soil structure.[10,13] Moreover, the carbon-rich nature of quail manure promotes soil aggregate stabilization, reducing the risk of erosion, improving porosity, and enhancing aeration.[34] These improvements create a more stable and resilient soil environment, ensuring optimal conditions for plant growth by facilitating root penetration, improving nutrient exchange capacity, and maintaining sufficient oxygen supply for root respiration. The combined effects of these transformations highlight the vital role of organic amendments in improving the fertility and structure of degraded soils.

Natural phosphate fertilizer further improved soil fertility by supplying a slow-release source of phosphorus, an essential nutrient often deficient in acidic soils. The amendments reduced the chemical fixation of phosphorus by aluminum and iron, thereby increasing its availability for plant uptake.[35] In addition, the combined application of quail manure and natural phosphate resulted in a slight increase in soil pH, which mitigated the toxicity effects of aluminum and improved overall nutrient availability.[36] These transformations highlight the synergistic effects of organic and inorganic amendments in enhancing

soil properties. The increase in soil pH from 5.2 to 5.8 is particularly noteworthy, as it suggests a reduction in soil acidity, which is critical for improving nutrient availability and reducing toxicity from aluminum ions. The organic matter content doubled from 1.25% to 2.50%, reflecting the contribution of quail manure in enriching the soil with organic carbon and enhancing its physical properties.[10,13]

The available phosphorus concentration increased from 8.3 to 18.7 mg/kg, demonstrating the synergistic effect of organic manure and natural phosphate. Organic manure enhances microbial activity, which facilitates phosphorus solubilization from natural phosphate, thereby improving phosphorus availability in acidic soils, where fixation is a major constraint.[17] These findings align with previous studies demonstrating that natural phosphate amendments can sustain phosphorus release in acidic conditions, preventing fixation and ensuring long-term nutrient availability to plants.[35,36] Similarly, Manono *et al.*[14] observed that organic amendments contributed to increased phosphorus availability in acidic soils, likely due to their role in enhancing microbial activity and facilitating phosphorus solubilization. The reduction in aluminum saturation from 40% to 25% further underscores the effectiveness of these amendments in mitigating the adverse effects of soil acidity.[37] Lower aluminum levels reduce phosphorus fixation in the soil matrix, thereby enhancing phosphorus availability and uptake by plants.[38]

In addition, bulk density decreased from 1.45 to 1.30 g/cm^3, indicating improved soil structure and porosity ($P = 0.027$). This finding aligns with Manono *et al.*,[14] who reported that the application of organic amendments significantly reduced bulk density, improving water infiltration, retention, and aeration, thereby enhancing root penetration and overall soil quality. These changes collectively demonstrate the potential of integrating organic and natural fertilizers to transform marginal soils into productive agricultural systems, offering a sustainable solution for improving soil health in tropical regions.

3.2. Effect of treatments on plant growth parameters

The application of quail manure and natural phosphate fertilizers significantly influenced the growth parameters of long beans, particularly days to flowering and stem diameter (Figure 2). The treatments resulted in a notable reduction in days to flowering, with the shortest flowering time observed under the P2R2 treatment (27.00 ± 0.85 days). In contrast, the control (P0R0) exhibited the longest time to flowering (34.66 ± 1.20 days). The reduction in days to flowering under the P2R2 treatment indicates that the combined application of quail manure and natural phosphate provided optimal nutrient availability,

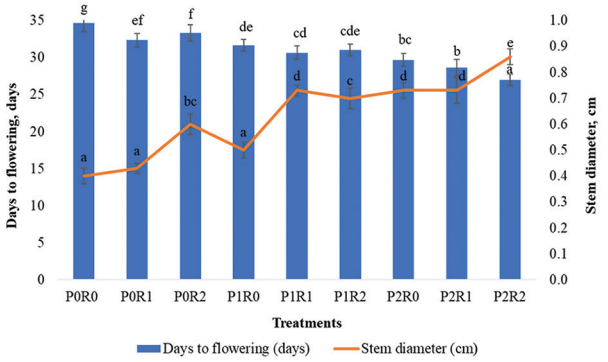

Figure 2. Effect of treatments on plant growth parameters (days to flowering and stem diameter; $n = 3$). Different letters (a-f) indicate significant differences at $P < 0.05$ according to Duncan's New Multiple Range Test. Treatments sharing the same letter are not significantly different from each other.

particularly nitrogen and phosphorus. These nutrients are essential for vegetative growth and accelerating the transition to reproductive phases.[30]

The enhanced availability of phosphorus likely supported critical metabolic processes, including adenosine triphosphate production, which is necessary for flowering initiation.[39] Nitrogen supplied by quail manure further promoted vigorous vegetative growth, enabling the plants to transition to reproductive development more rapidly. These findings are consistent with those of Míguez-Montero *et al.*,[40] who reported that balanced nitrogen and phosphorus inputs significantly reduced the time to flowering in legumes.

Stem diameter, an indicator of plant robustness and nutrient transport efficiency, was significantly affected by the treatments. The P2R2 treatment yielded the largest stem diameter (0.86 ± 0.03 cm), which was significantly higher than all other treatments ($P < 0.05$). In contrast, the control treatment (P0R0) exhibited the smallest stem diameter (0.40 ± 0.03 cm), with statistically significant differences from all fertilized treatments. The increase in stem diameter under the P2R2 treatment can be attributed to the synergistic effects of organic matter and phosphorus in enhancing soil structure and nutrient availability.[41] Organic matter provided by quail manure increased soil carbon content, which in turn stimulated microbial activity and improved soil aggregate stability. This enhancement likely facilitated better root penetration and moisture retention, allowing for more efficient nutrient uptake.[42]

The slow-release phosphorus from natural phosphate contributed to sustained nutrient availability, which supported cell division and elongation, resulting in thicker and sturdier stems.[43] The microbial solubilization of phosphorus further enhanced its bioavailability, improving

root elongation and branching, which facilitated greater nutrient uptake.[17,20] In addition, the increased nitrogen mineralization from quail manure decomposition provided a steady supply of essential nitrogen, which is crucial for chlorophyll synthesis and overall vegetative growth.[33,44]

These findings align with previous research by De Prato *et al.*,[43] who reported similar improvements in stem diameter in hemp crops when organic amendments were integrated with phosphorus-based fertilizers. Furthermore, the reduction in aluminum saturation (40% to 25%) observed in the soil analysis likely contributed to an improved root environment, minimizing toxicity and enhancing nutrient absorption efficiency. The effectiveness of the P2R2 treatment in improving plant growth parameters on podzolic soils highlights its potential as a sustainable soil amendment strategy. The integration of quail manure and natural phosphate not only enhanced nutrient availability but also improved soil physical properties, creating a more conducive environment for root development and nutrient transport. The consistent superiority of the P2R2 treatment across all measured growth parameters suggests that a balanced combination of organic matter and slow-release phosphorus is essential for optimizing plant development in acidic, nutrient-deficient soils.

3.3. Effect on yield components

The yield components of long beans, including pod length, number of pods per plant, and pod weight per plant, exhibited significant improvements with the application of quail manure and natural phosphate fertilizers. The combination of these amendments consistently outperformed the control treatment across all measured parameters, as displayed in Table 1. The pod length varied significantly among treatments, with the longest pods (96.66 cm) observed under the P2R2 treatment (3 kg quail manure per plot and 25 g natural phosphate per plant). In contrast, the control treatment (P0R0) produced the shortest pods (60.66 cm). The enhanced pod length under the P2R2 treatment can be attributed to improved nutrient availability, particularly phosphorus, which is essential for cell elongation and pod development.[45] The slow-release nature of phosphorus in natural phosphate ensured a consistent supply of this critical nutrient throughout the pod growth phase. These results align with findings by Rahaman *et al.*,[30] who demonstrated that phosphorus availability significantly increased pod elongation in legumes.

Table 1. Effect of treatments on yield components

Treatment	Pod length (cm)	Number of pods per plant	Pod weight per plant (g)
P0R0 (Control)	60.66±1.50^{a}	12.00±1.00^{a}	802.33±20.00^{a}
P0R1	67.16±2.00^{b}	13.33±1.10^{a,b}	852.00±25.00^{a}
P0R2	67.66±1.80^{b}	16.33±1.50^{b,c}	859.00±30.00^{a,b}
P1R0	69.33±2.10^{a}	18.66±1.75^{c}	1021.66±35.00^{b}
P1R1	76.50±2.50^{b}	23.00±2.00^{d}	1331.00±40.00^{c}
P1R2	75.16±2.00^{b}	23.66±2.10^{d}	1442.00±45.00^{c}
P2R0	78.33±2.50^{b}	25.66±2.20^{d}	1732.66±50.00^{d}
P2R1	84.33±2.80^{b}	31.00±2.50^{e}	2732.00±60.00^{e}
P2R2	96.66±3.00^{c}	36.66±2.80^{f}	2850.66±70.00^{e}

Note: Values are presented as the mean±standard error (n=3). Different letters (a-f) indicate significant differences at P<0.05 according to Duncan's New Multiple Range Test. Treatments sharing the same letter are not significantly different from each other.

The number of pods per plant also increased significantly with the treatments. The P2R2 treatment produced the highest number of pods (36.66/plant), while the control recorded the lowest (12.00/plant). This increase reflects the improved soil fertility and nutrient availability provided by the combined amendments, which supported robust reproductive growth.[46] Organic matter supplied by quail manure likely enhanced soil structure and microbial activity, facilitating efficient nutrient uptake.[13] These findings are consistent with those of Fekadu *et al.*,[46] who reported significant increases in pod production of faba bean with organic amendments.

Pod weight per plant was the most significantly impacted yield parameter, with the P2R2 treatment producing the highest weight (2850.66 g/plant) compared to the control (802.33 g/plant). This substantial increase highlights the effectiveness of integrating quail manure and natural phosphate fertilizers in enhancing nutrient availability, improving soil structure, and optimizing resource allocation to reproductive growth.[41,47] The high nutrient supply from these amendments likely boosted photosynthetic efficiency, increased biomass accumulation, and facilitated better assimilate partitioning toward pod development.[44,48] The P2R2 treatment also resulted in the longest pods (96.66 cm) and the highest number of pods per plant (36.66), indicating that the combined application of organic and phosphate fertilizers not only promoted individual pod development but also enhanced overall reproductive capacity. The increase in phosphorus availability from 8.3 to 18.7 mg/kg contributed to stronger root development, improved nutrient uptake, and enhanced energy metabolism, which are critical for fruit formation and filling.[47]

The observed yield improvements may be directly linked to microbial activity, particularly phosphate-solubilizing bacteria that facilitated the release of inorganic phosphorus from natural phosphate sources.[10,17] Furthermore, the enhanced nitrogen mineralization improved nitrogen uptake, optimizing the synthesis of

amino acids and proteins, which are essential for pod filling and biomass accumulation.[49] In addition, the reduction in aluminum saturation (40% – 25%) created a more favorable rhizosphere environment, mitigating potential root stress and supporting optimal nutrient absorption. These findings align with those of Islam *et al.*,[47] who reported significant improvements in pod weight when organic and phosphate fertilizers were applied in tropical legumes. Similarly, Manono *et al.*[14] demonstrated that phosphorus amendments in combination with organic matter can increase the efficiency of phosphorus use, enhance microbial activity, and improve soil aeration, all of which contribute to increased crop productivity.

The observed improvements in pod length, number of pods per plant, and pod weight per plant in the P2R2 treatment (3 kg quail manure + 25 g natural phosphate) underscore the interactive effects of organic and phosphate-based fertilization in enhancing crop productivity. Organic manure supplies essential macronutrients and improves soil moisture retention, while natural phosphate ensures a steady phosphorus supply, which is crucial for reproductive growth.[47] This interaction optimizes the efficiency of nutrient use, making the combined application more effective than either amendment alone. This integrated fertilization strategy not only enhances nutrient availability but also improves soil physical properties, leading to more sustainable crop production. These results are particularly relevant for tropical regions with inherently low soil fertility, where conventional chemical fertilizers may not be a long-term solution due to economic and environmental constraints.

The effectiveness of integrating organic amendments and phosphate fertilizers has been widely demonstrated across different cropping systems and regions, as summarized in Table 2. Studies on tropical legumes[47] and soybean-wheat rotations[50] consistently highlight the benefits of organic amendments in improving soil structure, enhancing phosphorus availability, and boosting overall crop productivity. In tropical legume cultivation, Islam *et al.*[47] found that vermicompost application improved soil structure and water retention, leading to increased plant height and pod production. Similarly, in soybean-wheat systems, Choudhary *et al.*[50] reported that long-term application of manure combined with nitrogen, phosphorus, and potassium increased soil organic matter, nitrogen availability, and overall grain yield.

For phosphorus-deficient soils, Namakka *et al.*[45] investigated the effect of single superphosphate

Table 2. Comparative studies on the use of organic amendments and phosphate fertilizers in different cropping systems

Study	Crop (region)	Fertilizer type	Main findings	References
Purnama *et al.*	Long beans (Indonesia)	Quail manure+natural phosphate[a]	Soil quality post-treatment: The pH increased from 5.2 to 5.8; organic matter doubled (1.25 – 2.50%); available phosphorus increased from 8.3 to 18.7 mg/kg; aluminum saturation decreased from 40% to 25%. Growth: Shortest flowering time (27 days); largest stem diameter (0.86 cm). Yield: Highest pod weight (2850.66 g/plant); longest pod length (96.66 cm); highest number of pods (36.66/plant).	This study
Islam *et al.*	Tropical legumes (Bangladesh)	Vermicompost (20%)[b]	Soil quality post-treatment: Improved soil structure, water retention, and nutrient availability. Growth: Highest plant height (314.19 cm for bush bean, 259.93 cm for winged bean, 72.87 cm for yard long bean). Yield: Highest pod weight (298.12 g/m² for bush bean, 728.69 g/m² for winged bean, 222.45 g/m² for yard long bean); longest pod length (10.76 cm for bush bean, 22.27 cm for winged bean, 30.00 cm for yard long bean); highest number of pods (58.93 for bush bean, 44.00 for winged bean, 20.86 for yard long bean).	47
Choudhary *et al.*	Soybean-wheat rotation (India)	Long-term organic manure+NPK[c]	Soil quality post-treatment: Increased organic matter, available N (373 kg/ha), P (10.58 mg/kg), and K (212 kg/ha). Growth: Highest plant height and stem diameter. Yield: Highest grain yield (2.56 Mg/ha for soybean, 4.31 Mg/ha for wheat); longest pod length; highest number of pods.	50
Namakka *et al.*	Cowpeas (Nigeria)	Single superphosphates (39 kg P/ha)[d]	Soil quality post-treatment: Soil pH 5.6; available phosphorus 3.50 mg/kg; low nutrient status. Growth: Highest plant height (48.79 cm at 9 WAS); highest number of branches (18 at 9 WAS). Yield: Highest grain yield (1830.71 kg/ha in 2015, 1994.62 kg/ha in 2016); longest pod length (3.927 cm at 9 WAS).	45

Notes: [a]Data were obtained from the best treatment (P2R2: 3 kg quail manure+25 g natural phosphate);
[b]Data were obtained from the vermicompost treatment (20%); [c]Data were obtained from the combination of manure and NPK fertilizer (MNPK);
[d]Data were obtained from the 39 kg P/ha treatment.
Abbreviations: NPK: Nitrogen, phosphorus, and potassium; WAS: Weeks after sowing.

(39 kg P/ha) on cowpea growth. Their findings revealed only moderate improvements in available phosphorus and soil pH, indicating the limited effectiveness of chemical phosphate fertilizers when applied in isolation. This aligns with previous research emphasizing the importance of combining organic amendments with phosphate fertilizers to enhance phosphorus solubilization and uptake.

The findings of this study further validate that integrating quail manure and natural phosphate in long bean cultivation significantly enhances soil fertility and plant productivity. The substantial increase in pod weight (2850.66 g/plant), pod length (96.66 cm), and number of pods per plant (36.66) observed in this study underscores the synergistic effect of organic manure and phosphate fertilizers. This integrated approach presents a sustainable alternative to synthetic fertilizers, particularly in nutrient-deficient tropical soils, where maintaining long-term soil health and productivity is essential for sustainable agriculture.

3.4. Implications for sustainable agriculture

The findings of this study highlight the potential of integrating quail manure and natural phosphate fertilizers as a sustainable approach to enhancing soil fertility and crop productivity on marginal podzolic soils. These results align with the global shift toward environmentally friendly agricultural practices that aim to reduce reliance on synthetic inputs while optimizing natural resources. This section explores the implications for sustainable agriculture and evaluates the economic benefits reported in related studies.

3.4.1. Environmental benefits

The integration of organic and natural fertilizers significantly improved soil properties, including increased organic matter, enhanced phosphorus availability, and reduced aluminum toxicity. These changes contribute to a healthier soil ecosystem, which is essential for long-term agricultural sustainability.[45] The increased organic matter content improves soil structure, water retention, and microbial activity, reducing the risk of soil degradation and erosion.[37,51] By using natural phosphate as a slow-release source of phosphorus, this approach minimizes nutrient leaching and protects water bodies from eutrophication.[52]

The adoption of these sustainable practices can also lower the carbon footprint of agriculture. Synthetic fertilizer production is energy-intensive and contributes significantly to greenhouse gas emissions.[6,7] Replacing synthetic fertilizers with locally sourced quail manure and natural phosphate reduces these emissions, supporting climate-resilient farming systems.[10,11]

3.4.2. Economic benefits

The economic benefits of this integrated approach extend beyond environmental sustainability. Utilizing quail manure, which is often an underutilized agricultural resource, offers a cost-effective alternative to synthetic fertilizers, reducing dependency on expensive chemical inputs.[53] In addition, natural phosphate, sourced from sedimentary rocks, is significantly more affordable than commercial phosphorus fertilizers, making it an accessible option for smallholder farmers.[19] A cost-benefit analysis conducted by Singh and Singh[54] demonstrated that integrating organic and phosphate fertilizers reduced fertilizer input costs by 25% while increasing crop yields by 30% in legume cultivation. Similarly, a study by Cen *et al.*[21] reported that the use of organic amendments in temperate farmland quadrupled farmer income, primarily through enhanced soil productivity and reduced reliance on chemical fertilizers.

The results of this study further confirm these economic advantages. Under the P2R2 treatment, the yield per plant reached 2850.66 g, which translates into a 50% increase in marketable produce compared to the control. At current market prices for long beans (approximately $1.20/kg or IDR 18,000/kg), this yield improvement could result in an estimated $600 – 750 (IDR 9 – 11 *juta*) per hectare increase in farmer income. Furthermore, compared to conventional synthetic fertilizers, quail manure and natural phosphate reduce long-term costs by minimizing soil degradation and maintaining sustained fertility. While synthetic fertilizers require repeated applications per growing cycle, organic amendments improve soil structure and nutrient availability over multiple seasons, reducing the frequency of external fertilizer inputs. These benefits provide economic resilience for smallholder farmers, allowing for higher net profits and improved financial stability in low-input farming systems.[21]

3.4.3. Social and policy implications

Adopting these practices on a larger scale could have broader socio-economic benefits. By reducing input costs and improving yields, this approach enhances food security in resource-constrained farming communities.[21] In addition, promoting the use of locally available organic amendments supports circular economy principles, where agricultural waste is repurposed as a valuable resource. Policymakers can play a crucial role in facilitating the adoption of such sustainable practices. Providing subsidies for natural phosphate, training programs for composting organic waste, and establishing market incentives for sustainably grown produce can accelerate the transition toward environmentally and economically viable farming systems.[55]

3.4.4. Broader relevance for SDGs

The integration of quail manure and natural phosphate fertilizers in this study aligns closely with global efforts to achieve sustainable agricultural practices and addresses multiple United Nations SDGs. The results demonstrate how locally available, low-cost resources can transform marginal soils into productive farmland, contributing to environmental sustainability, economic resilience, and food security in tropical regions.

One of the primary contributions of this research is to SDG 2 (Zero Hunger), which aims to end hunger and promote sustainable agricultural practices. By improving the productivity of long bean cultivation on podzolic soils, this study provides a scalable model for enhancing food production in regions with limited agricultural potential. The significant increases in pod length, number of pods per plant, and pod weight per plant observed under the P2R2 treatment suggest that integrating organic and natural fertilizers can optimize yields without relying on costly synthetic inputs. This is particularly crucial for smallholder farmers, who constitute over 80% of the world's agricultural producers and often lack access to advanced farming technologies.[56] By enabling these farmers to increase their productivity sustainably, this approach directly supports efforts to achieve food security and improve nutrition.

Furthermore, the environmental benefits of this study align with SDG 12 (Responsible Consumption and Production), which focuses on sustainable management of natural resources and reducing waste. The use of quail manure as an organic amendment exemplifies the principles of a circular economy, where agricultural waste is repurposed as a valuable resource for soil enrichment. This reduces the need for synthetic fertilizers, which are associated with significant environmental costs, including greenhouse gas emissions during production and nutrient runoff during application.[6,7] Similarly, natural phosphate provides a slow-release source of phosphorus, minimizing the risk of nutrient leaching into water bodies and reducing the environmental footprint of agriculture.[6] These practices demonstrate how agricultural systems can be designed to balance productivity with environmental stewardship.

This study also contributes to SDG 13 (Climate Action), which emphasizes the need to mitigate climate change and its impacts. By reducing reliance on synthetic fertilizers, which are energy-intensive to produce, the integrated approach explored in this research lowers the carbon footprint of farming systems. Organic amendments like quail manure not only enhance soil fertility but also sequester carbon, helping to offset greenhouse gas emissions. Improved soil structure and organic matter content reduce erosion and increase water retention, making agricultural systems more resilient to climate variability and extreme weather events.[57] These benefits are particularly important in tropical regions, where the impacts of climate change are expected to be severe.

The economic implications of this research further strengthen its relevance to the SDGs. By utilizing locally available resources such as quail manure, farmers can reduce input costs and improve their profitability, contributing to economic resilience and poverty alleviation.[21,54] The significant increases in yield observed in this study translate directly into higher revenues for farmers, enabling them to invest in education, healthcare, and community development. These outcomes align with the broader objectives of sustainable development, which aim to create inclusive and equitable growth opportunities while preserving natural resources for future generations.[21]

In addition to addressing these specific goals, this study demonstrates the interconnectedness of the SDGs. Sustainable agricultural practices, as explored in this research, create ripple effects that impact multiple aspects of development, from improved livelihoods and food security to environmental protection and climate resilience.[21] By focusing on the integration of organic and natural fertilizers, this study highlights a pathway for achieving these interrelated goals through innovative yet practical solutions tailored to local contexts.

4. Conclusion

This study demonstrated that integrating quail manure and natural phosphate fertilizers significantly improved soil fertility, crop growth, and yield of long beans on marginal podzolic soils. The P2R2 treatment (3 kg quail manure per plot and 25 g natural phosphate per plant) resulted in the shortest days to flowering (27.00 days), largest stem diameter (0.86 cm), highest number of pods per plant (36.66), and greatest pod weight per plant (2850.66 g). These findings highlight the potential of organic and natural amendments to mitigate soil acidity, enhance phosphorus availability, and sustainably increase crop productivity. The application of this integrated fertilization strategy has practical implications for field-scale implementation, particularly in tropical regions with nutrient-deficient soils. Strategies for large-scale adoption should focus on optimizing application rates, assessing cost-effectiveness, and ensuring long-term soil health benefits. In addition, this approach aligns with global sustainability goals, contributing to SDG 2 (Zero Hunger) by enhancing food production, SDG 12 (Responsible Consumption and Production) by reducing reliance on synthetic fertilizers, and SDG 13 (Climate Action) by promoting organic soil management practices. Future research should focus on long-term field

trials to evaluate the sustainability and scalability of these treatments under real farming conditions. Investigating their effects on soil biodiversity, microbial dynamics, and soil structural stability will provide further insights into their role in maintaining agricultural productivity and ecosystem resilience. Expanding this research across different crop species and agroecological zones will be essential for broadening its applicability and maximizing its impact on sustainable agriculture.

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Conflict of interest

The authors declare that they have no competing interests.

Author contributions

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Ethics approval and consent to participate

The research was conducted in accordance with ethical guidelines, and no human or animal subjects were involved in the study.

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Availability of data

Data are available from the corresponding author upon reasonable request.

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ACCSCIENCE PUBLISHING

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ORIGINAL RESEARCH ARTICLE

Industrial development and benefit sharing of mountain agriculture: The Tartary buckwheat (*Fagopyrum tataricum* Gaertn.) industry in Southwest China

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Abstract

In the context of corporate-led agricultural industrialization, the agricultural systems in the mountainous areas of Southwest China are undergoing significant transformations, profoundly impacting the local agroecological environment and farmers' livelihoods. This study aims to investigate how the "company + farmer" model influences the cultivation of buckwheat in the Liangshan Yi region in Southwest China. The study hypothesizes that while this model provides market opportunities for farmers, it also marginalizes them from equitably benefiting from industrial growth, leading to the abandonment of traditional crop production and negative impacts on the local agroecological environment and food culture. Drawing on anthropological fieldwork, this study gathers qualitative data from participant observation and interviews to analyze the socioeconomic and ecological implications of these changes. The findings revealed that the push for agricultural industrialization has resulted in the replacement of traditional food crops, including buckwheat, with cash crops, fostering a monoculture system that undermines biodiversity and local food security. The study concludes that future rural development efforts must prioritize the cultural and ecological roles of traditional farming communities and promote a farmer-centered, diversified agricultural production system.

Keywords: Mountainous agriculture landscapes; Agricultural industrialization; Food culture; Food security

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1. Introduction

In the era of globalization and market-oriented reform, Chinese agriculture is undergoing a profound transformation. The transfer of land use rights has led to the rapid emergence of new agricultural business entities, including agricultural leading enterprises, large-scale professional farming households, farmers' cooperatives, and family farms. These changes are reshaping the traditional smallholder-dominated agricultural landscape. At the same time, the growing commercialization and industrialization of agriculture are altering cropping patterns in many rural areas, with cash crops gradually replacing traditional food crops. As a result, the agricultural production system in the mountainous highland of Southwest China is undergoing fundamental changes, which

have far-reaching implications for both the local ecological environment and farmers' livelihoods.

The "company + farmer" model has emerged as the dominant production system driving agricultural industrialization in China. According to statistics from China's Ministry of Agriculture and Rural Development (MARD), by the end of 2020, more than 90,000 leading enterprises had been recognized by authorities responsible for agricultural industrialization at the county level or above.[1]

Policymakers argue that supporting these "dragon-headed" enterprises can provide capital, technology, and market access, effectively integrating decentralized agricultural production with processing and marketing. This integration is expected to increase farmers' incomes and boost the agricultural economy.

Scholars have varying perspectives on the corporate-led industrialization model. Proponents of mainstream economics argue that it promotes agricultural modernization, fostering a mutually beneficial relationship between enterprises and farmers.[1] Conversely, political economists critique this model, viewing it as the articulation of capitalist and non-capitalist production. They argue that while capitalist production secures the labor and raw materials necessary for accumulation, family farming faces structural constraints that lead to stagnation.[2,3] Other scholars highlight that corporate-led industrial development projects often result in land grabbing, the erosion of traditional values, and growing internal divisions within local communities, ultimately undermining farmers' livelihoods.[4-8]

Despite these critiques, there is limited literature evaluating the impacts of corporate-led agricultural development projects from the perspectives of biodiversity and sustainable agricultural development. This study aims to fill this gap by examining the transformation of buckwheat cultivation in the Liangshan Yi region, focusing on the socioeconomic and ecological implications of corporate-led agricultural industrialization.

The study focuses on buckwheat, a traditional crop with significant cultural, ecological, and nutritional value for the Yi people in Southwest China. Buckwheat is deeply embedded in the cultural practices and dietary traditions of the Yi community, serving not only as a staple food but also as a symbol of their agricultural heritage.[9] Ecologically, buckwheat is a resilient herbaceous plant in the Polygonaceae family, with two cultivated species: Common buckwheat (*Fagopyrum esculentum* Moench.) and Tartary buckwheat (*Fagopyrum tataricum* Gaertn.). Research has reported that Southwest China is the original region for cultivated buckwheat.[10,11] After thousands of years of cultivation and spread, buckwheat is now widely cultivated globally.[12,13] While common buckwheat is cultivated worldwide, Tartary buckwheat is concentrated in the Himalayan region, particularly in Southwest China.[14,15]

Buckwheat is a crop with a relatively short growing season that thrives in a variety of environmental conditions. Studies indicate that growing buckwheat can improve soil health and quality,[16,17] making it an ideal choice for organic and agroecological farming. Beyond its environmental benefits, this crop has attracted considerable interest from researchers due to its rich nutritional and medicinal value.[18-21]

Although buckwheat cultivation has a long history in China and remains an important staple crop for farmers in the mountainous regions of Southwest China, it has not received sufficient attention due to its low yield. However, increasing commercialization in China's rural areas has highlighted the value of buckwheat as a functional food ingredient, attracting significant investments from food companies in China over the past decade. Along with this trend, consumer demand for buckwheat-based products, such as noodles, flour, tea, wine, and other health products, has also been increasing.[22]

Despite growing demand for healthy foods, buckwheat production is facing increasing challenges. Researchers indicate that buckwheat cultivation is declining in the Yunnan Province due to reduced land, labor shortages, and changes in the living environment and dietary habits.[23] However, existing studies have mainly focused on sociocultural and policy factors.

This study seeks to address the following research questions:

(i) How does the corporate-led "company + farmer" model influence the cultivation of traditional crops, particularly buckwheat, in the Liangshan Yi region?
(ii) What are the socioeconomic and ecological implications of these changes for local farmers and the agroecosystem?
(iii) How can future rural development efforts balance agricultural industrialization with the preservation of traditional farming practices and biodiversity?

The research hypothesizes that while the "company + farmer" model provides market opportunities, it also marginalizes local farmers from equitably benefiting

[1] For details, please refer to: "Report on the Implementation of the National Economic and Social Development Plan for 2023 and the Draft National Economic and Social Development Plan for 2024," Xinhua. 2024-03-13. https://www.gov.cn/yaowen/liebiao/202403/content_6939276.htm

from industrial growth, leading to the abandonment of traditional crop production and negative impacts on local agroecosystems and food culture. By analyzing the transformation of buckwheat production methods, this study aims to provide insights into the broader impacts of corporate-led agricultural industrialization on traditional farming systems, biodiversity, and rural livelihoods.

2. Methods

This study employed a qualitative research approach. Data were collected through anthropological fieldwork conducted between 2010 and 2016, including participant observation and semi-structured interviews with farmers, enterprises, traders, and government agencies in Xichang, Zhaojue, Butao, Meigu, and Yanyuan in Sichuan Province, as well as Kunming and Ninglang in Yunnan Province. To gather the most up-to-date information, tracking surveys were conducted in the region over the past 2 years, 2023-2024. These surveys involved WeChat exchanges with previous respondents, follow-up phone calls, and the collection of publicly available data from online media.

3. Results and discussion

3.1. Traditional mountain agricultural systems in the Liangshan Yi region

The Greater Liangshan Yi Autonomous Prefecture (*Da Liangshan Yizu Zizhi Zhou*) and the Lesser Liangshan Yi Autonomous Prefecture (*Xiao Liangshan Yizu Zizhi Zhou*) are the main settlements of the Liangshan Yi people (autonym: *Nuosu*). These regions straddle the border between southern Sichuan and northern Yunnan, forming a transition zone between the Qinghai-Tibetan Plateau and Yunnan-Guizhou Plateau. Characterized by a mountain landscape of high hilly plateaus, they are located in a biodiversity hotspot[24,25] and are considered the earliest domestication areas of Tartary buckwheat.[26] Most *Nuosu* communities are found between 2,000 to 3,000 m above sea level, and their traditional livelihoods rely on a combination of dryland farming and livestock husbandry.

Our visit to the Lesser Liangshan Yi Autonomous Prefecture in the winter of 2011 revealed a landscape of high mountains and deep ravines, with solitary villages nestled among thick forests. On the slopes near the villages were banks of loess fields cleared by hand. In early spring, these fields would be planted with the region's staple grain crop, Tartary buckwheat (*F. tataricum* Gaertn.). Locals call buckwheat "*qiaozi*" in Chinese and "*mgep*" in their own Yi language. Resilient to cold, drought, and poor soils, buckwheat is one of the few grain crops capable of adapting to the region's alpine mountain environment. Alongside potatoes and maize introduced during the Qing dynasty, buckwheat remains one of the three major crops of the Liangshan Yi region today.[27] In high mountainous areas, buckwheat is rotated with potatoes and barley, while on the middle slopes, it is rotated with potatoes and maize.[21] In 1943, Lin Yaohua led a research team into the Liangshan hinterland and documented the local buckwheat production method known as "fire-fallow" in his book.[28;58] This mode of farming involved burning mountain areas to fertilize the land and sowing crops without a structured plan. It was later reformed by the government.

Before the democratic reforms of 1956, the Liangshan Yi society was primarily ruled by separate polities of the Black Yi clans. These clans maintained a strict caste order based on bloodline using clan organizations and customary laws[2]. Clans are considered to be groups with ties of kinship in the paternal line based on a belief in a common ancestor. Agricultural production was mainly carried out on a family-run basis. After the democratic reforms, agricultural production was instead organized and managed by rural collective bodies, such as the production brigades and people's communes.

According to the recollections of some elders, during the collective economy period from the 1960s to1970s, a 2-year cropping system with three harvests was practiced in the area. Spring crops were potatoes and buckwheat; winter crops were wheat and oats. After harvesting wheat in May of the 2nd year, farmers would plant a summer crop of broad beans since it was too late to plant spring crops. Compared to one-season cropping, this three-harvest, 2-year system not only increased annual farming income but also reduced losses from natural hazards through diversification. In addition, this cropping system regulated soil nutrients and contributed to biodiversity conservation.

In the 1980s, as part of market-oriented reforms, the collective economy of China's rural areas was dismantled. Instead, the family contract responsibility system for rural land was introduced, and the land was redistributed to individual peasant families. Consequently, China's agricultural production shifted to a decentralized smallholder model.

In 2013, fieldwork was conducted in Zhipu village, located in the Liangshan Yi region. This village is situated on flat land among the mountains at an altitude of over 2,600 m. The village has a total area of farmland of 4,016 *mu* (268 ha) and a population of 706 people in 213

[2] There were five castes: *zimo*, *nuohe*, *qunuo*, *ajia* and *xiaxi*. The *zimo* was the caste of headmen who dealt with the central Chinese government, known as *tusi* in Chinese. The *nuohe* were the Black Yi. The other three castes were all linked to the *zimo* and Black Yi in terms of personal bondage.[29;65-72]

households. After the distribution of land use rights to rural households, the original 2-year, three-harvest farming system in Lamo village could no longer be sustained, and wheat farming was gradually abandoned. This was due to the inability to address the irrigation issues that arose with the land division, as wheat requires irrigation. Some families' land was located far from the irrigation canals, making it impossible for them to irrigate, leading to the abandonment of wheat cultivation. Even those living near the canals might give up growing wheat because households upstream no longer cultivated wheat and, as a result, did not release water for irrigation. Consequently, the canals were no longer repaired and quickly became clogged and damaged. In reality, individual household farming, which was limited in terms of capital, labor, technology, and land, led to a reduction in the variety of crops grown, and even making animal husbandry impossible.

At present, the main local crops in Zhipu village are potatoes and buckwheat planted in rotation. Due to the relatively high altitude, maize yields are low; thus, only a small amount is planted. Other crops include oats, turnips, green manure plants, and a limited selection of beans and vegetables. There was only one season for planting the main food crops. Potatoes are planted by the end of March, followed by buckwheat in April. Farmers grow various buckwheat varieties in different regions, drawing on their experience and traditional knowledge to adapt to the soil conditions at different altitudes.[9]

On the day of cultivation, the villagers would perform a purification ceremony of their plowing tools and seeds early in the morning (*erchasu*),[9] hoping for a good harvest and to protect the crops from damage by hailstorms or pests. Their greatest concern is sudden hailstorms that occur just as the buckwheat is nearly ripe, which can knock all the wheat ears to the ground, or strong winds that flatten crops. *Erchasu* is a traditional ceremony of purification across the Liangshan Yi region. On that day, nine stones are placed in a fire until they glow red hot. Special plants are then placed on the stones, and the seeds and agricultural implements are passed through the smoke. This ritual is believed to dispel anything unclean and ensure a good harvest.

Throughout the cultivation period, villagers assist each other with their relatives and collaterals. Single-family plowing is inefficient, making it difficult to handle the rush of work during harvest and planting seasons. Working alone as a family makes it difficult to complete the intensive tasks required at these times. Typically, men lead the plow, guiding it and encouraging the ox, while women follow behind, planting seeds into the furrow and applying phosphate and homemade fertilizers. As the plow begins to cut the second furrow, the turned soil covers the seeds in the first furrow. In recent years, some families have begun to use small tilling machines that are slightly more efficient. After the dissolution of rural collective economic organizations, this family-based agricultural production—where labor is divided among family members and small-scale cooperation occurs within the community—has become the primary form of local agricultural production.

In traditional agricultural systems, local social organization and cultural practices—such as production management knowledge, cooperation among community members, cultural customs, religious rituals, and food habits—are essential for sustaining agricultural production and ecological development. For example, based on the local classification of buckwheat and religious taboos, people use different varieties of buckwheat for different ceremonial occasions,[21] which has contributed positively to the conservation of buckwheat diversity.

Consequently, the cultivation of buckwheat, a traditional crop, plays an important role in strengthening community cooperation and solidarity. Buckwheat has been both a vital food source for the Liangshan Yi region and a ritual significance in the Yi society (rich in cultural associations and an important cultural status). During the study, local scholar Dr. Jiarimuji mentioned that buckwheat was intrinsically embedded in the lives of the Yi people, supporting them materially and spiritually in every stage of life, from birth to death. Hence, researching buckwheat can serve as an entry point to understanding the development of the political economy, society, and culture of Yi society. Buckwheat is used for a variety of religious ceremonies and social occasions, granting it a transmittable soul and high status. Its cultural status is reflected in the local proverb: "Many people, the mother of man is great; crop varieties, crop buckwheat is great." In the local society, buckwheat symbolizes honor, security, fertility, and abundance. Whether it is an important event in an individual's life cycle or a major social event, buckwheat plays an integral role, including childbirth, the naming of newborns, the dress-changing ceremonies for girls (mitzvahs), weddings, funerals, ancestor worship, farming, hunting, traveling, festivals, hospitality, and making vows.[21] This significance is also reflected in the local saying: "Buckwheat for ancestor worship, buckwheat for hospitality."

In summary, production rooted in community cooperation and diversification is vital for sustaining agricultural production and supporting farmers' livelihoods. However, over the past decade, the farming system in the southwestern mountains has undergone significant transformation due to land transfers and the industrialization of agriculture.

3.2. Industrialization of mountain agricultural resources and the social and environmental impacts

Since the 21st century, buckwheat products have entered urban markets, with their high nutritional value and health benefits favored by green food consumers. The growth of the buckwheat industry became even more apparent after 2008. Within a few years, a large number of buckwheat specialty stores, specializing in the sale of buckwheat tea, appeared in cities across Southwest China, such as Xichang, Chengdu, and Kunming, and the market rapidly expanded to supermarkets in major cities across the nation. The health benefits of buckwheat tea were promoted online: "high rutin content" and good at reducing the three "highs" (high blood sugar, high blood pressure, and high cholesterol). Emphasis was placed on the environment in which buckwheat is grown: "grown at high altitude in a mountain region" and "a green product with no pollutants." This undoubtedly resonated with the present demand for safe food, leading to high sales of buckwheat tea. The buckwheat industry boomed and became a major local agricultural enterprise. This practice of using the cultural reinvention of local products to promote local economic development is not uncommon throughout the country and has even become a common development model. An example is the crayfish industry in Xuyi, Jiangsu Province, which can be regarded as a classic case where the local government stimulated the growth of lobster consumption by striving to create a lobster culture as a means of boosting the development of the local tourism industry and rural economy.[30]

The local government resolved to promote Liangshan as the "Hometown of Buckwheat." Under the supervision of the County Agricultural Bureau, a Buckwheat Association composed of various enterprises was established to assist enterprises in promoting their products and expanding their markets. This initiative aimed to drive the scaling, standardization, and development of the entire buckwheat industry. Similar to most agricultural development projects nationwide, the tartary buckwheat industry has adopted the "company + farmer" industrialization model. By directing support funds toward leading large enterprises, the government aims to leverage the scale effects and technological advantages of these companies to encourage surrounding farmers to participate in cultivation, ultimately increasing their income.

Tartary buckwheat enterprises rely on high-quality raw materials provided by farmers to develop a diverse range of products, such as Tartary buckwheat wine, tea, and noodles, which have been registered as national geographical indication products. In addition to deep processing of Tartary buckwheat products, these enterprises also make full use of the region's unique ethnic culture and ecological resources to develop ethnic tourism and eco-wellness industries.

In market research conducted in Kunming and Xichang in 2013,[31] a 450-g box of high-grade buckwheat tea cost nearly 1,000 yuan in a specialist buckwheat tea store, while medium- and low-grade teas cost between a hundred and several hundred yuan. During the peak tourist season, some of the stores made monthly profits of more than 100,000 yuan. As competition in the industry intensified, the price of buckwheat products declined accordingly. Despite these changes, the retail price of 450 g of buckwheat tea ranged from tens to several hundred yuan in 2015. The distinction between high- and low-end products is primarily based on packaging quality and rutin content. Black buckwheat, which grows at higher altitudes and yields less, is said to have the highest rutin content. However, unprocessed buckwheat that companies purchase from traders is often a mixture of different varieties; separating these variations is either impractical or too costly, making it impossible to process small quantities of black buckwheat separately. As a result, terms such as "black buckwheat tea" and other similar buckwheat products are often used as marketing strategies by companies to add value. For farmers in most areas, the purchase price of black buckwheat and other varieties remains the same. For companies, buckwheat is a small part of their production costs. The significant price difference between low-cost commodities and expensive "green health products" is generating substantial profits for companies and attracting a growing number of investors to the industry.

In Xichang, Tartary buckwheat tea and the Yi Torch Festival together form the core elements of the original Yi culture, making them a major attraction for local tourism. The Tartary Buckwheat Cultural Park, operated by a food enterprise, attracts a steady stream of visitors every day. The park not only showcases the history of buckwheat cultivation and processing techniques but also incorporates traditional Yi cultural performances, allowing visitors to savor tartary buckwheat delicacies while gaining a deeper understanding of the unique charm of Yi culture. Display cabinets in the cultural park exhibit a variety of local buckwheat seeds, neatly arranged by type. Each variety is labeled with its local Yi name, and some also include scientific name abbreviations and serial numbers. The exhibition strives to convey to visitors that local plant varieties and traditional knowledge are rich and diverse, the natural environment is exceptional, and the enterprise is well-equipped with the intelligence and capabilities to develop and utilize these resources scientifically. As a result, the company operates in an

ethical, responsible, and qualified manner, making it well-suited for scientific development. Hence, consumers can fully trust the company to provide high-quality health products. In this context, native knowledge of plant species, customs, traditions, and religious ceremonies are valued and respected, framed as potential solutions for the crisis of modernity. This approach adds value to buckwheat products, ultimately helping the enterprise above-average profits in the food products market.

However, most Yi farmers find it difficult to benefit from these development projects. The buckwheat industry is disconnected from villagers' lives, even though they supply the raw materials and are the original creators/practitioners of this cultural resource. As the processing and market linkages are controlled by corporations, farmers can only derive labor income from the crop. For example, the yield of bitter buckwheat is extremely low, typically 100 – 150 kg/acre of land, while the market price is 3 – 4 yuan/kg[3]. Cost accounting revealed that this price could not even cover the cultivation costs[4].[31] In addition, farmers have to face natural and market risks. In fact, farm income typically covers only basic food and clothing needs, making it difficult to meet the broader reproductive needs of a modern family, such as education, healthcare, and elder care. As a result, young and middle-aged farmers are forced to seek alternative employment opportunities. Unfortunately, urban migrant workers also often face unfair treatment in the labor market.[32]

The issue of fair distribution within local communities directly affects the sustainable development of the bitter buckwheat industry. As a large number of farmers migrate for work, the shortage of local agricultural labor has become more pronounced, resulting in the abandonment of bitter buckwheat in many villages. This affects the stability of the bitter buckwheat raw material supply and hinders the further expansion of leading bitter buckwheat enterprises. Enterprises complain that the supply of raw materials is tight, forcing them to compete fiercely to purchase unprocessed buckwheat. We can observe this situation in the following news report about the buckwheat tea industry: "Consumers love it; farmers won't plant it; investors build lots of plants; lack of raw material base areas to supply them. Annual production is high but enterprises struggle to buy in."[33] In fact, the question of who will farm has become an urgent issue for China.

Labor shortage and the advancement of agricultural industrialization have also had a profound impact on the local ecological environment. The traditional circular agroecosystem is becoming unsustainable as more farmers are forced to give up animal husbandry due to reduced family labor. Some families are even reducing the amount of land they farm. The decline of animal husbandry has not only diminished sources of agricultural income but also weakened families' ability to manage risks, making it harder to maintain a healthy ecological cycle in farming.

In the past, soil fertility largely depended on homemade fertilizers made from a mixture of fermented sheep and pig manure, buckwheat straw, pine needles, and oak leaves. At present, farmers increasingly rely on chemical fertilizers. For instance, in maca cultivation[5], high costs of seed led farmers to use excessive fertilizers and pesticides to ensure high yields, while neglecting crop rotation and fallow periods. This practice has detrimental effects on the local environment, including loss of agricultural biodiversity, deforestation, soil compaction, and contamination of agricultural plastics.

With the nationwide promotion of genetically modified crops, such as maize and soybeans, agricultural biodiversity is likely to decline even further. In addition, many traditional seeds have been patented by large agribusiness companies through biotechnological interventions, resulting in farmers losing their rights to these seeds.

Commercial cultivation not only impacts the local ecosystem but also threatens the sustainability of local culture and food systems. As traditional crops, such as buckwheat and oats, are increasingly replaced by cash crops, people are gradually adopting a rice-based diet and becoming more reliant on the food market, consequently altering their lifestyles and cultural values. Moreover, the volatility of cash crop prices has led to more speculative cultivation decisions among farmers, increasing the precariousness of their livelihoods and altering their perceptions of wealth accumulation through hard work.

4. Conclusion

In the process of enterprise-led agricultural modernization, the agricultural production system in the mountainous regions of Southwest China has undergone a profound transformation. The traditional pattern of local diversified cultivation is gradually giving way to monoculture structure and non-food cultivation, as farmers shift from subsistence agriculture to commodity agriculture focused on meeting market demand. Recently, with the acceleration

[3] More specifically, according to market research,[31] from 2009 to 2013, the market price of buckwheat ranged from 2.2 to 2.8 yuan/kg. In 2014, it reached a record high of 3.4 – 3.6 yuan/kg, but declined to 2.6 – 2.8 yuan/kg in 2015.

[4] In 2012 – 2017, the local market price for rural labor was 60 – 100 yuan/day. Cultivating an acre of buckwheat requires an investment of about five labor days.

[5] A plant of South American origin that had exploded onto the Chinese market between 2011 and 2016 and became widely grown in the southwestern mountains.

of land transfer and urbanization, the trend of farmers withdrawing from agriculture is expected to continue, profoundly altering the agricultural landscape in these mountainous areas, a change that will be difficult to reverse. This shift is primarily driven by evolving socioeconomic conditions in contemporary China, including changes in production organization, land policies, labor markets, and distribution relations. Ultimately, the cultural and agricultural landscapes reflect the design of the agricultural mode of production.

In the industrialization of buckwheat tea, dragon-headed enterprises have taken center stage in the development, supported by the government. The government aims to leverage these enterprises to facilitate sales of agricultural products, allowing farmers to indirectly participate in the market and increase their income. However, while these companies benefit significantly from low-cost raw materials and the utilization of local cultural resources to achieve substantial profits in the health food market, farmers do not share in these market gains. Instead, they often receive insufficient compensation for their labor in supplying raw materials and must bear production risks on their own. This development model has failed to meet the government's objective of "bringing farmers into development." Enterprises exploit farmers' surplus labor through market exchange, leading to capital accumulation at the farmers' expense and widening the wealth gap. Although government support has alleviated some burdens on farmers through road construction and agricultural subsidies, the intention to bridge the rich-poor divide through this secondary distribution often only reinforces farmers' subordinate status.

Industrialized agriculture in the mountainous regions of Southwest China has also had a significant impact on the sustainability of the local food system, reducing the ability of local farmers to adapt to climate change and market risk, and weakening the ability of communities to self-organize. In the long run, this shift could have serious implications for agrobiodiversity and national food security. Moving forward, many scholars and social organizations should focus on utilizing and restoring the food and cultural diversity of different regions while redesigning sustainable agricultural production systems.

Agricultural heritage systems (e.g., globally important agricultural heritage systems) are considered dynamic and adaptive living systems that embody values of multifunctionality and sustainability.[34] As a result, the traditional agricultural management of indigenous crop varieties has gained increased attention worldwide for its role in sustainable agriculture. China has also made great achievements in the conservation and management of agricultural heritage systems over the past 10 years.[35] At the same time, many scholars and social actors are working to position smallholder farmers as the cornerstone of development by promoting alternative models, such as People's Food Sovereignty, Participatory Breeding, and Nested Markets.[36] However, more scholars and development programs have focused only on market-oriented industrial development and the role of traditional cultural excavation in preserving traditional farming systems, but have seldom addressed the question of who truly benefits from these development programs. This study argues that to ensure more benefits remain with local farmers, it is crucial to organize them into diversified agricultural production and use local resources to develop agro-processing industries within local communities, rather than reducing farmers to mere suppliers of raw materials to the agri-food system. In fact, the practical experience from China's collective farming period can provide valuable insights into this farmer-cooperative approach to development.

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Conflict of interest

The authors declare they have no competing interests.

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LETTER

Protecting drinking water by establishing groundwater parks

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Clean groundwater is an important drinking water source in European countries, with some of the best found in Denmark.[1] Regrettably, the global perception of drinking water safety is faltering,[2] as toxic environmental contaminants such as pesticides and fluorinated surfactants pose a threat to these sources, and action is needed across Europe to ensure clean drinking water for the generations to come.[3] Water contamination with a plethora of pesticide and xenobiotic residues is problematic for drinking water producers to tackle and has an unforeseeable impact on European public health by threatening, *e.g.*, neuro-endocrine development and the function of internal organs.[4,5]

In 2018, the EU Commission did not renew its approval of using herbicide diquat in potato production given its adverse effects on human health. Despite this ban, the Danish Environmental Protection Agency (EPA) still allowed Danish potato farmers to use diquat-containing Reglone.[6] Regrettably, it is not the first time that the Danish EPA has approved the use of banned harmful pesticides. A few years ago, Danish sugar beet growers received a similar temporary dispensation of neonicotinoids to pickle beet seeds,[7,8] while glyphosate is still used in the EU ,[9] despite their threats to biodiversity and pollinators.[10,11]

The Danish EPA has in fact granted 131 releases during 2011 – 2019, claiming they are in line with food security.[12] These exceptions are incomprehensible and disappointing, given Denmark's Blue and Green ambitions to support the EU's environmental legislation, zero pollution ambition, and goal of reducing the use of agricultural pesticides.[13] Denmark should stop this political praxis to support the Global Goals as a pioneering country.[14] The lawmakers and EPAs need to resist the influential agricultural lobbying organizations and do its utmost efforts to manage and protect its ecosystems and environment. Denmark and other countries should follow the inspiring move made by Austria that implements a complete ban of both diquat, neonicotinoid, and glyphosate to ensure safe food production in the EU as a whole.[9,10]

In addition to pollution, global warming further worsens the situation as it runs global groundwater wells dry, threatening water security, and making 3 billion people lose their water supplies within 30 years.[15-17] To ensure clean groundwater for future generations, groundwater parks established across Europe (and other relevant regions worldwide) may be a good solution. This implies that these key areas are protected from the application of pesticides and nutritious sewage sludge, which pollute drinking water as they seep down through the soil and into water wells.[18] Aside from keeping the groundwater clean, new wetlands help to mitigate global warming while supporting the EU's Biodiversity Strategy for 2030 due to their more protected nature.[19,20]

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In addition to groundwater parks, the United Nations Educational, Scientific and Cultural Organization (UNESCO's) Internationally Shared Aquifer Resources Management should seek to add the world's largest *aquifers* including the US Ogallala to the UNESCO World Heritage List to protect groundwater from pollution and deterioration. Otherwise, the current situation would pose a significant challenge for Global Goals #3 Good Health and Well-being, and #6 Clean Water and Sanitation, thereby threatening sustainability, peace, and planetary health.[21-26]

Conflict of interest

The authors declared that they have no competing interests.

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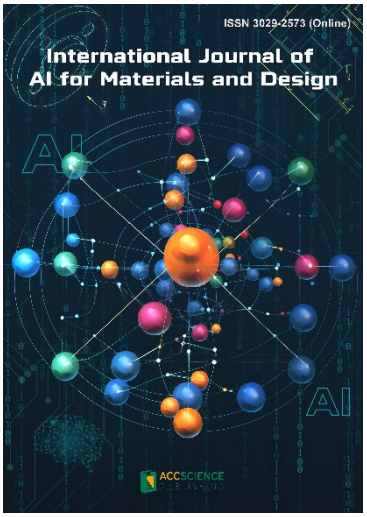

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