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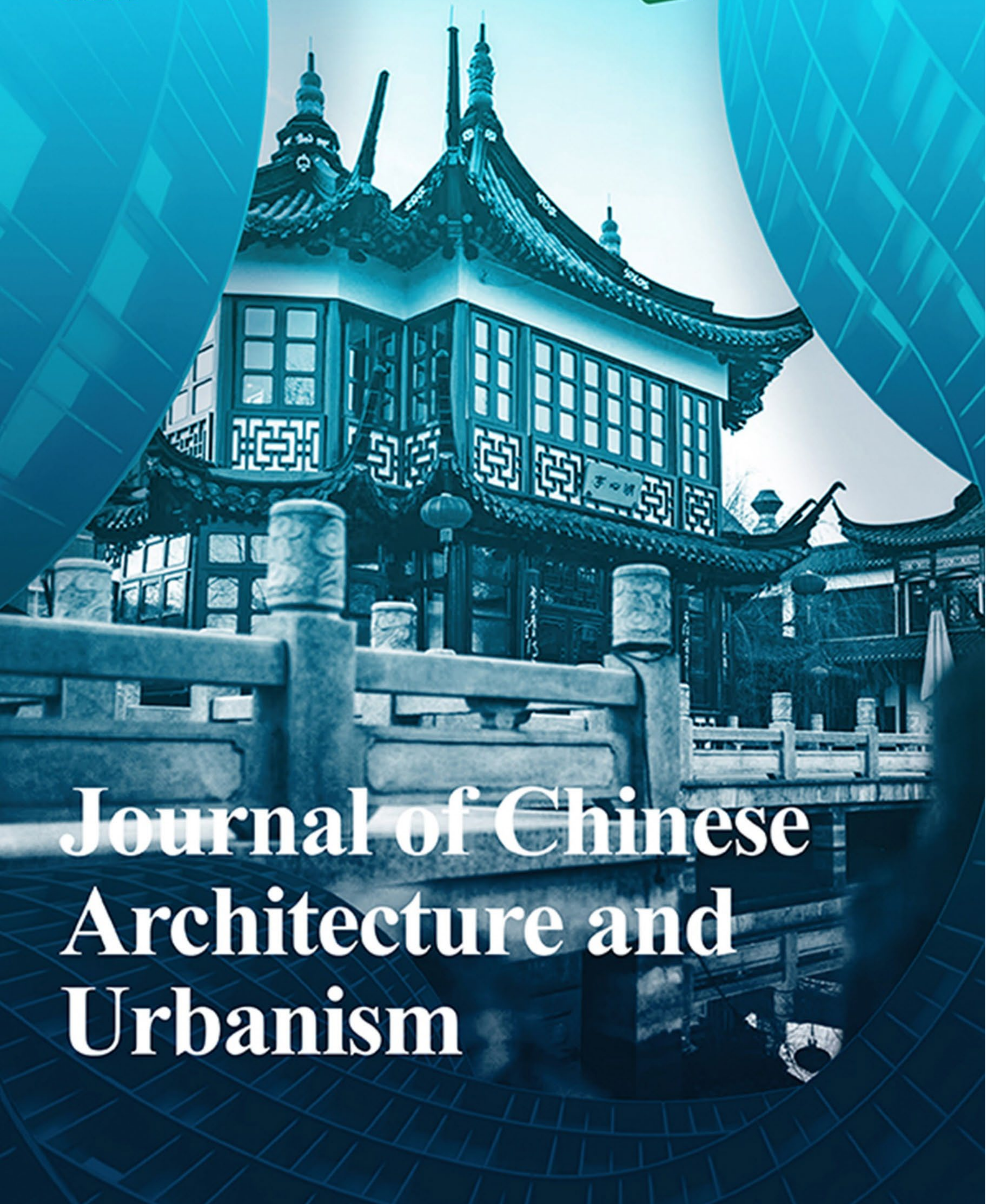

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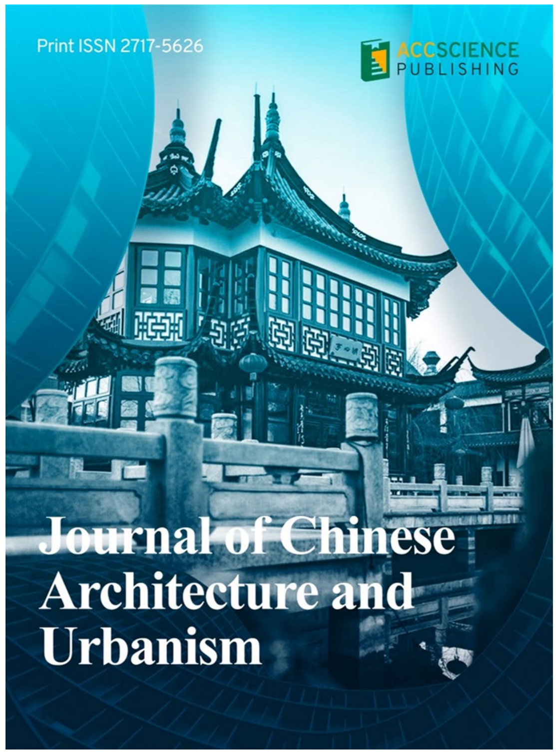


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A typical Chinese-styled building

# Journal of Chinese Architecture and Urbanism

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Journal of Chinese Architecture and Urbanism

REVIEW ARTICLE

# Gestures for interdependence: Expanding regenerative design through spatial dramaturgies for the unseen, the unheard, and the unfelt

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(This article belongs to the *Special Issue: Regenerative Architecture*)

## Abstract

The reality of the Anthropocene performs on us through various *esthetic spatial experiences*. To undo the consequences of modernity, spatial designers are moving toward a regenerative (restorative and non-extractivist) way of *thinking, doing, and being*. Situated in the growing field of spatial dramaturgy, this article focuses on how esthetic experience can contribute to attitudes toward regenerative spatial design through collaborations with more-than-human entities. If spatial design moves towards a pluriversality based on relationships of interdependence, how can spatial design generate esthetic experiences of regeneration accordingly? How do we design experiences of interdependence? In this paper, we discuss the experimental practice of the TAAT arts collective, a transdisciplinary practice aimed at developing performative installations. The fieldwork (situated in Lithuania and the Netherlands) covers processes in which rivers — as more-than-human entities — are taking up a leading role as cocreators. In every location, the spatial dramaturgical development is based on methods of embodied experiences, scoring, cocreation, and written reflections. These methods are implemented to prototype "gestures of interdependence". We will treat these as design gestures (attitudes and approaches) aimed at foregrounding unseen places (sites of extraction and exploitation) and unheard bodies (more-than-human entities that are silenced) in the field of regenerative spatial design. By revealing the agency of the unseen and the unheard in spatial design processes, we will broaden our understanding of "designing the unfelt". In conclusion, a design score will summarize our findings. This score can be implemented in spatial design practices (ranging from scenography, installation art, architecture, and social practice) focused on generating embodied esthetic experiences of regeneration.

***Keywords:*** Anthropocene; Situated knowledge; More-than-human entities; Relationality; Presencing; Performance

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***Note to the readers:*** *The author of the following text is speaking as an assemblage of partial perspectives meandering between an academic/universal "we", the "we" as part of a group of fieldwork participants, the "I" as a researcher, the "I" as a participant, and the imaginary "you" as a reader.*

## 1. Introduction

The field of regenerative spatial design sometimes seems to limit itself to concerns of biotechnological performance or the measurement of a building's carbon footprint. The starting point for this paper is the incorporation of practices that are concerned with how we relate ontologically to more-than-human entities — formerly known as *resources*. Through prototyping a series of performative experiments, this paper aims to expand the spatial designer's metaphorical toolbox from an efficiency-driven and human-centered design position toward an embodied design attitude. We are exploring how an engagement with rivers (as more-than-human entities that bridge site, place and space) can help spatial designers to regenerate their *thinking-being-doing* from a position of impermeability to an attitude of fluidity. New modes of cocreation are explored through a series of sensorial experiments, resulting in a performative script: A hands-on tool (the so-called "score") that aims to further nurture the field of regenerative design through collaborative, experiential, and embodied learning.

## 2. Spatial aesthetics of the unfelt

### 2.1. From a drain to a fountain

The reality of environmental and societal change performs on us through various *aesthetic spatial experiences*. The ontological turn (Escobar, 2018) rooted in humanities and the arts have been increasingly influencing the discourse on spatial design in the demand for a reconfiguration of how spatial design frameworks create regenerative[1] and relational ways of doing, thinking, and being (Escobar, 2018) instead of conforming the extractive and individualist approach installed by modernity. Sequentially, many transdisciplinary[2] practitioners in arts and design are exploring a transformation of the dominant design frameworks (colonial, neoliberal, exploitative, and binary) by generating provocative and innovative design attitudes and, consequently, new forms of spatial esthesis[3] (Ranciere, 2013; Vasquez, 2022). Collectively, we are moving away from spaces that generate aesthetic experiences based on extraction towards spaces that instigate reparative and regenerative modes of togetherness, co-existence and relationality. On the verge of extractivism[4], we wonder how spatial design oscillates between extractive or regenerative gestures. Where do both gestures meet in our spatial experience?

In the introduction of *Arts for Living on a Damaged Planet*, Nils Bubandt reflects on the Anthropocene as the"Great Acceleration" that is "best understood through immersion in many small and situated rhythms. Big stories take their form from seemingly minor contingencies, asymmetrical encounters, and moments of indeterminacy" (Tsing *et al*., 2017). In this paper, we aim to understand these "situated rhythms and asymmetrical encounters" as an aesthetic matter. To understand better the aesthetics of extraction, we will introduce the notion of the unfelt, trying to foreground *unheard bodies* and *unseen landscapes* of extraction in relation to spatial design. We will explore this through a *dramaturgical* approach to the site (see Section 2.2). The PhD project Regenerative Spatial Dramaturgies (RSD) focuses on the experience of the unfelt in artistic practices that are site-specific, process, and space-oriented[5]. For the purpose of improving the clarity of this article, we will focus on unseen bodies of water (the sea and the river) in relation to a series of fieldwork experiments. The aim is to renegotiate our relationship with bodies of water as more-than-human entities, where our focus will be to design with them instead of designing for them or against them. To illustrate this, I would like to share the following anecdote.

In 2020, I visited the Non-extractive Architecture exhibition[6] at VAC in Venice. The exhibition was by far one

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1 Using the term regeneration, we aim to expand it beyond neoliberal processes of landscape and city development. We use it to indicate processes of renewal and restoration of our relationality with more-than-human entities and biological systems. The term invites us to think of spatial design as designing-with-living entities as opposed to the dominance of the extractive and exploitative systems of late capitalism.

2 A form of disciplinarity in which procedures and esthetic features of different disciplines are merged into a new hybrid forms.

3 We understand esthesis as the subjective embodied process of esthetic experience, different from the abstract, objectifying, and distancing notion of "esthetics". The writing of Rolando Vasquez elaborates on a series of decolonial pedagogies regarding aesthesis in his essay Vistas of Modernity, 2020, Mondriaan Fund, Amsterdam (NL).

4 Extractivism is generally understood as the removal of natural resources particularly for export with minimal processing. In this paper, we expand the term toward sites and bodies that are exploited without consent for purposes within capitalist economies.

5 This paper is based on experiments in the 1st year of the PhD trajectory of Breg Horemans. Epistemologically, the larger attempt within the PhD is to make a shift from a (positivist) result based research methodology to an approach of artistic research where embodied and process based knowledge is foregrounded.

6 Grima J. and Space Caviar, *Non-extractive Architecture*, VAC, Venice (IT), March 2021-January 2022.

of my highlights of the Venice Biennale, knowing that it has not been part of the main program. Although the content of the exhibition is very relevant to the topic of this paper, I would like to direct your attention to one of the moments just before my visit: a moment of an "asymmetrical" encounter with the larger ecological environment (the island-as-city, the sea) that coconstitute Venice. When I left my hotel, I already noticed that the tide was high. The water was right at the edge of the shoreline near San Marco Square. Just a couple of meters away from the cathedral, my eye got caught by an extraordinary performance: A subtle upward flow of water was being extruded by one of the drainage grilles, resulting in a small but highly poetic little fountain. This infrastructural element — designed to evacuate and store incoming surface water — was in the process of reappropriation as a consequence of climate change. The non-intentionality of this esthetic experience touched me on a personal level. It made me wonder how I could be a better listener to the Mediterranean as a "body of water" for its unheard voice. From the perspective of a designer-as-researcher, this particular experience asked for a moment of renegotiation of a design attitude: from problem-solving (the water is rising, so let us "build a wall" around the island?[7]) to accepting the aesthetic experience of the consequences of global warming and working with its affects. But how do we raise our awareness of the esthetic qualities of climate change? And how do we welcome the rising water genuinely, making the act of listening to its unheard voice into a political gesture? Expansive questions that — in the instantaneousness of my aesthetic reality there and then — had a very down-to-earth answer: Wet feet.

As poetics and esthetics are central to this research, we will situate this paper in the growing intra-field of spatial dramaturgy, bridging performance design (Turner, 2015), installation art (Rebentisch, 2012), and architecture (Kleine, 2017). In the *actor-network*[8] between unseen places (sites of extraction and exploitation) and unheard bodies (more-than-human entities that are currently silent), spatial dramaturgy will allow us to explore relational gestures between the dichotomies of bodies/entities and places/sites. Following the work by Arturo Escobar and Sruti Bala[9], we will refer to our thinking-being-doing as a collection of design gestures. We will call them "gestures for interdependence". In this way, we aim to bridge the dichotomies installed by modernity and restore a design attitude and framework based on interdependence with sites, places, and more-than-human bodies, formerly known as resources. Our aim is to expand design gestures through staging and experiencing the unseen[10] (sites) and unheard (bodies) so that the unfelt (esthetics) can inform our design thinking, our design actions and our design "being".

Thanks to the "impromptu fountain" — and my feet getting wet — the Non-extractive Architecture exhibition questioned an ontological engagement with a site (in this case, the city-as-island we call Venice), in contrast to the comfortable "distant spectatorship" in regards to the problems of the "Great Acceleration". It made me aware of the urgency of "being with" the water and the island. Moreover, it made me aware of the possible different agencies, we can have as designers: Toward designing experiences of interdependence and reconciliation or designing slow engagement with unseen landscapes and unheard bodies. In short, this experience brought me closer to the necessity of designing the unfelt.

In Section 2.2, we will expand on the dramaturgies for the unfelt and how the fieldwork in Section 3 — all concerning "bodies of water" within the artistic practice of the TAAT collective — will help us develop new design gestures to cope with the consequences of the Anthropocene, allowing us to test the gathered gestures as design-tools for experiences of interdependence and coexistence. Our goal is to (i) understand better how spatial design can generate embodied ways of experiencing interdependence and (ii) turn these understandings into new polyphonic[11] spatial design attitudes. These findings will give us a toolset to radically[12] inform and expand ways of doing-thinking-being "ontological spatial design". As a conclusion to this paper, I will end with a *score*[13] that can be read and implemented as a performative exercise in site-specific and space-oriented artistic practices dealing with more-than-human entities. But let me first introduce you to a dramaturgical approach to spatial design.

## 2.2. Dramaturgies for the unfelt

To situate spatial dramaturgy as the main methodological approach in this research, allow me to briefly introduce my trans-disciplinary background as an *artistic practice-based researcher*. Through a series of collaborations (curatorial,

7 See also https://www.bbc.co.uk/news/world-europe-53361958.

8 Actor-network theory (ANT) is introduced by a.o. Latour, B. (2015).

9 Sruti, B., *Gestures of Participatory Art*, 2018, Manchester University Press (UK).

10 See also Marisol de la Cadena's work on the Anthropo-Not-Seen.

11 See Escobar, a way of designing in which different voices co-lead design processes instead of one dominant voice

12 Radical from the Latin word *radix* ('root'), not intending to break down dogma's and install new ones, but going to the root of design practices that generate design gestures focusing on grounding, rooting and therefor also interdepence.

13 A script that generate embodied action, in our case for workshops and experiments concerning groups of designers

scenographic, and installation), I discovered that a dramaturgical approach to the development of spatial experience was at the core of many of my professional intra-actions. Spatial dramaturgy is both the intra-field I move through and a set of methodologies I work with. The exploration of performative processes in relation to or with spatial design informed my attitude as a designer in "how to do things with space"[14] *performatively*[15]. Spatial dramaturgy allowed me to *queer* my own position and identity from the image of the heroic architect infused by modernity from somebody that is future-oriented, forgetting the now, to somebody that is now-oriented and sensitive to both past and future. In several artistic projects, I started taking up the role of spatial dramaturg, moving nomadically between different roles and esthetic frameworks and regimes.

The work that I've been doing as part of the TAAT collective (since 2012) focused on the development of performative installations — the earlier work was mostly wood — that have been evolving into growing architectures since 2020. The practice has been the backbone of my doing-thinking-being as a spatial dramaturg. Notions of theatricality and performance in regard to an ontological spatial design were always at the core of TAAT's thinking and prototyping processes, indicating a deep relation between performance and architecture but also opening up the role of the architect/designer as somebody who facilitates choreography, generates spatial aesthetic experience, "holds the space" and guides others through the processes of personal transformation maybe even offering a sense of existential safety[16]. During my year at a.pass[17] in Brussels, I once described TAAT as follows: "[…] TAAT is the institution I work through and pass through myself. An institution that is the same as the architecture that it produces. A vehicle, a temporary construction, through which Others can wander. And at the same time, a portable and shareable structure. A tender institution, maybe."[18] Consequently, spatial dramaturgy encompasses both making and holding space. It functions as both an intra-disciplinary field and methodology, serving as a collective practice that combines doing-thinking-being while also providing a personal way of meaning-making. In general, the methods used in the PhD study concern (i) cocreation through collective scoring and prototyping, (ii) diffraction as reflection through reading-writing, and (iii) drawing as an epistemic space.

To revisit the etymological roots of the word "dramaturgy", we have to go back to Old Greece. The meaning of the word *dramatourgia* lies in the combination of the words *drama* (meaning *a composition presenting in dialogue a course of human action or the description of a story converted into the action of a play)* and-*ourgia* (meaning a working activity). Dramaturgy refers to "the work that needs to be done on the composition and development of dialogical human actions and stories". Alberto Perez-Gomez refers to the role of the architect in Greek drama as "the one who leads others into action"[19], shifting the role from a modernity-infused "master builder" toward what Carlo Ratti calls an "architect-curator"[20]: somebody that regulates relationships between top-down and bottom-up agents in a design process.

Through collaborations with artists from different fields, a shift in my personal understanding of the role of the architect or spatial designer took place and opened up a multitude of possible attitudes and roles that I decided to explore. As these development processes were always prototypes and dialogue-based, they foregrounded spatial experience as the main directive for collective decision-making. This resulted in a radical hands-on approach enabling bodies, objects, materials, and spaces to work and act together. The spatial dramaturgical question we try to answer is then: How can we, as spatial dramaturgs, create new polyphonic and post-anthropocentric narratives through spatial design? If spatial design relies on the extraction of unseen and unheard bodies, how can we, as designers and artists, make space for these bodies to take part again in the formation of spatial experience? If these bodies are unfelt, how do we displace ourselves to learn from them? How do we help them to perform on us, or to design us?

### 2.3. Gestures for interdependence: Embodying relationality

In the problem setting, we introduced the notion of "gestures for interdependence" as design tools and attitudes that can improve our awareness of our interdependence with unheard bodies/entities and unseen places/sites. In what follows, we will share how to understand these gestures and how they can be read as innovative attitudes

14 In reference to JL Austin's *How to Do Things with Words*, 1955.

15 Performativity to be understood through movement and gesture instead of a technical quality (cr. the performance of a solar panel), see also the work of Judith Butler.

16 In reference to the daidala in greek drama, see Perez-Gomez A., Built upon love, 2018, The MIT Press, Cambridge (USA).

17 a.pass, advanced performance and scenography studies, Brussels (BE); see https://apass.be/.

18 Todoni D., Donoso E., Louwerens P., Van Den Brande K., a.pass Cycle II: What your research did to me, 2021, a.pass, Brussels (BE).

19 See Perez-Gomez A., http://www.architecturenorway.no/questions/histories/perez-gomez-performance/, 2012.

20 Ratti C., *Open Source Architecture*, 2016, Thames and Hudson, London (UK).

for spatial design.

In architecture discourse, the notion of gesture is often reduced to one-liners as "the building as gesture", connected to an understanding of "*gesture*" as introduced by the god-like figure of the heroic architect. In our attempt to seek overlaps between architecture and spatially oriented practices in other disciplines, we decided to direct our research to the broader notion of spatial design. As the word design (from *de-signare*) is a combination of the prefix *de,* meaning "out", and *signare*, meaning "to mark" (from *signum*, "identifying mark"), we start to see that design can also be rethought as a discipline that identifies or embodies performative gestures.

Let us, therefore, try to expand the notion of gesture as an esthetic tool for meaning-making that can be used to undo processes of extraction on the one hand and help us to instigate processes of regeneration on the other. Giorgio Agamben describes the notion as follows: "Gesture is the name of this intersection between life and art, act and power, general and particular, text and execution. It is a moment of life subtracted from the context of individual biography as well as a moment of art subtracted from the neutrality of aesthetics: It is pure praxis. The gesture is neither use value nor exchange value, neither biographic experience nor impersonal event: it is the other side of the commodity that lets the "crystals of this common social substance" sink into the situation." (Agamben, 1999). Following Agamben, the gesture seems to be a generative "container" that has the potential to be multiple things in multiple contexts at the same time (and in different temporalities). This quality seems pretty close to how the "*I as an assemblage*" (as mentioned in the note to the reader) works on an abstract level or as the idea of any "concept"[21] as an empty space through which we can move and give meaning on the go.

Reflecting further on Agamben's writings, we can read gestures as speculative building blocks for world-building (between act and power), where the spatial practices we study serve as micro-societies. When Agamben talks about a gesture as "a moment of life subtracted from the context of individual biography", we can read it as an attempt to go beyond the individual and reach for connection. And when a gesture can only become "art" when it goes outside the neutrality of aesthetics, he invites us to rethink the fullness of different possible aesthesis that gestures can offer (and words can sometimes not). The gesture as pure praxis then speaks to our ability as practitioners to be submerged in a moment of making, not even being aware of the subtlety and care we put into the gestures we make. This is where the attentive eye of the researcher can make a difference: by re-enacting specific moments in spatial practice where gestures are performed. Here, we can trace gestures that work implicitly on processes of reconciliation on the spectra of places/sites and the bodies/entities.

In the discourse on participatory art, Sruti Bala uses the idea of the gesture as a *tool* for *relationality* that go beyond the modernist separations in the presentation and production processes of participatory works. Very often, spatial design plays a crucial role in increasing connectivity between bodies/entities and places/sites involved in these works.

### 2.4. The epistemic space of drawing

In choreography/performance, "gesture drawings" are used to convey meaning-making as positions of bodies in space (in a visual regime, to convey meaning to the audience). Our interest lies in how we can bring these drawings in as a reflective framework (the gesture happens first, and the drawing comes after). And how these "tracings" as a method of observing and a method of activation of the archive can help us retrace the micro-engagements between the design actors at play.

While drawing, we seek to expand the frameworks for situated knowledge-making in which the recognition of different conceptions of body and bodying are at stake. This entails an expansion of the early feminist epistemic notion of the *partial perspective* toward a queer, decolonial (Vasquez, 2022) and post-human episteme. We will not go deeper into how these epistemic directions take shape for the sake of focus. Figure 1 — as part of the bigger "archive of gestures" — contributes to the discourse on relational and spatial esthetics (going from Bourriaud, via Ranciere to Vasquez), returning feedback to the expanded field of critical spatial practice. In this way, we will develop attitudes and tools for the *unfelt* to inform emerging transdisciplinary design practice(s).

## 3. Fieldwork: tracing bodies of water

### 3.1. Rethinking spatial design through situated knowledge(s)[22]

In **Section 3**, we sketch a series of site-specific practices/experiments. Every situation will be part of a spatial dramaturgical development, organized through the macro-gestures of (i) approaching, (ii) arriving, (iii) taking-

[21] From Groot-Nibbelink L., *Nomadic Theatre*, 2019, Bloomsbury, London (UK); the approach of 'concepts' as spaces to move through where the meaning making as a multilayered and multidirectional process taking place through association and reasoning.

[22] Haraway D., Situated Knowledges: the science question in Feminism and the Privilege of Partial Perspective, Feminist Studies, Autumn, 1988, Vol. 14 No. 3

**Figure 1.** *Walking down the stream*. Source: Drawing by Breg Horemans as part of the BAC Arts Lab Residency.

making, and (iv) presencing[23] and the micro-gestures within every step of the development: Breathing, asking permission, and intuitive cocreation (a.o., experimental exercises). Every site-specific experiment, we discuss fits larger developments toward a series of performative installations[24]. In all situations, an "unseen body of water" is staged as a guiding force in the design process. Every subsection carries the name of the river it refers to. I will generally be speaking in the first person singular, making reflections on micro-moments and in the first person plural for the reflections concerning a group process. The *design gestures* that were tried out and implemented are gathered from previous work or other spatially oriented practices. Some of the discussed *design gestures* emerged in the moment as a situated reaction to the site's givens. I took the liberty to combine different "bodies of water" (Neris, Dommel and Maas) and different encounters with these bodies. I will lay the different dramaturgical moments (approaching, arriving, taking-making, and presencing) over these encounters. I will do this for reasons of dramaturgical composition and to open up senses of polyphony throughout your reading experience.

23 Presencing refers to the consciousness of being present, where — in the case of this group process — we incorporate the aesthetic qualities of the site, the walk, the silent score, the reading-writing to augment processes of meaning making in regards to the Maas as an unseen body.

24 Within and alongside the practice of TAAT arts collective; for more info go to the website www.taat.live.

### 3.1.1. Neris

The Neris' fountainhead lies in the north of Belarus. It passes by the Lithuanian capital of Vilnius to continue to Kaunas and ends in the Baltic Sea. During my three encounters[25] with the Neris, I was present as part and cofacilitation of a multidisciplinary team gathered within the ecosystem of the TAAT arts practice. As a working location, we engaged

25 March 2020, November 2021 and September 2022, all within the Vilnius city limits.

with a small uninhabited island called Blackberry Island, just west[26] of the Vilnius city center.

The island is shaped like a larva, about 100 m long and 9 m wide and partly human-made[27]. The common aim was to cocreate the installation with more-than-human entities (the specific entities were still defined at the time of the research trips). The group process was initiated as the formation of a "multi-species community" (Escobar, 2018). My aim here is to share (i) how the encounter with the river — and consequently the island — informed the different "spatial dramaturgical moments" and (ii) which design gestures informed the design of the performative installation.

(a) Approaching: Gesture surrendering to the speed of the river

In November 2021, our group[28] mounted a raft 5 km upstream from Blackberry Island. After a long process of inflating the raft — a second-hand safety raft which appeared to be leaking air — we adventurously embarked on the raft and swopped the steady concrete jetty for a cold liquid surface. Our limbs touched the rubber surface of the boat, the rubber surface touching the water surface of the Neris. Our arrival was suspended for about 3 – 4 h, and the speed of the water asked us to defamiliarize with our "human speed". Accordingly, the situation invited us to defamiliarize ourselves with our habitual "modern designer attitude": visiting the territory, formulating a vision based on needs and programs, drawing it in the studio, and building it. In this case, not our modern human will, but the will of the river was taking the lead.

We brought food and shared it with each other. There were moments of awkwardness, being close to each other in silence. This generously unplanned slow approach toward the island altered the question of necessity in our design actions: How does this approach (as the act of approaching, not as the "visionary approach") change our way of projecting (from *pro-ject,* literally meaning "being thrown forward") a design upon an unknown site? What kind of design gesture can be left if we "cease to *pro-ject*"? In the concluding feedback session, we discussed how the slowness of the approach informed the inaction at the moment we arrived (which we perceived as an anti-climax in regard to our designed projections). For what kind of other design gestures does this process of "unlearning to *project*" make space here?

(b) Arriving: The gesture of asking permission

In September 2022, largely the same group[29] arrived on the island with a different raft[30]. With the impact of our previous approaching experience stored in our bodies' memory, we transgressed the lateral strength of the water of the Neris toward the mooring place, central on the island. After dropping the material, we gathered among a constellation of trees. A guided meditation was initiated by one of the cofacilitators, in which we were invited for a moment of deep listening[31] followed by a small performative ritual inspired by Robin Wall Kimmerer's writings on reciprocity: We asked permission for the island to arrive and to be there. We shifted our intention from a *colonial* attitude (arrive, ignore, inhabit the unknown territory, and take its resources) to an intention of attention and reciprocity with the island as body and all bodies present with *her.* It took around thirty seconds of silence until an unidentifiable bird sound provided us with a possible answer: a sign of other life to acknowledge our co-presence or at least a way of connecting to this as an esthetic experience at that moment.

The lesson learned here is an embodied understanding of place through a series of simple performative gestures. The gesture of "surrendering to the speed of the river" reminded us to slow down in our thinking-doing-being. It performed its force on us, introducing a balancing act between the raft, the human bodies on it, the "witches hair", and the tree next to the mooring place holding the raft cables. The gesture of asking permission augmented our awareness of other bodies and other voices. It effectuated a form kinship that allowed for a multi-species community to emerge.

#### *3.1.2. Dommel*

In spring 2022, I cofacilitated a day-long workshop, entailing a canoe trip to gather natural materials from the river surface and banks in the morning and the cocreation of small spatial interventions on the river bank next to the Van Abbe Museum in Eindhoven in the afternoon. The workshop was part of a program titled "Territories of Attention"[32], in which the Dommel delta (the area where

26 Located between the Gariunai area and quarry.

27 Constructed in the 1950' to improve the flow of the river in favour of small boat traffic.

28 Consisting out of three students with an Arts (Vilnius Academy) and Architecture (Vilnius Technical University) background, the curator/artist and guardian of the Blackberry Island, and two members of the TAAT arts collective, including the author.

29 A student from Art Academy Vilnius, a weaving designer, a professor from Vilnius Technical University, four members of the TAAT arts collective, a local biologist, and the curator/artist and guardian of the Blackberry Island.

30 The curator/artist and guardian of the Blackberry Island provided us with a lateral raft from the south bank of the river to the island.

31 I'm using the term that composer Pauline Oliveiros used as a way to bundle her situated group practice of attentive and active listening.

32 The program was a collaboration with Embassy of Inclusive Society, iDrops and Van Abbe Museum and was focussing on prototyping a series of design gestures related to a neurodiverse approach in design.

the river Dommel and a series of small side rivers) was introduced as a research environment. The group that took part was explicitly (neuro-)diverse[33] in an attempt to gather a variety of ways of attentive listening and sensing to question rather neurotypical[34] ways of thinking about spatial and environmental esthetic experience. In this part, we will focus on (i) the intentional gathering of materials and (ii) the construction of small-scale interventions that were reflected on by the participants. The reflection I will make is on the moment of *taking* (a) and the moment of *making* (b) as they recalibrate the relationship with more-than-human entities, formerly known as resources. Through a series of implemented gestures, we will engage with the questions on *taking* (where do you get material, how do you relate to the action of "taking"') and the questions of *making* (how does a different relation to taking inform the "making").

(a) Taking: The honorable harvest as gesture

In the introduction to the canoe trip, the question of, "what are you allowed" to take was shared with the participants. As everybody was aware of the purpose of this material (creating an impromptu performative installation), we shared the purpose of the "gesture of taking" as both a political act (of extraction) and the potential of this gesture as a way to restore a reciprocal relationship with the Dommel delta and its more-than-human inhabitants. All participants were invited — so not obliged — to grow awareness of "taking with care" and to develop an attentiveness for "what the river was already giving us" (elements drifting on the surface, for example). We explained the principle of "taking with care through ideas as the *honorable harvest*[35]" by Robin Wall Kimmerer.

Through the introduction, a general attentiveness and tempo were installed for the workshop. While sharing the canoe with a biologist, we reflected on how plants communicate their "readiness" to be taken (some species produce reddish colors, so animals know that these are not yet ready). Without going deeper into the biological process, what is important here is the ability of more-than-human species to communicate. What counts for plants also counts for the river (her speed, her way of flowing and overflowing). It is rather a matter of training our attentiveness and re-designing our design gestures from a renewed embodied positionality toward them. Half of the participants picked up floating grass from the water surface; some also took elements of debris from human activities (a can, artificial fishing lure), and others collected reed, chestnuts, flowers, and leaves.

(b) Making: the gesture of reading interrelations

We facilitated an intuitive design score that was not aimed at a consensual process (all working on one coherent end result) but that allowed for an intuitive and relational approach. We worked in pairs and in silence, creating a way of communicating design decisions through a gestural approach. Within the cocreation setup, participants were invited to "read each other silently" while cocreating and react intuitively, similar to the approach in the process of taking. Dance theorist André Lepecki refers to this performative process from dance theory as a way of "leading-following" (moving with and alongside each other, taking space, and making space for the other reciprocally). The final interventions were first experienced in silence and then discussed in groups. We looked at the interventions as both future building blocks or foundations for a performative installation, but we also looked at them as scale models or spaces for other-than-human entities to coexist with us, humans.

The collective learning here was twofold: (i) The participants' understanding of "dealing with unseen bodies, formerly known as resources" expanded through the different dramaturgical moments and the implemented design gestures. (ii) The combination between taking and making (a process that in a lot of design projects is disconnected) was valuable for the regenerative approach to design we are aimed at, and this is (1) on the level of the group process where we learned to work together intuitively with each other, (2) on a renewed relationality with other-than-human bodies, and (3) on the collective process of aesthetic experience and the polyphonic reflection upon these experiences. After the workshop, we dismantled the bigger installations and positioned the different bodies on the banks, ready to take them to other destinations alongside the Dommel (going further north).

#### *3.1.3. Maas[36]*

(a) Presencing: Gestures for a regenerative *aesthesis*?

In December 2022, I cofacilitated a performative walk toward and alongside the Maas in Maastricht as part of the Winternights Festival[37]. A group of 10 participants was invited for (i) an introduction on the framing and aim of the walk (renegotiating our human relationship to the river), (ii) a walk toward the river in silence, and (iii) following a

33 About 10 participants with different cultural backgrounds, sexual orientations, and a different positionality on the spectrum of neurodversity (o.a. ADD, dyslexia and autism).

34 Neurotypical people are those who are considered as neurologically normal.

35 Wall Kimmerer R., *Braiding Sweetgrass*, 2013, Milkweed Publishing Minneapolis (USA).

36 This chapter is written on the Eurostar between Calais and London, 75 m deep on the bottom of the sea.

37 An event co-organised by SoAP Maastricht, Via Zuid and C-TAKT in several locations in the city of Maastricht.

piece of floating material (a leaf, a branch, a feather) on the surface of the river by mimicking its speed and direction with their body. In the third part, an experience of presencing took place. The score allowed us to surrender to the speed of the Maas (see also how rafting on the Neris river in Section 3.1.1 had a similar effect) while staying connected to the *space-time*[38] of the aesthetic framing of the experience and the group process of moving together alongside the river.

In 3.1.3 (b), I will use fragments of the written reflections to bring in participating voices, and I will reflect on every text, along the way. The reflection session was set up as a reading-writing[39] exercise (Sedgwick, 1993): All participants were invited to sit around a table for short sessions of automatic writing and out-loud reading. In this way, a slow, attentive, and polyphonic conversation appears, where both (i) an inner dialog with the river Maas is represented in the writing and (ii) resonances between the different participants' writings are made spontaneously.

(b) Reading-writing (fragments of participants)
*Opsomming*[40]. *Oplossing*[41]. *Dissolving.*
*You hear a story about a skeleton in the room.*
*Your writing is relaxing.*
*De maas komt terug.*
*In verschillende gedachten.*
*Dood. En of levend*[42]. *There are dead entities floating down the Maas.*
*You are remembering the flood from last summer.*
*Images of floating rubbish.*
*Floating furniture en dissolving memories.*
*All melts into water. Alles rot weg. Drijft weg.*[43]
*You are slowing down your flows of thought.*

A reflection is made on the great flood caused by expansive rainfalls in July 2022[44]. The participant imagines how the river took personal belongings from people's homes (literally) and evacuates these material things in the direction of the North Sea. Reflections on impermanence and transience come into play. This, though, invites us to situate the aggression of the flood as part of the unheard voice of the river and confronts us with aspects of ignorance in (i) our way of thinking about the river and (ii) in the infrastructural and political decisions that are made to "tame" the wild and unheard body of the river.

*You walk back to the Maas.*
*You feel calm.*
*You hear your own footsteps.*
*Come to yourself more and more.*
*You see the water, it heaves and flows, it is dark.*
*You see leaves on the water.*
*You are going to follow a leaf,*
*a light yellow leaf. It shakes,*
*and seems to lie still, but*
*it appears to be moving anyway*

In this reflection, the contrast between moving and stillness appears. The participants "come to themselves" while moving. The leaf seems to become a representation of the "moving stillness" in the participants' esthetic experience.

*You hear something about rhythms.*
*The rhythm of life that seems unstoppable.*
*The thought of being carried by the river, follows you.*
*And pushes you forward.*
*Other languages are present.*
*You listen to their rhythm.*
*The rhythms you recognize in their sounds.*
*Then: a moment of eye contact.*

Here again, a gesture of being carried by the river — a gesture of surrender — is part of the meaning-making apparatus. Next to that, a consciousness of different languages[45] that appear constitutes a polyphonic dialogue with each other and the Maas. Not everybody at the table is able to understand what everybody says, but what we can hear are the rhythms, the sounds, the wavelengths and the implicit flows of *thinking, doing and being* carried by the river Maas' affective force.

## 4. Conclusion: To the scores

In this paper, we staged a series of unseen bodies of water as the guiding force in spatial design. We used the Venice "fountain" anecdote as an example to shift our relationship to water from an act of "othering" (seeing the sea or the river as an "object" outside of our human self) towards an act of resonance and relationality (we are the water and the water is in us). Through the fieldwork, we studied experimental design processes aimed at the development of a series of performative installations (as part of the TAAT arts collective) in which unheard bodies of water were framed as genuine co-creators. Although these performative installations are not yet come to a distinguishable form, the focus here was on the in-the-making esthetic experience. Through the prototyping of a series of new design gestures

38 In reference to the notion coined by Bakthin.
39 Method inspired by the writings of Eve K. Sedgwick and the conversation scores by Building Conversation.
40 Translated from Dutch to English: summary.
41 Translated from Dutch to English: solution.
42 Translated from Dutch to English: The Maas is coming back. In different thoughts. Dead, And or alive.
43 Translated from Dutch to English: Everything decomposes. Drifts away.
44 See news item on the effects of the flood in Liege and Spa here: https://www.vrt.be/vrtnws/nl/2021/07/14/rampenplan-spa-jalhay-theux/
45 There was reading in Dutch, English and Turkish during the session.

(performative scoring and exercises), we expanded our designer toolbox from modern efficiency-driven human-centered methods aimed at the projection of ideas and the execution of these ideas, toward a performative here-and-now approach to sensing site, place, and the coexistence of bodies, formerly known as resources.

We questioned the extractive forces in spatial design and tried to heighten our awareness of spaces built on the exploitation of unseen landscapes and unheard bodies. Through working within the field and methodology of spatial dramaturgy, we expanded our spatial design methods through a haptic and sensorial space-time conception. Through the fieldwork, we shared a series of experimental exercises that focused on (i) collaborative prototyping together with more-than-human bodies, (ii) developing a heightened awareness of the spatial aesthetics of (unseen) sites/spaces, and (iii) contributing to the conception and development of a regenerative spatial esthesis in co-creation with (unheard) bodies/entities.

The final part, "the score", serves as a hands-on sharing of this article's findings. You are invited to implement it in your spatial practice to shift perspectives to the site, space, place, your own body as a designer, and other bodies that (already) coexist with you.

### 4.1. The score

#### *4.1.1. Pre-score*

- *You gather a diverse group of people*
- *You plan a site visit through an alternative route and a low-tech means of transport (walk, canoe, bike, and crawl)*
- *You make time for it and communicate as such.*

#### *4.1.2. Score*

The aim of this score is to de-center ourselves as designers by displacing our*selves* in other bodies, recognizing these bodies, their speed, the sites they inhabit, and the present. We are exploring an embodied understanding of relating systems of coexistence through the making of temporary spatial constructions with gathered material on site. You are welcome to do the score(s) as separate exercises or as a longer workshop. Feel free to adapt to your specific needs or the needs of the group you work with.

You might encounter resistance following the score (you can recognize a feeling of purposelessness or ridiculousness, or you might have difficulties seeing the relevance of this "ritual" for your day-to-day job as a designer). Try to be explorative and embrace the resistance. Be aware that these feelings might come from the oppression of play and open-mindedness learned to us by modernity.

(a) Approach: surrender to different speeds
- *You gather with the other group members.*
- *Before you start moving to the site, recognize how you feel in relation to the score. If you feel resistance, don't fight it and allow it.*
- *You start moving, in silence.*
- *You are invited to be aware of what you feel, hear and see.*
- *Please try to be aware of the other group member's speed.*
- *Reflect on your sensations and thoughts at the threshold of "entering the site" (in case this is physically possible).*

(b) Arrive: Ask for permission
- *You are invited to either follow the next steps or design your own exercise. If you are the one who invites everybody present, you can also read out loud the following sentences:*
- *Close your eyes.*
- *Start breathing at a slow but comfortable speed.*
- *Find a rhythm that suits you for a couple of breaths, take a deep breath, and hold your breath for four seconds.*
- *Breath out and repeat several times.*
- *Take a moment consciously ask for permission. You can ask permission to the site as a whole or different parts that constitute it (the weather, a flock of birds, a tree). The question can be voiced out loud or through a movement or a gesture. Or even in complete silence.*
- *Take at least a minute so every group member can perform their proper gesture.*
- *Go back to normal breathing.*
- *Reopen your eyes and acknowledge the presence of the other group members.*

(c) Taking-making: A temporary architecture
- *As a group, you choose a gathering place.*
- *From here, you start exploring the site's "other bodies", formerly known as resources (meaning plants, pebbles, flowers,…).*
- *In that process of exploration, try to create an awareness of how these bodies speak to you, and what they communicate.*
- *When you feel ready to start collecting, ask yourself the question: what is my affordance and purpose to take? What am I taking, and how much? Take the time to do this with awareness.*
- *You bring the material to the gathering place and start exploring intuitive possibilities to assemble the materials. You can make up your own rules on how to do this. Take about 10 min.*
- *Take some distance from what you made.*

- *For about 5 min, you walk around and study the other interventions.*
- *Choose another intervention — so not your own — to continue working on.*
- *After 10 min, take distance and switch positions.*
- *You can go on as long as you want.*

(d) Presencing: Experience

- *Make a large circle with the whole group around your creations.*
- *Walk around and observe your work in silence for 5 min.*
- *Notice how different assemblages make meaning.*
- *Discuss your findings.*

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The authors declare that they have no competing interests.

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This is a single-authored paper.

## Ethics approval and consent to participate

Consent-taking was not performed, as the contributions were treated anonymously.

## Consent for publication

Consent-taking was not performed, as the contributions were treated anonymously.

## Availability of data

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ORIGINAL ARTICLE

# Style evolution rules of Tibetan dwellings in the Amdo Tibetan region: An architectural typology perspective

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## Abstract

The Amdo Tibetan region is one of the three major Tibetan regions in China, along with the Jiarong Tibetan region and the Kangba Tibetan region. The Amdo Tibetan region is located in the Tibetan-Qiang-Yi corridor, where many ethnic groups have migrated for a long period, and the Tibetan dwellings in the region have typical characteristics such as the intermingling of multiple cultures and various construction methods. With post-disaster reconstruction and rural revitalization work, the architectural landscape of the dwellings in the region has gradually become homogenized with that of other Tibetan regions, suffering construction damage and distorting the architectural culture. However, the current academic circle lacks a description of the evolution rules of folk styles in the Tibetan areas of Amdo. To fill this knowledge gap, this paper selected typical folk styles in Jiuzhaigou Valley in the Tibetan areas of Amdo as the research subject. Based on the perspective of architectural typology, this paper classified folk styles based on field research and constructed a quantitative analysis framework using a "classified-iconic index- characteristic calculation index." Finally, the following conclusions were reached: (1) The Tibetan dwellings in Jiuzhaigou, as a whole, are evolving in a direction that reflects originality in the plans, modernity in the structure, and autonomy in construction. (2) In the rural settlements of the Ando Tibetan region, the environment, managers, and villagers interact with each other, and the method and degree of influence are intuitively reflected in the appearance of the dwellings. The results of the above study reveal the evolution of the residential landscape in the Tibetan area of Amdo, enriching the theoretical perspective and implementation approaches for the study of residential landscapes, and providing new ideas for the conservation and development of residential houses in ethnic areas in the future, contributing to rural revitalization.

***Keywords:*** Style evolution; Tibetan dwellings; Amdo Tibetan region; Architectural typology; Jiuzhaigou

## 1. Introduction

"Feng Mao" is a Chinese word interpreted as a style, appearance, or scenery; thus, the architectural style can be understood as the style characteristics of the building (Wang *et al.*, 2019). As one of the three major Tibetan regions, the Amdo Tibetan area is mainly located in the Sichuan, Gansu, and Qinghai provinces and is a multi-ethnic "Tibetan-Qiang-Yi corridor" area that has been used for migration for a long period of time. Due to its unique geographical location and historical multi-ethnic integration, the residential style of Amdo has retained the characteristics of Tibetan architecture in terms of ethnic origin but also developed diversified regional characteristics due to the influence of surrounding cultures. The Tibetan region of Amdo is located in an area prone to earthquakes, with a number of earthquakes of magnitude 5.0 or above occurring in the last 30 years, and many damaged houses have been repaired and rebuilt. Furthermore, with the development of rural urbanization, a large number of rural construction projects have been implemented in the Amdo Tibetan area. While the living conditions of Tibetans have been improved, the dwellings in this region have become increasingly homogenized with those of other Tibetan areas. Ethnic culture is crucial for the development of ethnic minority regions, but post-disaster reconstruction and rural development have resulted in a serious distortion of the residential landscape in the Amdo Tibetan region, which will slow down the development of the Amdo Tibetan region in the long term.

In contrast to traditional Tibetan dwellings, scholars have focused almost exclusively on the "black tents" and "towers" of the Tibetan people, and there has been less literature on Tibetan dwellings in the Amdo Tibetan area. Wang (2015) and Ke (2015) classified the types of residential buildings according to plan form, materials, construction, and decorative arts; Guo (2016) discussed the cultural heritage of dwellings in terms of plan function and spatial order; Cheng (2017) proposed a model of residential renewal that takes into account environmental, technological, and cultural factors based on a summary of residential construction models; and Li *et al.* (2022) studied the structural characteristics and seismic performance of the dwellings. Most of these studies focused on the common temporal symbols to measure the category, value, and cultural authenticity of the dwellings, ignoring the fact that the greatest authenticity of the dwellings should be their "evolutionary authenticity" and the "living information authenticity" of their long-term use by the inhabitants in the process of social development; therefore, studies on the temporal nature of the dwellings in the Tibetan area of Amdo are urgently needed. As a methodological system of categorization and grouping, the study of architectural typologies is a potential solution to induce building construction to follow a broad-based, territorial, and culturally appropriate trajectory (Wang, 2003). Architectural typologies can summarize a series of complex architectural forms that are intrinsically linked to simple "archetypes" and "variants" (Cao *et al.*, 1999), whereas the "archetypes" do not change with historic development, *i.e.*, uniformity, while the "variants" are variations of the archetypes that change with historical, political, economic, social, and other influences, *i.e.*, variability. Jiang (2007) proposed a typology of dwellings based on a review of Rossi's and Manchurian's research on local traditional dwellings, arguing that, through this approach, the essential meaning of the dwelling could be explored. In recent years, Chinese scholars have studied the plan (Xin, 2020), façade (Li & Wang, 2015; Xiang, 2019), interior interface (Zhang, 2016), doors (Yuan *et al.*, 2022), house form (Meng & Luo, 2016; Zhu *et al.*, 2016) and structure of dwellings (Deng, 2021) from the perspective of architectural typology, with qualitative analyses as the main method of research with less reliance on quantitative analyses. The style of dwellings is influenced by the natural and human environment and is always in a state of dynamic change, producing complex appearances. Using the idea of "prototype-variant" in architectural typology, the core elements of the style of dwellings can be effectively grasped, and on this basis, the quantitative analysis method can be expanded to obtain objective knowledge of the evolution of the style of dwellings, thus promoting the protection and inheritance of the style of dwellings.

From an architectural typology perspective, this article presents a case study on the Tibetan dwellings of Jiuzhaigou, a World Natural Heritage site located in the Tibetan region of Amdo. Based on field research, we have clarified the prototypes of the dwelling styles and their variants and constructed a quantitative analysis framework of "classification-iconic indicators-characteristic calculation indicators" to explore the evolution of Tibetan dwelling styles under changes in natural, policy, and human environments, with a view to providing a basis for subsequent village planning and spatial optimization of dwellings, inheriting and promoting the culture of ethnic regions and aiding in rural revitalization.

## 2. Methodology

### 2.1. Presentation of the case study

The Jiuzhaigou World Natural Heritage site is located in the southeastern part of the Tibetan region of Amdo and belongs to the Aba Tibetan and Qiang Autonomous Prefecture of Sichuan Province. The site is named Jiuzhaigou because of the nine Tibetan villages of Heye, Pangya, Yana, Jianpan, Heijiao, Shuzheng, Zechawa, Zaru, and Guodu (Figure 1). In 1992, it was added to the World Heritage List, meeting the criteria of Article VII of the Convention for the Protection of the World Cultural and Natural Heritage—"Areas of outstanding natural phenomena or of rare natural

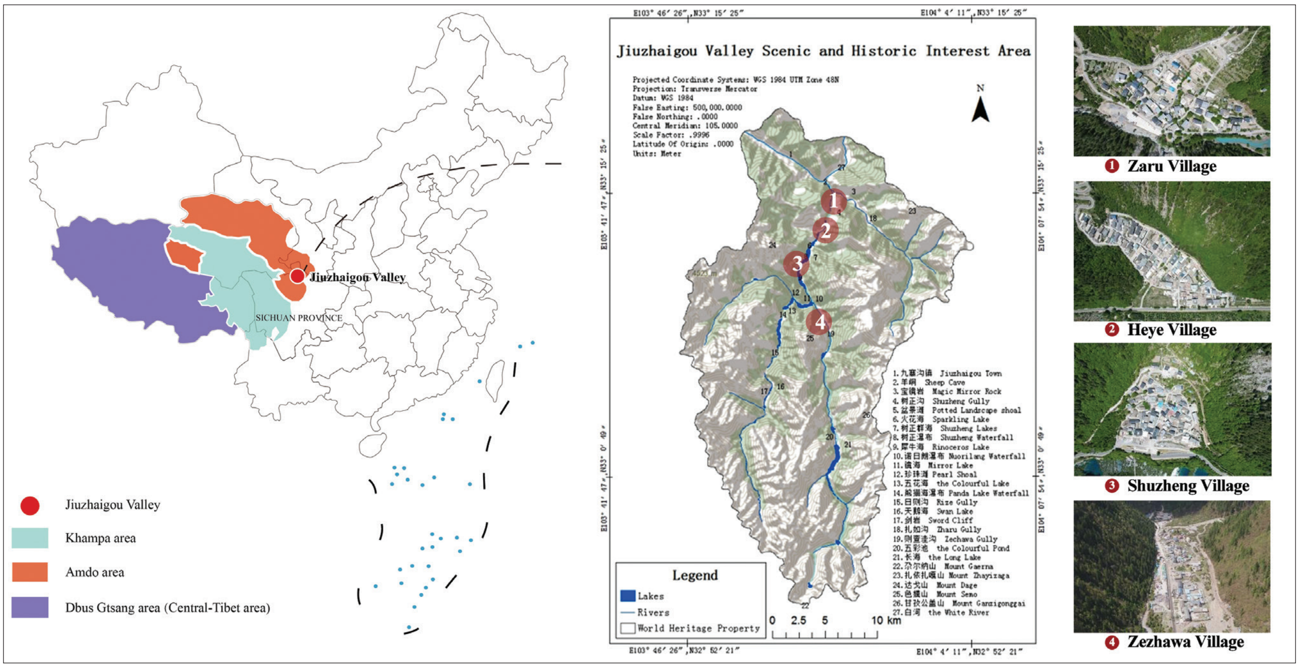



**Figure 1.** Location of Jiuzhaigou Valley and Amdo Area. Source: Drawing by the authors

beauty and aesthetic value" (UNESCO, 2023). The dwellings are a testament to the integration and transformation of the Tibetan and Chinese peoples in the region, and have been passed down to the present day, and are as unique and historically valuable as the natural landscape (Meng & Chen, 2015). The relatively good state of preservation and the large number of Tibetan dwellings in the Jiuzhaigou World Heritage Site compared to other research subjects ensure the diversity of the study sample. In 1984, Jiuzhaigou began exploratory, small-scale, and rough tourism development, and the villagers began a major renovation of new houses; in 2000, cultural heritage tourism took off, and villagers actively renovated old houses. On 8 August 2017, a 7.0 magnitude earthquake struck Jiuzhaigou Valley, causing massive damage to the local dwellings, and villagers began a new round of large-scale dwelling restoration and new construction. Thus, the dwellings in the Jiuzhaigou World Heritage Site have witnessed the social changes that have taken place in China since the reform and opening up of the countryside; in addition, the modern appearance of the dwellings in the current context of rural revitalization is a common problem faced by ethnic villages in the Tibetan areas of Amdo, which further highlights the representativeness of the research sample (Figures 2-5).

### 2.2. Sample data source

Field surveys were one of the primary methods of collecting basic data on dwellings. With the development of tourism, the higher altitude and less accessible villages in Jiuzhaigou

**Figure 2.** Indigenous villagers at the Jiuzhaigou World Heritage Site. Source: Photo from Jiuzhaigou Valley Administration Bureau

were gradually abandoned, and four larger-scale living-type villages, namely Zaru, Shuzheng, Zezhawa, and Heye, have now been formed. To fully clarify the types of local dwellings, in July 2018, the team entered the Jiuzhaigou Tibetan village, which was still under post-disaster reconstruction after being affected by the 7.0-magnitude earthquake, to investigate the evolution of the style of and damage to the dwelling architecture. In August 2019, based on the previous study and analysis, a more in-depth survey of the appearance of the dwellings in the four villages of Shuzheng, Heye, Zechawa, and Zaru was carried out. A total of 320 dwelling units were studied, and a list of household names and architectural drawings was

**Figure 3.** Aerial view of an original village at the Jiuzhaigou World Heritage Site. Source: Photo from Jiuzhaigou Valley Administration Bureau

**Figure 4.** A traditional dwelling at the Jiuzhaigou World Heritage Site. Source: Photo from Jiuzhaigou Valley Administration Bureau

compiled. To study the development history and pattern of Tibetan dwellings in Jiuzhaigou, the follow-up team collated the field research data and classified the types of dwellings into traditional, partially renovated A, partially renovated B, and modern, according to their different characteristics in terms of the building plan, structure, and construction. This classification resulted in 20 traditional, 75 partially reconstructed A, 152 partially reconstructed B, and 73 modern dwellings in the study sample (Figure 6).

### 2.3. Analysis methods

The architectural typology considers that building types reflect the evolution of entities and that there is a certain "origin" for all types in history, called the "leading type" (Canigia, 1979). This study simplified this "reading" of the evolution of building types into a "prototype-variant" approach. First, based on the four types of dwellings, one dwelling of each type in good condition was selected as a sample for further study, making a total of four dwellings, as shown in Table 1. Second, one type of dwelling was set as the prototype, and the other three categories were

**Figure 5.** A modern dwelling at the Jiuzhaigou World Heritage Site. Source: Photo by the authors

set as variants. Then, considering that the characteristics of dwellings are mainly reflected in the three aspects of the building plan, structure, and constitution, and based on the criteria of being reasonable, holistic, easy to calculate, and realistic, a quantitative analysis framework was constructed, which consisted of three categories: building plan, structure, and constitution, as shown in Table 2 (Qujijiancaim, 2009). Each category included landmark indicators and characteristic calculation indicators, from "type" to "indicator," *i.e.*, from geometry to quantitative analysis, which would help to analyze and study the evolution of the residential landscape in a more intuitive way. The change in the way of living is reflected in the functional changes in the layout of the dwellings, and the proportion of functional spaces (P) can visually demonstrate this change (Lu, 2007). Space, as an objective form of material existence, is expressed in terms of length, width, and height, and the form ratio W: D:H, of which they are composed can reflect the change in the form of the dwelling's appearance. The material of rammed earth is one of the characteristic materials of dwellings in Jiuzhaigou, compared to other Tibetan areas, and its proportion of the front façade area (M), together with the window-to-wall ratio, can reflect the richness of the façade (Xu *et al.*, 2019). Finally, the technical drawings of the dwellings were drawn in AutoCAD 2022, and the data were visualized in Excel, Auto Illustrator 2022, and Origin 2022.

## 3. Analysis

### 3.1. Analysis of architectural features of different styles

#### *3.1.1. Traditional dwellings*

Traditional dwellings, built before the opening of the scenic area in 1984, have a history of more than 60 years (Figure 7).

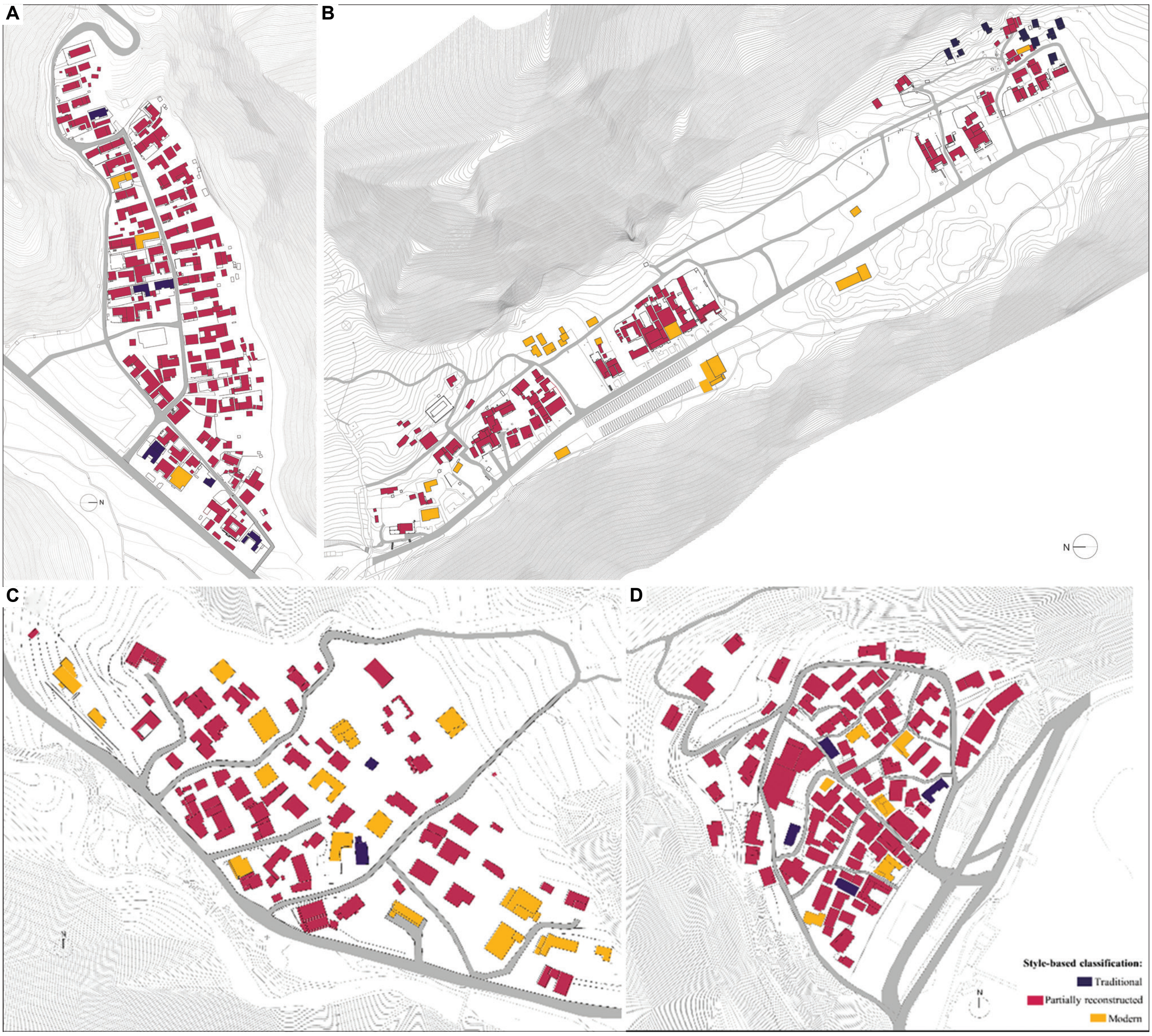



**Figure 6.** Style-based classification diagram of the four villages. (A) Heye Village; (B) Zezhawa Village; (C) Zaru Village; (D) Shuzheng Village. Source: Drawings by the authors

**Table 1. Key research objects**

| Type | Traditional (before 1984) | Partially reconstructed A (1984–1990) | Partially reconstructed B (1991–2010) | Modern (2010–present) |
|---|---|---|---|---|
| Name | Youzhongdingda's house | Xiongya's house | Sebulang's house | Yang Qingxia's house |
| Appearance |  |  |  |  |

The layout of the buildings' main structure reflects the Tibetan belief in Bonpo (Zheng, 2022), and the structure and constitution demonstrate the cultural characteristics of Han-Tibetan integration. The simple façade can be

**Table 2. Indicator system for quantitative analysis**

| Type of characteristic indicators | Iconic indicators | Characteristic calculation indicators | | |
|---|---|---|---|---|
| | | **Name** | **Formula** | **Notes** |
| Plan | Area of production space ($m^2$)<br>Area of living space ($m^2$)<br>Area of spirituality space ($m^2$)<br>Area of storage space ($m^2$) | Proportion of functional spaces (P) | $P=\frac{a_i}{A}$ | $a_i$: Area of functional space ($m^2$)<br>A: Total construction area ($m^2$) |
| Structure | Height (m)<br>Total width (m)<br>Total depth (m)<br>Floors | Dwelling form ratio | W: D:H | W: Total width (m)<br>D: Total depth (m)<br>H: Height (m) |
| Constitution | Typical windows (mm)<br>Entrance door (mm) | Façade window-wall ratio (B) | $B=\frac{T}{G}\times 100\%$ | T: Exterior window area ($m^2$)<br>G: Exterior wall area ($m^2$) |
| | Wall thickness (mm) | Front façade rammed earth material ratio (M) | $M=\frac{s_i}{S}\times 100\%$ | $s_i$: Rammed earth material area on the front elevation ($m^2$)<br>S: Front elevation area ($m^2$) |

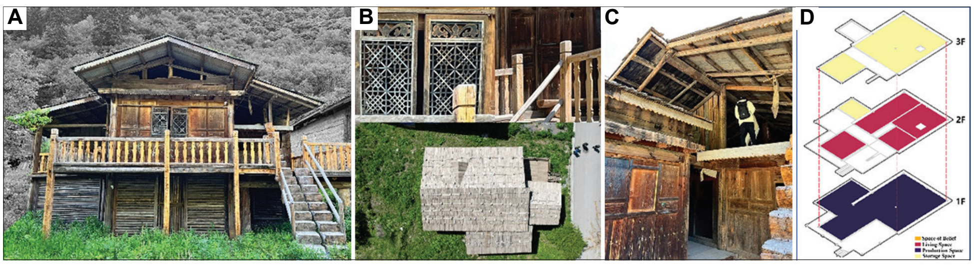



**Figure 7.** Illustration of typical dwelling features of traditional dwellings. (A) Appearance; (B) construction; (C) structure; (D) floor plan showing functional zones. Source: Photos and drawing by the authors

considered a vernacular expression of the traditional Tibetan lifestyle in Jiuzhaigou. Regarding the building plan, this type of dwelling is mostly rectangular, with a depth greater than the width, and it has 3 stories dominated by inner corridors. The internal functional areas are usually divided into the ground floor, which is usually used for storing farm implements and livestock farming; the middle floor, which is usually enclosed and used for living; and the top floor, which is usually used for storage or guest rooms. The middle floor is the core part of the house with featured spaces such as fire-ponds (a kind of Chinese fireplace) and flat roofs (e.g., for drying clothes). The top floor may also have a sutra area or flat roof and often appears to be low and cramped because of the irregular spatial form and low height (Chen, 2017), such as in Lang Jiebo's house and Gega's house in Zhengshu Village. The floors are connected by single log ladders with Tibetan characteristics, consisting of zigzag steps chiseled from a log that leans against the upper floor and is placed outdoors (Wu *et al.*, 2022).

In constructing the dwellings, the first floor uses a well-pole wooden structure—"Beng Kou" in Tibetan, meaning a house made of wood — and is wrapped in compressed earthen walls on its left, rear, and right sides. A beam rests on it, with the beam-column connection mostly adopting a two-beam connection, and the floorboards are made of wood (Zhang, 2017). The wall base thickness is 1.2–1.4 m, and the top mountain wall is 400–600 mm. The structural system and key components in Jiuzhaigou are very different from those of typical Ming and Qing dynasty wooden structures in southern China, but it is similar to other Tibet-related dwellings in western Sichuan (Chun *et al.*, 2019). The walls of Tibetan dwellings in the Jiuzhaigou Valley have an upward division, with an obvious division on the outside and mostly vertical on the inside (Cao, 2016). The middle and top layers use the column and tie wooden construction commonly used in traditional dwellings of Han ethnicity but do not use a connecting edge pillar. Instead, only the ridge and eaves beams are used in the peripheral protection structure on both sides and the center. Traditional mortise and tenon joint system is used in the wall-column connection simply. In some cases, the roof ridge and diagonal beams are tied with hemp ropes at the connection for reinforcement. The width of a room is approximately 4–5 m due to the size of the materials used.

In the construction, the main façade or exterior wall of the building is generally made of hard cedar wood boards. Given the abundant rainfall in the region, most dwellings in Jiuzhaigou Valley adopt a double-slope roof. Some dwellings have no ridges between the two roof slopes, and the ends are separated and interleaved, with the gap in the middle serving as a smoke exhaust channel (Liu, 2005). The roofs are covered with small planks of wood, and to protect the lower compressed earthen wall, rainwater is not diverted to the edge of the eaves but collected in a drainage groove made of a whole piece of wood on the eaves (Chen & Liu, 2008). Windows with a long-pattern lattice are commonly used as casement windows. The doors are relatively small, and the door and window eaves are undecorated (Yuan, 2022). The overall dwellings maintain their original wooden color, with neither paint nor decoration on the surface. The simple construction method and original color make these residential buildings blend seamlessly with the natural environment (Hou, 2021).

### *3.1.2. Partially reconstructed A dwellings*

Partially reconstructed A dwellings refer to brick and wood (or brick and concrete) dwellings built by villagers, with a lifespan of approximately 40–60 years, from the opening of the Jiuzhaigou Scenic Area in 1984 to the 1990s (Figure 8). For these dwellings, the functions of the livestock pens and human habitats are separated, and the main building materials shifted from only wood to wood, stone, and bricks, resulting in significant changes to the architectural style. There are several specific features of these transformed buildings.

First, in terms of plans, villagers typically added floors to maximize the space for tourism, leading to the emergence of L- and T-shaped layouts. Inner corridors connected the original space with the added space, with the outer corridors built in the added part. As a result, the traffic flow became more complex, and cross-shaped intersections appeared inside buildings, such as Changqing's house and Segezuolailai's house in Zharu Village. In addition, due to the shift towards tourism, agricultural and pastoral production spaces were replaced, and traditional Tibetan residential features were changed. For example, the livestock pens on the ground floor were phased out, the outdoor flat roof on the second floor decreased in size, the building mass was weakened, and the scale of the staircase, which was moved into the house, increased.

Second, in terms of structure, dwellings during this period saw improvements in their structural designs and artisanship. The ground floor was still dominated by rammed earthen walls, while the upper floors adopted penetrating and mortised wooden frames with wooden boards separating the space internally. The overall span of the houses increased, with some having as few as 9 pillars and others having as many as 40 (Chen & Tian, 2022).

Third, in terms of materials, villagers began to use materials such as red bricks to replace traditional wood,

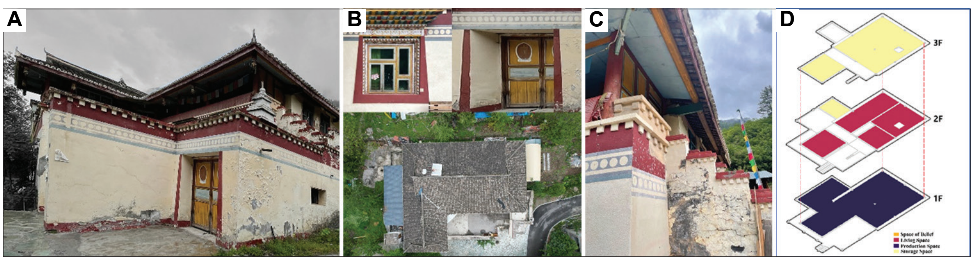



**Figure 8.** Illustration of typical dwelling features of partially reconstructed A dwellings. (A) Appearance; (B) construction; (C) structure; (D) floor plan showing functional zones. Source: Photos and drawing by the authors


**Figure 9.** Illustration of typical dwelling features of partially reconstructed B dwellings. (A) Appearance; (B) construction; (C) structure; (D) floor plan showing functional zones. Source: Photos and drawing by the author

and changes to the doors, windows, and roofs were made mainly for better lighting and protection from the rain. To increase the amount of natural light in each room, the residents opened many windows on each side. Stronger structures were used for the roofs to support small blue tiles that could withstand more rainfall. façade decoration also gradually increased, with the overall building remaining relatively simple, except for the decorative colors of doors and windows.

### *3.1.3. Partially reconstructed B dwellings*

Partially reconstructed B dwellings refer to homes built by villagers between 1991 and the 2010s that have been preserved for 10 – 30 years. Most existing dwellings were constructed during this period (Figure 9). They have simple floor plans with brick and concrete structures and incorporate traditional western Sichuan dwellings with Tibetan-style Buddhist murals in their decorations. The overall style combines varieties, but modernist features are dominant. For the structural changes, first, in terms of building plans, the floor plans of newly built and renovated homes are influenced by modern and Han Chinese architectural styles to varying degrees. The main feature is an outer corridor and an L shape, represented by Sebulang's house in Shuzheng Village, or a U shape, enclosed by independent buildings that overlap on three sides, represented by Longzhuta's house in Shuzheng Village. These houses have barely any changes in the blocks, with the second-floor flat roof vanishing, which is enclosed and rigid.

Second, brick and frame systems are widely used (expanding to the entire area of Jiuzhaigou Valley) instead of traditional wooden structures for safety, stability, and durability. This has led to the disappearance of traditional wooden construction techniques.

Third, dwellings near the main path in the Jiuzhaigou Scenic Area gradually abandoned traditional simple façades and began to use techniques such as coatings, wood veneers, and murals to decorate the exterior walls to attract tourists. The application of wood veneers involves attaching wooden boards to the outside of stones or rammed earthen walls to imitate the materials used in traditional building façades. The murals often depict traditional Tibetan Buddhist geometric patterns on window lattices and eight auspicious treasures combined with bright colors on new timber, which are very different from the original deep and simple natural wood color of traditional dwellings.

### *3.1.4. Modern dwellings*

Villagers have built modern dwellings since 2010, with a lifespan of approximately 10 years (Figure 10). With the advent of modern construction techniques and the evolving needs of the villagers, the plan of buildings has become more functional, with cast-*in-situ* concrete frame structures characterized by flexible spatial separation, rigidness, and completeness. However, façade design often departs from traditional styles because of self-organization characteristics.

The specific features include the following. First, commercial spaces for selling tourism products have been incorporated, represented by Zhaxizeren's house and Sangjiezhu's house in Zezhawa Village, with some being designed to sell food and beverages, display and sell souvenirs, and be used as tourist dining and resting spaces. The front yard in front of the entrance of the building, combined with the space of the first-floor eaves-column gallery, increases the visibility of the entrance to attract passing tourists, and the owners' living spaces have expanded. The second floor is usually reserved for living space (rather than homestay business), and additional functional rooms, such as study rooms, game rooms, and sunrooms, are set up, reflecting the increased attention to the quality of personal life.

Second, owing to the short construction period, low construction costs, and high stability brought about by new construction techniques, after the earthquake in 2017, many traditional wooden buildings were demolished and rebuilt with more stable and safe framed structures, which have had a devastating impact on traditional architectural style. As economic and social development continues, traditional Tibetan residential culture is gradually disappearing.


**Figure 10.** Illustration of typical dwelling features of modern dwellings. (A) Appearance; (B) construction; (C) structure; (D) floor plan showing functional zones. Source: Photos and drawing by the authors

Third, the façade of most new dwellings is plastered and decorated, and no longer pursues the expression of traditional cultural elements in detail, leading to the disappearance of artistic and cultural value. The doors and windows are mostly replaced with modern materials for performance considerations, and the roofs are mostly replaced with new materials such as windowsills and colored steel plates for lower maintenance costs and construction difficulties. Guided by the latest policies on architectural style updates, the exteriors of local dwellings use light yellow imitated rammed earthen coatings, decorative wood veneers, and blue-grey machine-made tiles, which have resulted in the loss of traditional Tibetan-style architectural features in forested areas, in terms of the proportion of wood veneers (more like the dwellings in the Tibetan Region in Jiarong (Editorial Committee of the Atlas of Tibetan Dwellings in Sichuan 2016)).

### 3.2. Proposal of dwellings' prototype

Combining the preservation status and representativeness of the dwellings studied, we selected four types of typical dwellings in the study area as samples for our next study: the Dingda house in Youzhong as the traditional type, the Xiongya house as the partially renovated A type, the Selangbu house as the partially renovated B type, and the Yang Qingxia house as the modern type. The four houses were mapped in detail, their iconic indicators

**Table 3. Data of building plan**

| Building plan | | | | | | |
|---|---|---|---|---|---|---|
| No. | Name | 1200×1500 | Area of each space ($m^2$) | | | |
| | | | Production Space | Living space | Spirituality space | Storage space |
| 1 | Dingda's house | 354.77 | 126.67 | 78.11 | 0 | 80.05 |
| 2 | Xiongya's house | 926.98 | 170.68 | 431.15 | 48.25 | 51.10 |
| 3 | Sebulang's house | 587.24 | 253.15 | 91.98 | 22.21 | 105.26 |
| 4 | Yang Qingxia's house | 682.99 | 0 | 482.56 | 9.90 | 9.08 |

| Building structure | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| No. | Name | Structure type | Height (m) | Total width (mm) | Total depth (mm) | Floors | Height of each floor (m) | | | |
| | | | | | | | 1st floor | 2nd floor | 3rd floor | 4th floor |
| 1 | Dingda's house | Wooden structure | 6.5 | 11300 | 17000 | 3 | 2.2 | 2.2 | 2.1 | - |
| 2 | Xiongya's house | Brick-wood structure | 10.6 | 28000 | 18000 | 3 | 2.7 | 3.0 | 3.0 | - |
| 3 | Sebulang's house | Brick-wood structure | 10.6 | 29100 | 15300 | 3 | 2.7 | 2.7 | - | - |
| 4 | Yang Qingxia's house | Brick-concrete structure | 13.0 | 15100 | 16700 | 4 | 3.3 | 3.3 | 3.0 | 2.9 |

| Building Constitution | | | | | | |
|---|---|---|---|---|---|---|
| No. | Name | Wall thickness (mm) | Typical windows (mm) | Entrance door (mm) | Façade window-wall ratio (%) | Roof slope |
| 1 | Dingda's house | 460 | 1000×800 | 700×1600 | 3.1 | 17° |
| 2 | Xiongya's house | 400 | 1500×1500 | 2100×2300 | 4.4 | 23° |
| 3 | Sebulang's house | 280 | 1300×1300 | 900×2000 | 15.6 | 21° |
| 4 | Yang Qingxia's house | 280 | 1200×1500 | 2700×2700 | 12.7 | 21° |

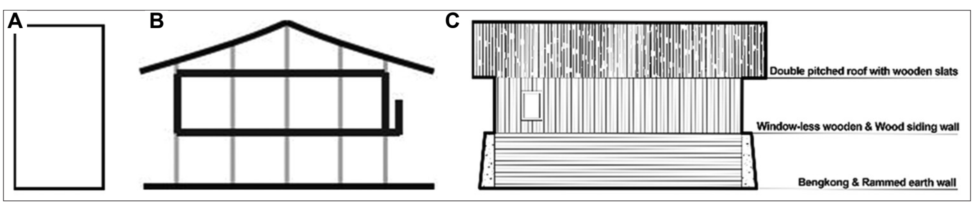
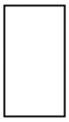
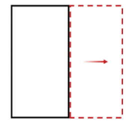
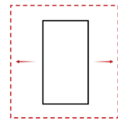
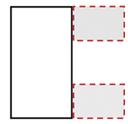
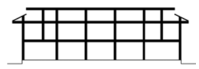
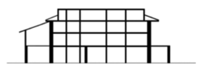
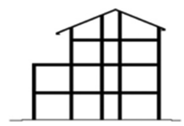
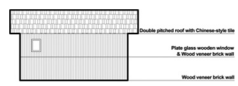
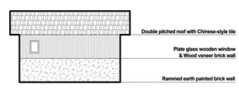
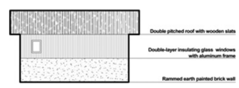



**Figure 11.** Prototypes of each dwelling factor. (A) Plan prototype; (B) structure prototype; (C) construction prototype. Source: Drawings by the authors

**Table 4. Evolution rules**

| Plan prototype | Operations | Motivation for transformation | Variant |
|---|---|---|---|
|  | Lateral extension | Space, population |  |
| | Integral extension | Space, economy, population |  |
| | Addition of wing rooms | Space, function |  |
| **Structure Prototype** | **Operations** | **Motivation for Transformation** | **Variant** |
|  | Lateral extension | Space, function, economy, population |  |
| | Elevate | Space, function, economy, population |  |
| | Addition to the ground floor | Space, function, economy, technology |  |
| **Construction Prototype** | **Operations** | **Motivation for transformation** | **Variant** |
|  | Use of modern materials | Economy |  |
| | Add finishing coat | Economy, culture |  |
| | Partial use of vernacular materials to add a finishing coat | Economy, culture |  |

were extracted, and feature calculation indicators were calculated, as shown in Table 3 below. In accordance with the architectural typology of "prototype-variant," the Dingda house in Yuzhong was used as the prototype residence (Figure 11), and the Xiongya house, the Selangbu house, and the Yang Qingxia house were used as variants, and the three aspects of the building plan, building structure, and building construction were compared and analyzed to obtain the pattern of evolution of the local residential landscape.

## 4. Results

By summarizing the elements of the prototypes in Table 4 and using operational methods and conversion motivations, we drew a table of the evolution rules of dwellings from traditional to modern architectural styles in three aspects: building layout, structure, and construction (Table 4).

### 4.1. Evolution of building plan—return to the original

Before 1984, Jiuzhaigou was inhabited by generations of semi-agricultural and semi-pastoral people in the Amdo Tibetan area. Traditional dwellings in Jiuzhaigou gradually adapted to local production and lifestyles through the natural evolution of rectangular L-, T- and U-shaped plans in terms of plan forms and functions. The dwellings mainly had four functional spaces, respectively for storage, spirituality, living, and production, reflecting the production and living conditions of Jiuzhaigou (Zheng, 2022). In 1984, the Jiuzhaigou Scenic Area officially opened to the public and attracted many tourists, leading to a surge in demand

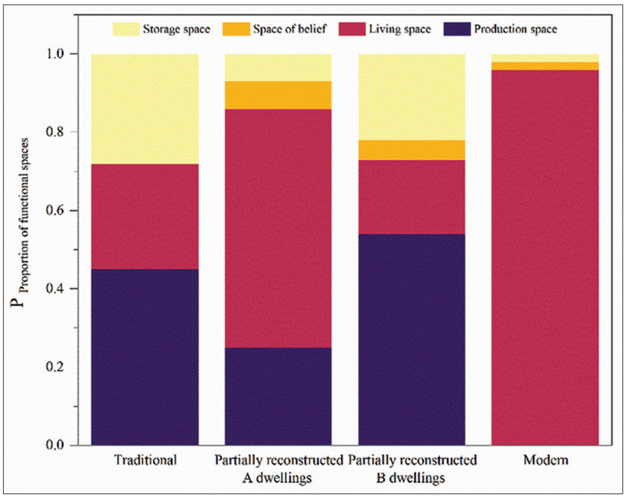



**Figure 12.** Changes in the proportion of living, production, and storage spaces in Jiuzhaigou dwellings. Source: Graph by the authors

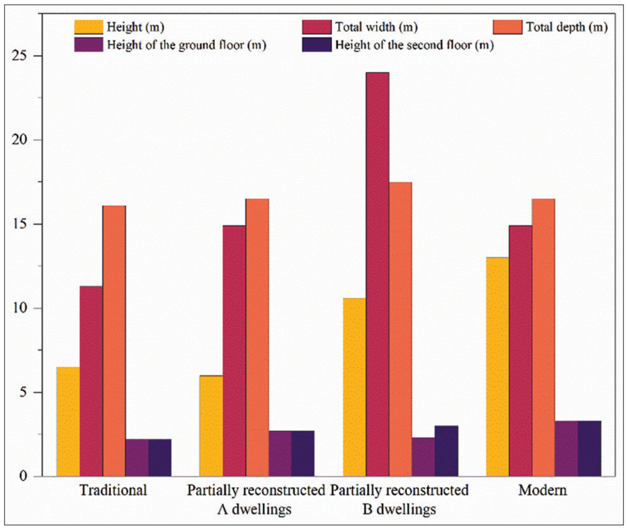



**Figure 13.** Changes in the building structure in Jiuzhaigou dwellings Source: Graph by the authors

for tourism. Against this background, the government encouraged residents to partially renovate their courtyards and provided bonuses based on the number of beds (Hu & Lei, 2014). The specific values of indicator P for each typical dwelling are shown in Figure 12; it can be observed that in the early stage, living space accounted for only about 20 percent of the entire house, but the development of tourism has stimulated the replacement of traditional production spaces, such as livestock sheds, storage spaces, and flat roofs, with living spaces. Apart from the space required for living needs, almost all other spaces were used for tourism reception and further reached about 60 percent of the proportion of living space.

After the 2017 earthquake, new or rebuilt houses prioritized safety and comfort, with living spaces accounting for more than 90 percent. The spatial structure is consistent with modern architecture, and some 4-story buildings have begun to appear. However, due to changes in tourism policies, many bedrooms are now unoccupied, as tourists are not allowed to stay overnight in the scenic area, causing economic losses for the locals. Thus, this problem must be addressed.

### 4.2. Evolution of building structure—adaptation to the environment

Jiuzhaigou is located in a forest area. Before 1984, traditional dwellings were mainly simple Tibetan dwellings with "rammed earthen walls and wooden structures," which created a high demand for wood. Between 1984 and 2000, Jiuzhaigou gradually became a World Natural Heritage site, a national key scenic spot and national nature reserve in China, and a world biosphere reserve, resulting in strict environmental protection regulations within the scenic area. By around 2000, the individual or collective felling of trees was completely prohibited in the scenic area. According to interview results with local villagers, since the end of 1990, modern structures and materials have been extensively adopted in the villages of the Jiuzhaigou Scenic Area. Owing to these policy requirements and the high cost of purchasing wood, residents began to use modern structures and materials in their homes, such as brick-concrete and frame structures, instead of traditional ones. After the 2017 earthquake, reinforced concrete frame structures were the only choice for safety considerations.

Traditional dwellings were mainly 2–4 stories high, supported by nine pillars with a pillar spacing gradually increasing from 2.3 m to 3.6 m. As dwellings evolved from traditional wooden frames to safer, more stable, and simpler brick-concrete and framed structures, the building volume increased, and the total opening width could reach 23 m. The floor height increased from 2.2 m to 3.3 m on the ground and the middle floor with an average of 2.7 m, and from 2.1 m to 3.0 m on the top floor with an average of 2.7 m (Figure 13). The dwelling form ratio expressed as W: D:H for each typical dwelling was calculated; it changed from 1.7:2.6:1 to 1.1:1.2:1, leading to an imbalanced building form according to the box-like models of dwellings of the four types of styles based on the above data of the building plan and their plan ratios (Steiniger *et al.*, 2008) (Figure 14).

### 4.3. Evolution of building construction—self-selection

The roof forms of traditional Jiuzhaigou dwellings have transformed from gable roofs to flat roofs and then back to gable roofs. Before 1984, traditional dwellings were mainly

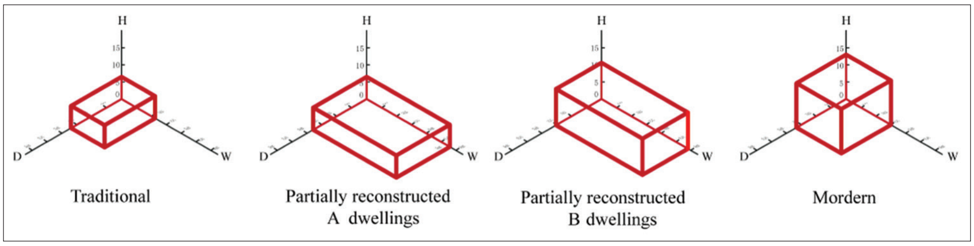



**Figure 14.** Box model of dwellings in those four styles Source: Drawings by the authors

built with gable roofs, which incorporated architectural features from the Chinese and Tibetan regions with a slope of approximately 17°. Around 2000, traditional Tibetan flat-roofed houses became prevalent due to forest environmental protection and planning policies. In recent years, villagers have focused on practicality rather than appearance. Considering the pressure from rain, frost, and snow on roofs, the roof form of the dwellings gradually returned to gable roofs with a steeper slope of 23°, which performs better in the local environment. Today, the slope is slightly reduced to 21° in modern dwellings.

In terms of wall construction, traditional dwellings have a wooden panel enclosure on the front, and the other three sides often have a rammed earthen wall outside the wooden enclosure layer, which is approximately 40 cm thick (with an average thickness of 460 mm), with distinct layers formed by tamping every 20 cm (Li, 2016). For more refined construction, horizontal wall reinforcements, such as tree branches or wooden slats, are inserted into the rammed earth, and stone masonry is used at the bottom of the wall depending on the foundation conditions. In renovated dwellings, the bottom enclosure structure adopts bricks or stones with a thickness of 40 mm, thus enhancing the enclosure stability without changing the traditional wooden structure. Modern dwellings have adopted new structural systems and materials with improved performance. Since the earthquake in 2017, the materials used in residential construction have been almost the same as those used in modern buildings, with the adoption of more sturdy brick structures. Under the guidance of construction styles, the surface of the dwellings is usually coated with rammed earthen wall paint or a wood veneer with a thickness of 280 mm.

In terms of doors and windows, traditional-style dwellings have narrow (700 mm) wooden doors that are wide enough for one person to pass through. With the rise of tourism, in renovated dwellings, Western-style large aluminum alloy anti-theft doors with widths of 2700 mm have replaced wooden doors. With technological development, flat glass windows with traditional wood carvings have gradually replaced traditional wooden windows. In modern-style dwellings, double-layer insulated

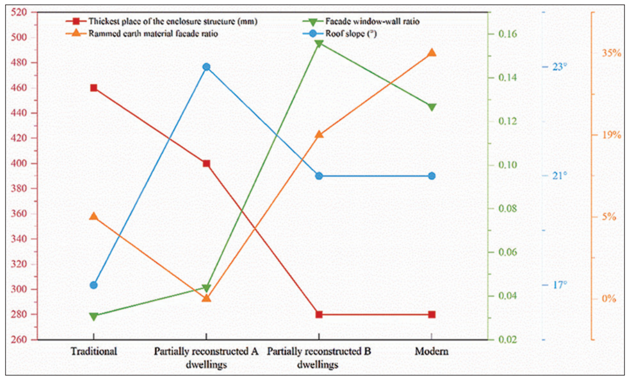



**Figure 15.** Changes in the building construction in Jiuzhaigou dwellings Source: Graph by the authors

aluminum-framed or Low-E glass windows are typically used for thermal insulation and light transmission. The specific values of indicators B and M are shown in Figure 13, and it can be found that the window-wall ratio increased from 3.1 percent in traditional dwellings to 12.7 percent in modern dwellings (the maximum was up to 15.6%). With the emergence of accommodation functions, windows increasingly appeared on the side and back façades. It is important to note that in modern-style dwellings, due to the influence of style control regulations, while the decoration is returning to local characteristics, they also face the problem of being over-proportioned. For example, the value of indicator M in traditional dwellings was only 5 percent, whereas, in modern dwellings, it has increased significantly to 35 percent (Figure 15). In addition, for the first time, a quantitative and historic study of cultural heritage in natural heritage sites has been conducted, using an inductive comparative approach to classify existing Tibetan dwellings, using architectural typology to obtain prototypes, and establishing a characteristic indicator system to compare prototypes and variants horizontally. It was found that tourism development in natural heritage sites is in full swing, and post-earthquake reconstruction is underway, but tourism development has adversely affected cultural heritage in heritage sites, and the direction of post-earthquake reconstruction has deviated from the traditional culture of Jiuzhaigou.

## 5. Discussion and conclusions

### 5.1. Discussion

From the perspective of architectural typology, this study revealed the evolution pattern of Tibetan dwellings in the Tibetan area of Amdo, taking Jiuzhaigou Tibetan dwellings as a case study through field research, literature review, index calculation, and other research methods, it explained the reasons for this pattern.

In the theoretical part of the study, it was found that the dwelling prototype used in the paper is consistent with the findings of Li *et al.* (2022), who pointed out that "the dwelling architecture in the Tibetan area of Amdo combines the characteristics of Tibetan towers and Chinese pierced wooden frames." At the same time, Wang *et al.* (2019) and Lu (2017) have integrated the architectural and morphological elements of traditional dwellings into the three elements of architectural plan, structure, and construction and have conducted an empirical study to confirm the scientific validity of this classification.

Meanwhile, compared to previous qualitative studies (Wang, 2015; Ke, 2015; Guo, 2016; Chen, 2017), this study constructed a quantitative analysis framework, and the findings are more objective and scientific, which can effectively bridge the development of subsequent design practices.

Finally, in addition to abstracting buildings into different symbols as most architectural typology studies do (Xin, 2020; Li & Wang, 2015; Xiang, 2019; Zhang, 2016; Yuan *et al.*, 2022; Meng & Luo, 2016; Zhu *et al.*, 2016), this study also focused on the environment in which the buildings are located, which includes the natural, policy, and human environments. While Guo (2016) argued that the adaptability of dwellings in the Tibetan areas of Amdo is reflected in the choice of economic and technological development, new needs brought about by changes in living patterns, and the role of integration with foreign cultures. This study found that due to the specificity of the geographical environment, changes in management policies brought about by environmental changes such as earthquakes can also have an impact on the style of dwellings; the "prototype-variant" comparison further revealed the dominant role of policy change in the evolution of the landscape.

### 5.2. Conclusions

In summary, the study yields the following conclusions:

(1) In the evolution of the building plan in the Tibetan area of Amdo, the plan forms have become more flexible, and the functional space types have become increasingly rich, but on the whole, building plans are still returning to the traditional type. This is reflected in the fact that with the changes in production and lifestyle, the plan form has evolved from traditional rectangular shapes to L-shape, T-shape, and U-shape through horizontal and vertical extensions or additions. Functionally, the production function of the ground floor has disappeared; the first-floor outer corridor has been formed, and the sun terrace has disappeared; storage space has been reduced from 28.1 percent to 1.8 percent; and the proportion of living space has increased from 20 percent to over 90 percent. This is mainly related to the change in production and lifestyle brought about by the rural revitalization policy. In the past, the Tibetans in Amdo lived by the traditional primary industry, so the living space placed more emphasis on the production function, but now there is a complete conversion from traditional primary industry to tertiary industry, stimulating a focus on the comfort of living space.

(2) Traditional dwelling structures in the Amdo Tibetan area have been influenced by modern architecture, with a structural selection giving priority to economy, space size, and safety performance, and the use of traditional structures is gradually decreasing, as evidenced by the evolution of traditional Tibetan dwelling "rammed earthen wall with crumbling hollow" into the Han Chinese through-drawer and beam-beam styles, or a mixture of both. This is consistent with Li *et al.* (2022)'s finding that "the architecture of dwellings in the Tibetan area of Amdo has the characteristics of both Tibetan towers and Han-style pierced wooden frames," but the new dwellings are mostly of reinforced concrete frame construction; the total openings and depths tended to increase, and dwellings with more than 3 stories began to appear, with the height of each story increasing. This is directly related to the current policy of restricting timber harvesting in the Tibetan areas of Amdo. If Tibetans need to reuse traditional timber construction materials, they need to transport them from distant cities into the Tibetan areas, which will result in a higher cost; therefore, most Tibetans choose to buy modern materials from the building material markets closer to the Tibetan villages.

(3) The architectural structure of the Tibetan area of Amdo reflects the cultural consciousness of the owners of the dwelling themselves and is more selective, with individual differences gradually becoming apparent compared to the traditional plain style, as shown by the following. At the level of the transparent envelope, the window area on the façade of the residential buildings has increased from 0.6 percent in traditional type to 23.5 percent in the modern type, and the window

materials have evolved from non-glass, wooden windows to flat glass, wooden windows and double, hollow glass, aluminum-framed windows. At the level of the opaque envelope, the walls have evolved from traditional rammed earthen and wood-paneled walls to stone and wood, brick and wood, steel, and mixed materials, accompanied by an increase in the number of façade finishes. At the same time, the proportion of rammed earth paint finishes on the façade is much larger, developing from 5 percent in the traditional style to 35 percent in the modern style. The roof has undergone a transformation process of "sloping roof-flat roof-sloping roof," and the materials have evolved from traditional wooden tatting boards to small green tiles, colorful steel plates, and other modern materials.

(4) In the rural settlements of the Ando Tibetan region, the environment, managers, and villagers interact with each other, and the method and degree of influence are visually reflected in the style of the dwellings. Guo (2016) argued that the adaptability of the dwellings in the Ando Tibetan region is reflected in the choice of economic and technological development, the new needs brought about by changes in living patterns, and the role of integration with foreign cultures. This study argues that environmental changes such as earthquakes have led to changes in the management policies of heritage sites and that this has fundamentally transformed the villagers' mode of production and determined the direction of the evolution of the residential landscape; villagers chose the detailed components of their dwellings on their own, out of their local cultural awareness. However, the existing guidelines for the design of the Tibetan landscape in Amdo have deviated from the control of building heights, the choice of façade materials, and the proportion of the area of different façade materials, leading to a distortion of cultural heritage.

## 6. Further works

This study explored the evolutionary patterns of the residential buildings of the Amdo Tibetan ethnic group, who have settled and thrived in the western Sichuan region over an extended period. Adopting an architectural typology approach, this study dissected residential buildings into prototypes and variants and examined the specific impact of various factors on their style through visually appealing illustrations and charts. However, owing to the limited scope of the study, sample size and disciplinary constraints, this study may not be free from errors, and further research is required to address these limitations. For example, in the selection of "prototype and variant" as dwelling types, this research was based on the state of preservation. A follow-up study can improve the research methods while expanding the sample research quantity, such as establishing evaluation indexes to evaluate samples and then identifying prototype dwellings. Moving forward, new technologies such as finite element analysis and structural dynamic characteristic testing can be used to study the structural models of different types of traditional timber buildings (Chun *et al.*, 2019). The research team plans to leverage the findings on the architectural heritage and evolution of Tibetan dwellings in Jiuzhaigou to evaluate the effectiveness of government guidelines on village appearance by incorporating village color schemes. In addition, the team will conduct further research on the organic renovation of village dwellings, building on existing surveys, and mapping foundations in the context of industrial transformation.

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## Conflict of interest

All authors declare they have no competing interests.

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ACCSCIENCE PUBLISHING

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ORIGINAL ARTICLE

# Renewal of industrial space in Hong Kong and Shanghai: Policy review and comparison

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(This article belongs to the *Special Issue: Theoretical and Practical Innovations in Relation to China's Urban Regeneration*)

## Abstract

Industrial space renewal is a strategic planning choice for cities undergoing de-/post-industrialization against the backdrop of land resource constraints. This study reviewed industrial space renewal policies in Hong Kong and Shanghai from a political economy perspective. With the analytical framework of political economy, the study reveals that, in the power flow of industrial space renewal (stressed on ownership), Hong Kong's private sectors are active, and Shanghai is dominated by public power. In the political and economic environment, differences in government and market forces lead to different planning models and outcomes. Industrial building renewal in Hong Kong is mostly progressive due to diversified developmental forces, whereas industrial land renewal in Shanghai is mostly comprehensive and rational, assisted by blueprint-based planning. Pros and cons are rooted in both cities. Thus, an in-depth examination is of great significance for better decision-making in the future.

***Keywords:*** Reuse of industrial building; Transition of industrial land; Restructuring; State-market; China

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## 1. Introduction

Renewal of industrial space refers to the reuse of industrial structures or built environments that are obsolete due to deindustrialization or post-industrialization. Such abandoned or underutilized space is often a brownfield, which has the potential for redevelopment or other economic opportunities. The specific definition of industrial space renewal varies, depending on the targeted place and local policymakers. As a special, significant segment in urban renewal, the renewal of industrial buildings or land is an indispensable issue against the backdrop of space resource constraints and socioeconomic transition in China. On the one hand, quotas for construction land are limited in large cities, such as Beijing, Shanghai, and Shenzhen. Thus, urban land redevelopment, especially industrial land redevelopment, has been a crucial pathway toward high-quality built environment development. On the other hand, reindustrialization in developed countries and the higher threshold for manufacturing industry due to rising human capital and land costs have shocked the advantage of "made in China," thus dropping production in many places. Disentangling the transitional path and dynamics behind it would assuredly buttress policymaking in industrial space renewal.

Given the widespread prevalence of neoliberalism across the globe, political economy has proved to be a viable and explanatory lens for examining diverse urban phenomena and spatial development (Li & Chan, 2017a). Reading urban industrial space renewal from the perspective of political economy, the process involves interactions between stakeholders such as the original and new owners of the land (or buildings), the planning approval and compilation authorities, and the potential developers and tenants. This is, essentially, space (re)production under the capitalist operation of society wherein social relations have been (re) produced (Lefebvre, 1991). Therefore, it would be reasonable to infer that industrial space renewal shall not isolate from social restructuring and may result in disparity under different political-economic contexts. In this regard, Hong Kong and Shanghai are the selected cities for a comparative observation given their similar industrial transitional reality but dissimilar political-economic backgrounds: similar transitional needs from industrial to post-industrial phase but dissimilar political-economic milieus shaped by the role and relation of government, market, and society. Both cities have formulated policies and measures to guide industrial renewal, but Hong Kong grew in a free-market ideology embracing "small government, big society" concept where factories continued to be privatized, whereas Shanghai underwent the transition from a centrally planned system to a socialist market economy where statization was the main theme for local factories. The main responsible stakeholders for industrial space (re)production in these two cities are, therefore, essentially different, and the renewal path and consequences bear their unique characteristics, which will be reviewed and discussed in the article.

## 2. A political-economic analysis toward urban industrial space renewal

There are two layers of political economy in this research for follow-up study. First, it serves as the governance environment for industrial space renewal, in which cities are undergoing an economic transition of deindustrialization or post-industrialization, and disparity in urban politics leads to different renewal paths and planning modes. Second, it offers a theoretical framework to unveil public–private forces and their interrelations. Change of power structure and its relation with an urban function and space in industrial renewal are particularly emphasized. These two layers are considered interdependent constituents for political-economic analysis toward industrial space renewal in Shanghai and Hong Kong.

### 2.1. Urban political-economic environment and industrial space renewal

Obsolete industrial space is co-reshaped by state and market forces in cities. This means that different political-economic milieus may result in contrasting renewal paths and planning modes.

Since neoliberalism prevailed across the world in the 1970s, there have been two main political-economic environments: roll-back neoliberalism, characterized by laissez-faire, deregulation and dismantlement of state power, and roll-out neoliberalism, characterized by active state intervention and re-regulation. These two types of governance ideologies have profoundly influenced development across the world (Peck & Tickell, 2002). Laissez-faire economic policies stress on forces from the private sector instead of government intervention, resulting in a "small government, big market" political-economic setup. Against this backdrop, planning approaches are often gradual and progressive. The idea of progressive planning believes that renewal and transformation begin with partial, individual exploration and then being solidified as an integrated social regulation and culture (Healey, 2006). A political-economic environment that attaches importance to state regulation and intervention would suppress market mechanisms, resulting in a "strong government" or "omnipotent government." In this context, planning approaches evolve as rational and comprehensive, characterized by blueprint planning. Blueprint planning emphasizes the systematic promotion of functional, power, and spatial changes through meticulous methods and believes that elite decision-making should be assisted by scientific methods and technical rationality (Taylor, 1998).

Renewal of industrial space occurs mostly in areas undergoing de-industrialization or post-industrialization, where the proportion of industrial activities (especially heavy industrial activities) has dropped significantly or transferred to other places or upgraded to service industries due to rising capital or labor costs (Iversen & Cusack, 2000). Since the 1960s, with a new round of globalization and economic restructuring, many cities have experienced de-industrialization or post-industrialization, manifested in the abandonment and underutilization of factories and warehouses (Golland & Watkins, 2002; Andres & Gresillon, 2013; Marshall, 2014). The adjustment of economic structure makes those traditional, productive buildings outdated or unused, calling for the transformation of industrial spaces for non-production purposes.

Although the economic environment of industrial space renewal is overall similar, differences in the political environment often lead to diversified paths of functional restructuring. In a political milieu where private force has been increasingly active, the renewal of cities was mostly private-led and initiated from the bottom. For instance, in America, though the large-scale reconstruction of overcrowded slums was promoted by the public sector during the 1960s, urban renewal later in the 1980s encouraged the private sector and was characterized by a bottom-up approach. In a political milieu with an omnipotence of government power, such as China, urban renewal is mostly carried out under the guidance and regulation of the public sector, characterized by top-down approaches.

Although market forces have played an increasingly important role in renewal in recent years in cities such as Shenzhen, China's marketization does not mean the retreat of government power. Instead, the government's regulatory power has been strengthened through marketization (Li & Chan, 2017b; Ding & Wu, 2017).

### 2.2. Urban political-economic theory and industrial space renewal

The theory of urban political economy opens the way to understanding urban governance contextually and informs renewal research of urban industrial space (Shen, 2000). The earlier political-economic analysis focused on how urban government copes with urban affairs and relations of government and business community (Stone, 1989; Logan and Molotch, 1987; Kantor, 1996). With the acceleration of capital expansion against economic globalization, the theory of urban political economy has been widely used in countries and cross-regions to analyze the influence of the flow of capital and local politics on cities; examples include governance of urban renewal in shrinking cities in East Germany (Bernt, 2009), comparative study of urban planning mechanisms in Hong Kong, Singapore, and Taiwan (Ng, 1999), and comparative study of the developmental paths of large-scale projects in Kop van Zuid Island in Rotterdam and Glasgow Harbor (Doucet, 2013). These studies mainly address the role of private forces or how government and the market interact in urban operations, but changes in policies and the consequent planning modes remain less understood.

In China, market mechanisms were introduced to accumulate wealth rather than to reduce the capacity of the government (Zhang & Chen, 2016). This is reflected in cases such as Tian Zifang in Shanghai, where grassroots-level authority that the street office administratively empowered enabled the mobilization of social resources and the enlargement of interest-binding coalitions to promote urban renewal. The case study of Songjiang New Town unfolds that investment and development companies with networked relations to government and economic autonomy are able to expand the jurisdictional power of district government over new towns, thus propelling new town development (Li & Chiu, 2017). Research on the spatial restructuring of the Shanghai Expo identifies the key role of municipal government, whose power upgrades to the national level to negotiate with central state-owned enterprise (SOE) and downscales to the district level for efficient relocation (Chan & Li, 2017). Therefore, disentangling the roles and functions of governments at multiple levels and those "government-affiliated agents" (such as administrative committees, subdistrict offices, and development companies with government backgrounds) is the key to enriching literature on urban political economy in the context of China.

Renewal of industrial space is shaped by different participants (including original owners or land rights holders, public sector of renewal implementation entities, planning preparation and approval entities, developers, etc.) wherein powers flow in between to create diversified paths to policy mobility and policymaking (Smith, 1992; Li *et al.*, 2022; Feng & Tang, 2013).

## 3. Industrial space renewal policy and practices in Hong Kong

Since the 1980s, with policy implementation of opening up and FDI attraction in mainland China, the manufacturing industry in Hong Kong has continued to transfer to the Pearl River Delta and inland areas due to geographical proximity, social relations, and lower costs, resulting in the well-known "front door, back factory" mode between Hong Kong and Guangdong (Yeh & Xu, 2008; Liao & Chan, 2011). Hong Kong has experienced rounds of de-industrialization, with substantial industrial spaces vacant or unused, and renewal of industrial buildings has become the foci of the government of the Hong Kong SAR. Given that private industrial buildings with multiple ownerships account for nearly 70% of the total number of industrial buildings[1], the Hong Kong government has been working hard to deregulate and released two rounds of revitalization policies in 2010 and 2018 to encourage flexible reuse, retrofitting, and renovation of industrial buildings. These reconstructions were mainly distributed in Kwun Tong, Kwai Chung, Tsuen Wan, Sheung Shui, Tuen Mun, Shatin, Chai Wan, and Aberdeen (Figure 1), which played an important role in promoting the socioeconomic transition of Hong Kong.

The first round of revitalization policy was implemented from April 2010 to March 2016, also known as "Industrial Building Revitalization Policy 1.0," in line with the six-pillar industries: education, medical care, testing and certification, environmental protection, innovation and technology, and cultural and creative industry. During this period, the Lands Department received 22 reconstruction applications and 226 retrofitting applications. As of

1 Refer to: Industrial buildings in Hong Kong (ISSH30/18-19). (2019). Legislative Council Secretariat, Research Office, Hong Kong.

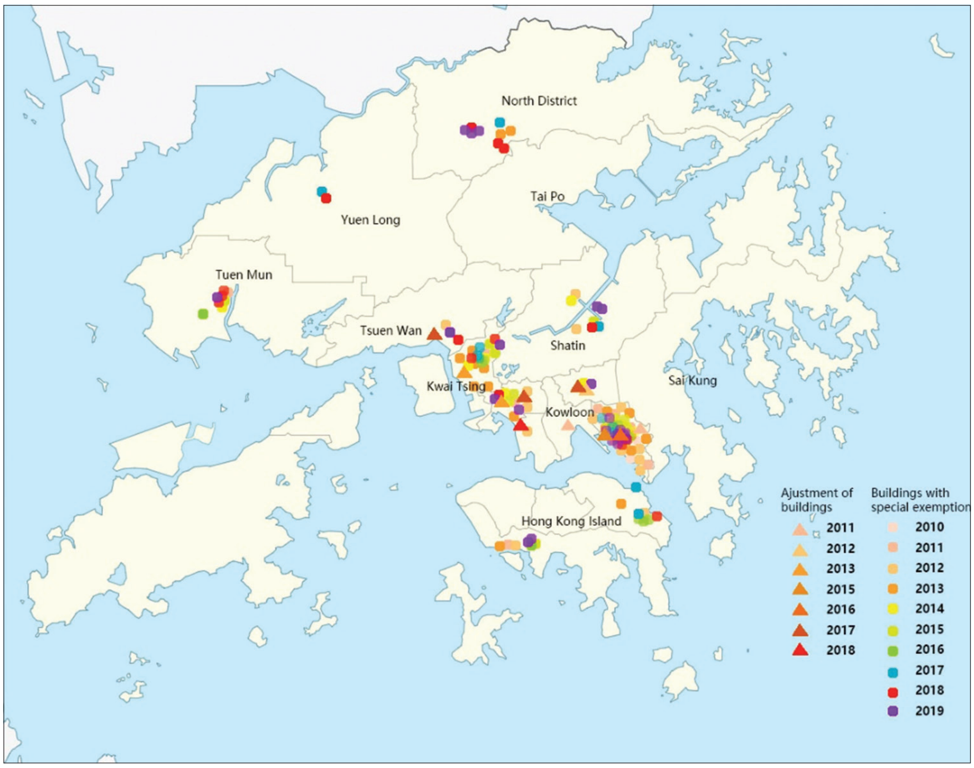


**Figure 1.** Distribution of industrial building renewal in Hong Kong (2010 – 2019). Source: Lands Department in Hong Kong

December 31, 2019, except for the cases withdrawn or terminated after approval, 14 reconstruction applications and 138 applications for whole-building retrofitting have been approved, accounting for 9.5% of the total number of industrial buildings and able to offer more than 340,000 and 2,130,000 sqm floor area respectively. However, the effectiveness of the first-round revitalization policy was not satisfactory due to the sharp rise in price for industrial buildings and rents. Figure 2 shows that the growth rate of the price index of private industrial buildings with multiple ownerships in Hong Kong was significantly higher than that of other types of properties during the same period.

According to the report from Rating and Valuation Department, the price and rental indices of industrial buildings in Hong Kong have risen by an average of 16% and 8.9%, respectively, each year. Although the vacancy rate of industrial buildings dropped to 6.1% at the end of 2017 (from 10.9% in 2001) in the first round of policy, many buildings no longer fit modern fire safety standards, and the cost and difficulty of renovation are considerable. In addition, quite a few industrial buildings have been used for non-industrial purposes through an informal transition that does not comply with the statutory planning system or land leases, motivation from the market to renew these buildings thus is limited, and the process is slow (Xian & Chen, 2015). This led to limited success in the reconstruction of

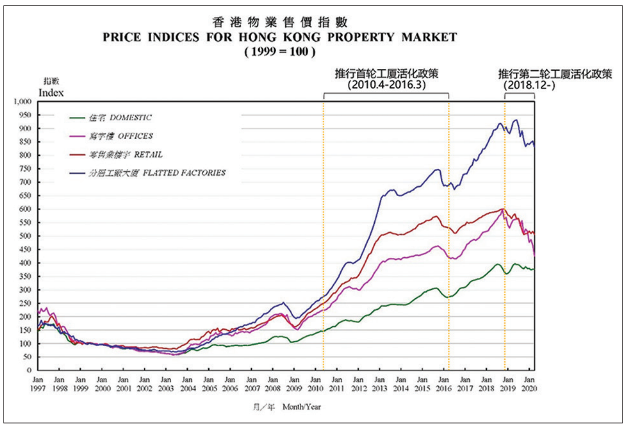


**Figure 2.** Price indices for Hong Kong property market (1997 – 2020). Source: Rating and Valuation Department in Hong Kong

industrial buildings. Urban Renewal Authority (URA) was set up to speed up the renewal, under which the residential development plan of Cheung Hing Industrial Building in 12P Smithfield, as well as the reconstruction plan of Wing Hong industrial building at 777 – 783 Yu Chau West Street, were two schemes to cope with the socioeconomic transition of Hong Kong (Figure 3). However, due to the disagreeable negotiation with multiple owners and unaffordable compensation, the former case failed to be renewed, and the latter was only partly renewed.

The Hong Kong SAR government announced to restart the "Industrial Building Revitalization" plan in October 2018, in its Chief Executive's 2018 Policy Address based on the review of the effectiveness of the first round of policies, known as "Industrial Building Revitalization Policy 2.0." The policy aims to stabilize the price of industrial buildings and to improve market motivation for renewal. The second round of measures relaxed the rate of increase in the floor area ratio of industrial building redevelopment, allowing the increase in the floor area ratio of non-residential redevelopment land to 20%. Fee waiver of title deed transfer is also allowed on retrofitting of buildings, if the owner provides no less than 10% of the floor area for government-designated purposes. The measure aims to incentivize private capital to intervene in revitalization. For spontaneous renovations by the society, flexible planning and design regulations are allowed during the transitional period. The second round has received positive feedback from the market. Until January 3, 2020, only 1 year after the policy was launched, the Town Planning Board had received 37 reconstruction applications, 12 of which have been approved and distributed in Kwun Tong (5 cases), San Po Kong (2 cases), Tsuen Wan (2 cases), Kwai Chung (2 cases), and Hung Hom (1 case) (Figure 1). Among them, 4 cases have applied for lease modification to the Lands Department, and the activity is much higher than that in the first round. Another distinct outcome of policy in the second round is the dropping down of the price index of industrial buildings compared with that of residential buildings.

## 4. Industrial space renewal policy and practices in Shanghai

Shanghai has been in a leading position in China's industrial development since the mid-19th century when the city opened its ports. For the past 30 years, the city has transited into a post-industrial society, with the ratio of tertiary industry surpassing 60% in 2012. Alongside, this transition was an increase in unused or vacant industrial land against the backdrop of a shortage of quotas for construction land. According to the data from Shanghai Municipal Planning and Natural Resources Bureau, until the end of 2013, there was 772 sqkm of industrial land, which accounted for 26% of urban construction land and is mostly characterized by low efficiency, low-end, and extensive (Figure 4).

Indeed, policies made for the renewal of industrial land can be traced back to 1998, when SOE reform led to the crisis of unemployment. To support the survival of those SOEs, the government has issued "Interim Provisions on the Management of Administrative Allocation Land Use


**Figure 3.** The withdrawal case of Cheung Hing Industrial Building and the partly renewed case of Wing Hong industrial building. Source: https://hk.on.cc/hk/news/

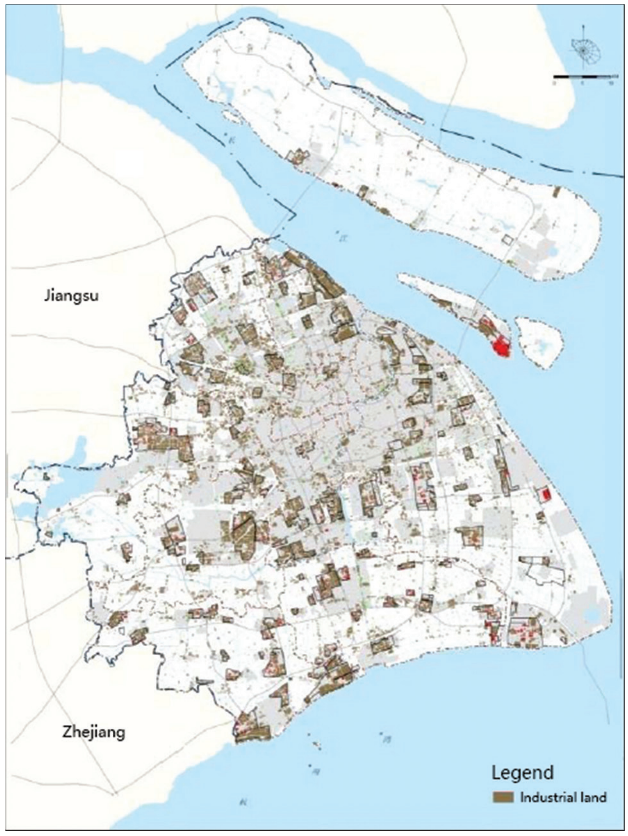


**Figure 4.** Distribution of industrial land in Shanghai (2011). Source: Shanghai Urban Planning & Design Research Institute

Rights in the Reform of State-owned Enterprises" (Order No. 8, State Land Administrative Bureau), allowing the functional transition of the administrative allocation land by compensation of land price without change of land use. Many SOEs thus could enter the real estate market by paying a small amount of money, making profits from real estate development projects on administrative allocation land. Such renewal of industrial land, however, primarily benefits the original property owners and developers and results in the loss of state-owned assets and rent-seeking. After 2000, "Interim Provisions on Strengthening the Planning and Management of Land Use Change in Central

City" (No. 355, 2004, Shanghai Planning Legislation) and related policy control over land use change were issued, strictly limiting residential development projects on administrative allocation land and forbidding land lease through agreement. Market incentives were suppressed, and revenue generated from real estate developments decreased; substantial administrative allocation of industrial land was left unused. Informal renewal came into being at this stage when some industrial buildings were retrofitted to serve office or commercial use without the alteration of land use. For some period, informal renewal balanced the interests of government, enterprises, and investors and was permitted by local government. "Notice of the Shanghai Municipal Economic Commission and the Publicity Department of the Municipal Party Committee on Accelerating the Development of Creative Industries in Shanghai" (No. 452, 2008, Shanghai Economic and Information Committee, regulation) and "Notice of Several Opinions on Promoting the Economic and Intensive Utilization of Land and Accelerating the Transformation of Economic Development Modes by General Office of the Shanghai Municipal Government" (No. 37, 2008, Shanghai Municipal Government Office) were issued to support the informal renewal, which to some extent pushed up the price of industrial land (Figure 5). However, informal renewal was only a transitional solution; a formal, rational renewal path is needed to specify the control.

Since 2005, the renewal of industrial land in Shanghai has evolved increasingly formal. This is exemplified in

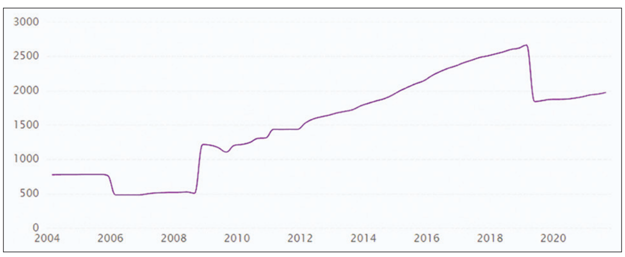


**Figure 5.** Price for industrial land in Shanghai (2004 – 2021). Source: Ministry of Natural Resources (www.ceicdata.com)

the stricter industrial land classification and management with added land use types and supporting land policies by the local government. In the issued "Shanghai Regulatory Detailed Planning Technical Guidelines" (No. 51, 2011, Shanghai Municipal Government Office), the land uses for industrial research and development (R&D) (M4) and scientific research and design (C65) were added to distinguish the nuance of functions and keep land income in industrial parks. The guidelines aim to promote refined governance over industrial land but were yet to be satisfied. The main problem is the lack of supplemented land operation rules and clear renewal actions for land use change. Most of the renewal remains stuck to the transition to industrial R&D (M4), which is more simple, more convenient, and can be exempt from land auction, leading to mixed land use of industries, offices, and residences. In this regard, "Pilot Opinions on the Related Work to Add Land Use for R&D Headquarters" (No. 1023, 2013, Shanghai Municipal Government Office) was promulgated to clarify land use types and transaction policies. The opinions regulate land transaction procedures from many aspects, for example, development index, the nature of the land, floor ratio, and so on. However, the market was disinterested in the transition as this regulation was too strict. Another round of policy adjustment took place in 2014 with the launch of "Implementation Measures for the Revitalization of Industrial Land in Stock (Trial)" (No. 25, 2014, Shanghai Municipal Government). The measures clarify the land leasing policy, improving the land price for R&D headquarters, introducing full lifecycle management for land, allowing retreat from land transition and relaxing the access at the same time, and setting lines for the ratio of self-owned properties, thus promoting public service and green construction. All these policies have facilitated the transition of industrial land renewal from informal to formal; formal renewal paths have become the mainstream in the market, and the holistic transition has become prevalent under a "strong government" or "omnipotent government" environment. The factory area renewal of Bright Dairy & Food is one example to illustrate this (Figure 6).


**Figure 6.** The holistic industrial land renewal case of Bright Dairy & Food factory. Source: Shanghai Minhang Bureau of Planning and Natural Resources

**Table 1. Comparison of industrial space renewal policy and practices in Hong Kong and Shanghai**

| City / Items of renewal | Hong Kong | Shanghai |
|---|---|---|
| Political economic milieu | Roll-back neoliberalism characterized by laissez-faire policy and less intervention from the government, "small government, large market" for economic regrowth | Roll-out neoliberalism characterized by active state intervention, "strong government," or "omnipotent government" for socioeconomic rebalance |
| Industrial adjustment | De-industrialization with the hollowing out of manufacturing to Pearl River Delta and inland | Post-industrialization, with manufacturing transferring to the outskirts, Yangtze River Delta, and inland |
| Planning approach | Gradualist planning with multi-interaction, social process consolidated by partial exploration | Blueprint and rational planning, scientific decision-making to form a stable social process |
| Policy evolution of the two rounds of renewal | Relaxation of policy in line with the market response, improve floor ratio of industrial buildings and waive fees for wholesale reconstruction, promote renewal, and secure public interest | Informal to formal renewal; functional renewal into commerce, creative industry, and producer service industry; seek a balance between state and market in line with the market response |
| Participatory bodies in two rounds of renewal | First round: slow renewal, market is reluctant to join<br>Second round: active renewal, relaxation of renewal policy to introduce private capital | First round: informal and passive renewal, SOEs make profits from administratively allocated land<br>Second round: formal and active renewal; state encouragement, enterprises followed |
| Outcomes of the two rounds of renewal | Offering space for economic transition<br>First round: unsatisfactory results due to rising price and rent of industrial buildings<br>Second round: improved results under active participation of market | Propelling industrial land renewal but with resistance after the informal renewal<br>First round: loss of land income and unordered space function under informal renewal<br>Second round: regulated market with the fair market response |

## 5. Discussion and conclusion

The evolving policies on industrial space renewal in Hong Kong and Shanghai have exemplified the dissimilarities of renewal paths and planning approaches against different political-economic contexts (Table 1). In Hong Kong, the "small government, large market" concept was embraced by local governance, leading to a gradualist, sometimes tough negotiable renewal process. The established Urban Renewal Authority (URA) has aimed to intervene in building and land redevelopment, but often confronted resistance from uncooperative landlords that hindered the process, resulting in the failure or limited success of renewal plans, such as the Cheung Hing and Wing Hong industrial buildings. In this regard, the wholesale reconstruction would be replaced by partial or minor renewal under market pressure. This is indeed a result of "continuous limited comparison" by all parties in the society, rather than a "rational comprehensive decision-making" by individual leaders (Lindblom, 1959). Although such renewal may sacrifice some efficiencies for urban development, negotiable forces from society could also be the sources of conditional equity that are indispensable for modernity and legalization. It reflects that renewal has been solidified to social regulations through partial exploration in the context of pluralistic gradualism. Another significant feature of Hong Kong's industrial space renewal is the small scales of the projects, which are often industrial buildings located in a confined territory. This is especially true in Shatin and Kowloon, with few exceptions in the New Territories, Yuen Long, and Kwai Chung.

In Shanghai, governments, especially those with authority in land approval and development, dominate industrial land renewal, and most projects are large scale in the nature. As the value of land in Shanghai has been increasing annually, industrial enterprises occupying a large amount of land in the city center constantly moved out and left room for high-value-added urban functions. With intervention from the government, holistic renewal is possible, and the plan is blueprint and comprehensive in nature to deploy functions in space. In Shanghai, the municipal, district, and street office level authorities ensured the smooth progress of the renewal project through systematic plan implementation. This "strong government" force-led renewal paradigm showcases the efficiency and executive power of the top-down planning and control system and explains why such a large-scale renewal project is possible. As indicated in the case of Bright Dairy and Food factory area renewal, unified deployment from the Minhang district government has fostered a systemic, holistic renewal plan, which not only resumed industrial land for higher density development, but also responded to policy initiatives of the central and Shanghai government, offering public rental housing to resolve social issues. Based on research and scientific decision-making, the renewal has evolved to be a stable social procedure under blueprint-style comprehensive rationalism (Taylor, 1998). Yet, over-unification is likely to lose diversity, leading to a solidified urban process. With the development of social diversity, blueprint planning lacking bottom-up guidance would confront increasing challenges in the near future. It is, therefore, imperative to integrate top-down plans and bottom-up participation to maintain the balance of efficiency and equity, consistency, and diversity. Moreover, independent and adaptive plan-making by professionals and a stable local organization may be helpful for enhancing policy consistency and continuity, especially during the leadership transition so that plans are possible to rely on both local technical forces and leadership, with dual track scenarios to guarantee implementation.

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## Conflict of interest

The authors declare they have no competing interests.

## Author contributions

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*Investigation:* All authors
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*Writing – review & editing:* Lingyue Li, Yueli Xu

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## Availability of data

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ORIGINAL ARTICLE

# Indoor photothermal environment in traditional Miao dwellings in western Hunan province: Field measurements, data simulation, and mitigation strategies

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## Abstract

Rapid urbanization and population growth have escalated demands on the built environment, quality of life, and energy consumption. Consequently, the academic community has delved into the exploration of design methods, construction techniques, building materials, and other climate adaptation strategies, particularly focusing on traditional houses. This study examines the indoor photothermal environment and energy consumption of traditional Miao dwellings in Xiangxi Tujia and Miao Autonomous Prefecture, Hunan Province, China. Through monitoring and simulation, the paper investigates the compatibility between the dwellings and their surrounding environment, shedding light on the efficacy of traditional Miao houses in adapting to local climatic conditions. The findings reveal notable improvements in indoor temperature and humidity levels within typical Miao dwellings, showcasing enhanced climate adaptability compared to the outdoor environment. Nonetheless, the study highlights inadequacies in the indoor natural light environment of these dwellings, necessitating the introduction of light wells to meet contemporary standards. By summarizing the strengths and weaknesses of the indoor photothermal environment in traditional Miao houses in western Hunan Province, this research further evaluates the adaptability of local houses to the regional geographic climate. Additionally, the study offers targeted recommendations to address the identified weaknesses.

***Keywords:*** Western Hunan; Miao; Traditional dwellings; Indoor thermal and light environment; Simulation update

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## 1. Introduction

Energy scarcity and climate change have emerged as pressing global concerns, with buildings accounting for over 30% of the world's total energy consumption. Significantly, within this consumption, 30–60% of energy is allocated towards enhancing indoor thermal conditions (Bodach *et al*., 2014; Lee *et al*., 1996; Vefik Alp, 1991). Rapid urbanization in China has contributed to a 45% surge in building energy consumption over the past two decades (Nguyen *et al*., 2011). The Chinese government has committed to achieving peak carbon emissions by 2030 and establishing a carbon-neutral society by 2060 while concurrently ensuring a comfortable and healthy indoor environment with a target building energy consumption below 1% (Qi *et al*., 2020; Fang *et al*., 2019). Therefore, improving building energy efficiency by exploring passive energy design is one of the most effective ways to achieve sustainable building development (Zhang *et al*., 2021).

Traditional dwellings of all types still exist in nearly a third of China's mountainous regions (Hou *et al*., 2021). Traditional dwellings enhance the comfort of the indoor environment through rational site selection, site design, spatial layout, structural optimization, and material selection. It reflects the unique and locally adapted dwellings gradually formed by the local people during long-term development and evolution according to the natural geography and climate, social and economic development, historical and humanistic environment, as well as ethnic and social customs, which to a certain extent achieve harmonious coexistence between humans and nature. At present, many researchers are engaged in the study of traditional dwellings in different regions and ethnic groups (Fernandes *et al*., 2019; Li & Zhu, 2022; Liu *et al*., 2023; Rijal, 2021; Sözer & Bekele, 2018; Yang *et al*., 2020; Zhang *et al*., 2022; Zhao *et al*., 2020). For example, Juan *et al*. (2019) monitored and simulated the indoor heat, light, and ventilation environments of traditional dwellings in the Qinba Mountains in summer and winter and summarized the advantages and disadvantages of the physical environment of the dwellings in coping with climatic characteristics (Juan *et al*., 2019). Chi *et al*. (2020) selected a traditional dwelling in Sizhai, Zhejiang Province, as the case study and calculated the daylight coefficient, air temperature, and airflow rate in test scenarios with different combinations of building orientation and window-to-wall ratios. The optimal interval of the window-to-wall ratio of the building was investigated (Chi *et al*., 2020). Through the testing and simulation of the indoor physical environment of traditional residential houses and the analysis of the adaptability of the houses to the outdoor environment, they summarize the strengths and weaknesses of the indoor physical environment of local traditional residential houses. With that, they aim to maximize the use of local materials and resources, adapt to the regional climate and environment using passive energy-saving technologies, improve the indoor comfort of traditional residential houses through scientific quantitative analysis, propose corresponding renovation strategies, and apply them to the renovation of traditional houses. The study provides a reference for the optimization of thermal comfort in traditional houses in other regions.

## 2. Materials and methods

### 2.1. Research rationales

The emergence of ecological architecture, rooted in bioclimatology, gained prominence in the early 1960s, with Olgyay spearheading the systematic integration of architectural design with climate, regional characteristics, and human comfort (Olgyay, 1963). Olgyay advocated for designing buildings that align with the fundamental principles of the natural climate of a given region, enabling controlled adaptation of specific climatic elements to positively impact indoor comfort. Sustainable architecture, therefore, embodies an approach that harmoniously integrates local architectural traditions and specific environmental attributes, thus addressing growing environmental concerns associated with climate change, resource depletion, and severe pollution. In this context, the construction industry plays a pivotal role in reducing building energy consumption and achieving sustainable buildings through the adoption of ecological building concepts (Liang *et al*., 2021; Maxineasa *et al*., 2021). Notable examples include kiln dwellings on the Loess Plateau in China and hanging foot buildings in Southeast Asia and western Hunan Province, China (Jin & Zhang, 2021). These constructions exemplify the utilization of localized architectural approaches that effectively respond to the regional environment and contribute to sustainable building practices.

The indoor thermal environment of buildings is significantly influenced by various architectural and structural characteristics, including layout, space dimensions, window-to-wall ratio, external shading, and thermal envelope properties (Zhang *et al*., 2023). Traditional dwellings in the western Hunan region predominantly employ raw earth and wood as construction materials, featuring simple wooden-framed windows, often without glass. These traditional dwellings face challenges related to thermal insulation and exhibit substantially lower airtightness compared to urban houses. Consequently, occupants of traditional dwellings in rural areas demonstrate higher adaptability to fluctuations in the indoor thermal environment when compared to their urban counterparts. Previous research has indicated that traditional dwellings exhibit superior thermal comfort in comparison to modern dwellings due to their semi-open spaces and variable envelope structures, enabling enhanced adaptability to local climatic conditions (Zhang *et al*., 2019; Pardo, 2023).

### 2.2. Research area

The Miao ethnic group in western Hunan primarily inhabits mountainous areas ranging from 500 to 1200 m. The region is characterized by unfavorable and intricate climatic conditions, influenced significantly by altitude, leading to notable temperature variations. It falls within the humid central subtropical monsoon climate category, characterized by hot and rainy summers and cold and wet winters. The average annual temperature stands at 15.9°C, with only 10.5 days per year experiencing temperatures equal to or exceeding 35°C. The average sunshine difference is 8.3°C, and the annual rainfall amounts to 1308.1 mm. During the summer, the natural environment and the rational design of traditional dwellings facilitate cooling and dehumidification through natural ventilation techniques. Conversely, in winter, the mountainous regions become cold and damp, necessitating heating measures to counter the chilly and moist indoor environment. The present study focuses on Zhushan village (Figure 1), which has been included in the fifth batch of the "Chinese Traditional Villages List" and selected as the sample site for field monitoring and simulation investigations.

Located in Machong Township, Phoenix County, Xiangxi, Zhushan Village (Figure 2) exhibits specific geographical attributes. The village is situated on a south-facing mountain with an average elevation of approximately 620 m and an average slope of around 30°. Notably, it lacks public buildings but benefits from favorable natural light and ventilation, exemplifying a typical mountainous village layout in the original Miao region of western Hunan. The traditional houses in Zhushan Village typically comprise a main house, an attached house, and a courtyard. The total construction area spans approximately 90–150 sq m, while the courtyard occupies an area of approximately 30–70 sq m. Surrounding the courtyard is a low wall featuring a gatehouse at the front and a sunbathing pad within the courtyard. The sunbathing pad serves as a dedicated space for sun exposure and outdoor activities.

### 2.3. Research content

#### *2.3.1. Field research*

A thorough and extensive field survey was conducted by our research team over a period of nine days, spanning from January 10, 2022, to January 18, 2022, in Zhushan Village, Phoenix County, in the Tujia and Miao Autonomous Prefectures of Hunan Province. The survey encompassed meticulous measurements using tools such as tape measures and laser rangefinders, enabling us to gather precise data pertaining to the village. In addition, computer-aided design (CAD) drawings were generated to accurately depict the architectural features of the dwellings in Zhushan Village. Furthermore, the collected data were systematically organized to categorize and classify the fundamental types of dwellings prevalent in Zhushan Village.

#### *2.3.2. Measurement settings*

Past studies have shown that the neutral temperature in summer ranges from 18.4 to 29.8°C, with the lowest

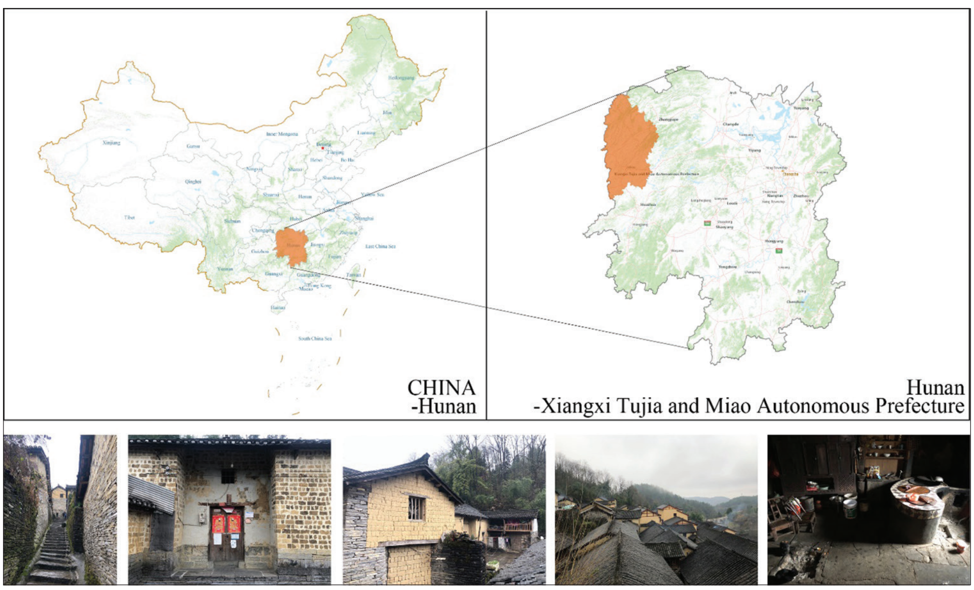



**Figure 1.** Study area. Source: Maps and photos by the authors

**Figure 2.** Zhushan Village. Source: Photos from the Traditional Chinese Village Digital Museum (http://www.dmctv.cn/)

temperature recorded in brick houses in western Hunan (Fang, 2020). It is evident that the residential houses in western Hunan have good thermal insulation performance in the summer, while the insulation performance in the winter remains to be explored. Therefore, we collected data for the winter period from January 10, 2022, to January 18, 2022. Indoor parameters such as air temperature, relative humidity, and indoor light were collected using Testo174H (measurement accuracy: ±0.5°C, ±3.2%, measurement range: −20±70°C, automatic recording every 15 min) (Figure 3). The monitoring points were located at four locations at 1500 mm above the floor on the outer wall of the main entrance: the hall, the fire pit room, and the bedroom (Figure 4), which were distributed among the rooms and located at the ventilation openings and were not disturbed by sunlight, while 1500 mm was the optimal height for detection.

### *2.3.3. Simulation settings*

A specific traditional dwelling was selected in Zhushan Village to measure the indoor photothermal environment, taking into consideration its localized characteristics. This dwelling, constructed in 1947, has retained its original architectural form without undergoing any alterations or modifications. It exemplifies the typical "Tun Kou" style traditional Miao residential layout prevalent in western Hunan. As built facing south to north, the house features a courtyard in front of the entrance and is arranged with three open rooms. The bedrooms are positioned on the eastern and western sides of the dwelling, with no partitioning between the two rooms. The perimeter walls of this dwelling are constructed using a 600 mm thickness of rammed earth and shale, exhibiting a heat transfer coefficient of k=2.13 W/(m$^2$·K). The exterior windows are single-pane glass windows measuring 1200 mm × 1300 mm, while the doors are wooden and measure 1500 mm × 2000 mm. Ventilation openings in the storage space on the first-floor measure 650 mm × 550 mm.

Based on the field measurements of dwellings and climate data, the simulation software Ecotect Analysis (2011) and Designbuilder were employed for the simulations


**Figure 3.** Air temperature monitoring instrument. Source: Photo by the authors

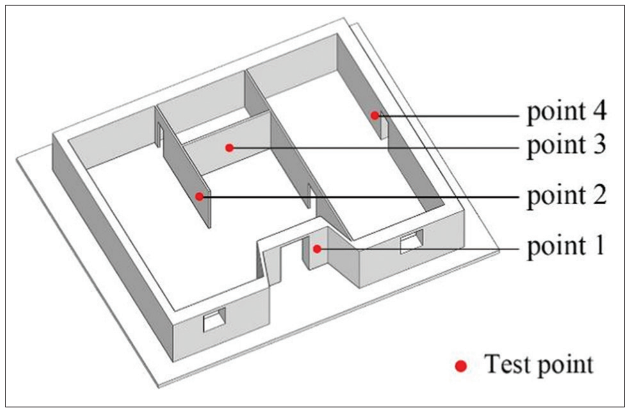



**Figure 4.** Air temperature monitoring points. Source: Drawing by the authors

(Figure 5), with the intention to objectively evaluate the difference between indoor light and heat environments before and after the renovation through simulation software and to provide a database for subsequent targeted updates (Juan *et al.*, 2019). The study examines the degree of adaptation of traditional dwellings in the Miao region to the local climate. The model simulates the plan form and dimensions of a typical dwelling using the building materials of the Raw Miao traditional dwelling (Table 1). The results of the simulations were used to further validate the data measured in the field.

### *2.3.4. Update settings*

To improve indoor light intensity, a strategic intervention was employed to optimize the lighting environment within the traditional residential houses by incorporating light wells on the roof. This architectural modification was executed with the utmost care to ensure the preservation

**Table 1. Material parameter performance of traditional housing envelope**

| Type of building envelop | Construction method | Material thermal index | | | |
|---|---|---|---|---|---|
| | | Thickness (mm) | Density (kg/m$^3$) | Specific heat (kJ/[kg·K]) | Heat conductivity (W/[m·K]) |
| External wall (outside-to-inside) | 300 mm clay brick | 600 | 1800 | 1050 | 0.81 |
| Partition wall | 10 mm wooden board | 20 | 500 | 2510 | 0.17 |
| Roof (outside-to-inside) | 6 mm gray tile roofs | 80 | 2300 | 1050 | 0.96 |
| | 20 mm wooden board | 20 | 500 | 2510 | 0.17 |
| Exterior door | 10 mm wooden door | 40 | 550 | 2510 | 0.17 |
| Interior door | 10 mm wooden door | 20 | 500 | 2510 | 0.17 |
| Floor | 20 mm rammed earth | 200 | 1800 | 884 | 0.72 |

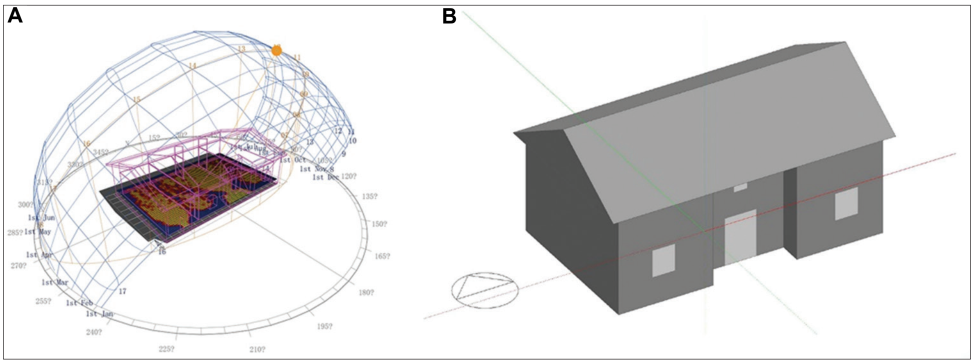



**Figure 5.** (A) Simulation model in Ecotect Analysis software. (B) Simulation model in Designbuilder software. Source: Drawings by the authors

of the original façade shape and window dimensions. By adhering to these design considerations, the fundamental esthetic elements associated with the traditional architectural heritage of residential houses in the region were respected and safeguarded (Figure 6).

At the same time, to improve the indoor thermal environment, we renewed the interior of the maintenance structure of the traditional house, based on the premise of preserving and passing on its regional culture. We added polyurethane and wood panels with varnish veneer on the inside of the envelope and attached them to the wall with wood rivets and bolts (Figure 7).

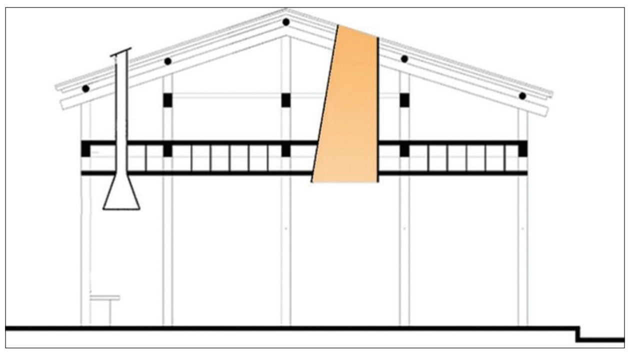


**Figure 6.** Lightwell setting. Source: Drawing by the authors

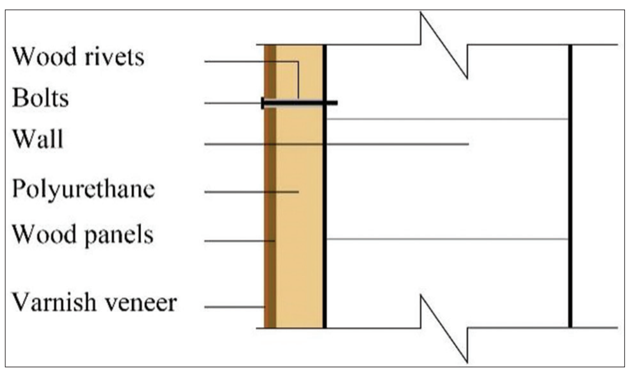



**Figure 7.** Wall update settings. Source: Drawing by the authors

## 3. Results

### 3.1. Actual measurement results

#### *3.1.1. Dwelling form*

Most of the traditional Miao dwellings in the western Hunan region are composed of wooden frames and earth and stone exterior walls, and the buildings consist of a main dwelling and an annex, which have "I," "L," and "U" forms (Table 2). The main dwelling has three rooms and one hall, with the middle room facing backward one column, forming a "swallowed mouth" type main dwelling plan. The original Miao dwelling has only one fire pit, located near the central pillar of the room on the East or West side of the hall, depending on the family name of the head of household. The interior of the dwelling is not partitioned, and only black gauze is used to enclose the beds.

#### *3.1.2. Dwelling structures*

Traditional Miao dwellings in the western Hunan region follow framed structural designs (Figure 8), where the outer walls form an enclosure and the wooden frames provide load-bearing support for the roofs, ensuring structural stability. The ground floor serves as the primary living space and is elevated approximately 2800 mm above ground level by the addition of a wooden slab. The upper floor is designated for storage purposes and can be accessed through a movable staircase.

#### *3.1.3. Dwelling materials*

Traditional Miao residences in western Hunan are built with local cedar and pine wood, raw earth, and shale (Figure 9). Because of the challenging transportation in their remote mountainous location, they used locally produced cedar and pine wood for the roof frames, rammed raw earth for the floors, mountain shale and rammed raw earth for the exterior walls, and small green tiles for the roofs, with no decorative sculptures in the details of the buildings.

### 3.2. Measurement results

#### *3.2.1. Luminous environment*

In this study, the exterior window size of selected typical sample house for simulation is 1200 mm × 1300 mm. The

**Table 2. Typical traditional dwelling plan types**

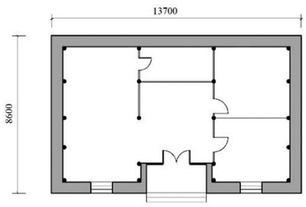
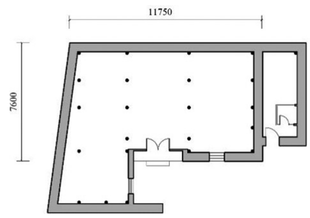
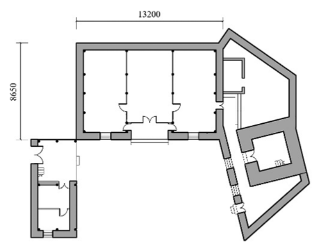
| Type of plane | Frontispiece | Plan view (mm×mm) |
| --- | --- | --- |
| "I" shaped |  |  |
| "L" shaped |  |  |
| "U" shaped |  |  |

**Figure 8.** Dwelling structures. Source: Photos by the authors

**Figure 9.** Dwelling materials. Source: Photos by the authors

window-to-floor area ratio in the rooms on both sides is calculated as 1/18.92, significantly deviating from the recommended minimum lighting coefficient of 1/7 per the Building Light Design Standard GB50034-2013 in China. Conversely, the window-to-floor area ratio in the hall room is determined to be 1/7.10, which approximates the recommended minimum value. Given the overall north-to-south orientation of Zhushan Village, with doors and windows primarily facing south, the hall room benefits from ample direct sunlight during the day, resulting in favorable illumination conditions. However, the side rooms suffer from inadequate lighting due to their limited window openings and substantial depth. Through the conducted sampling in three areas, the measured light intensity levels from outside to inside were determined as follows: 20,400 lux, 1632 lux, and 476 lux for the hall; 2312 lux, 204 lux, and 136 lux for the fire pit; and 4080 lux, 272 lux, and 136 lux for the side room (Figure 10). Thus, the interior light in the sample room is deemed insufficient.

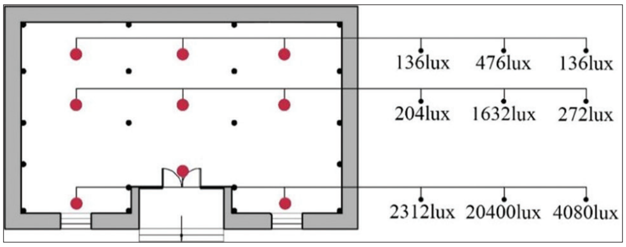



**Figure 10.** Location of light measurement points and corresponding illuminance. Source: Drawing by the authors

### *3.2.2. Temperature*

The data provided in Figure 11 presents the findings from the monitoring of four indoor and outdoor locations within a representative Miao residential dwelling. Throughout the monitoring period, the average outdoor temperature was recorded at 5.56°C, exhibiting a temperature fluctuation of 11.5°C. Conversely, the average indoor temperature was measured at 6.32°C, with respective temperature fluctuations of 6.45°C and 5.5°C in the hall room, 6.49°C and 4.1°C in the fire pit room, and 6.01°C and 4.0°C in the side room. These observations indicate that during the winter season, the indoor temperature of traditional Miao houses in western Hunan remains marginally higher than the outdoor temperature by <1°C while demonstrating significantly reduced fluctuations compared to the outdoor temperature.

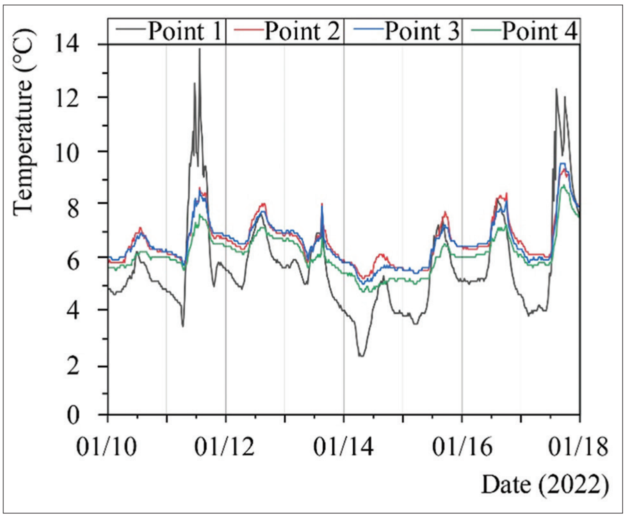



**Figure 11.** Temperatures of the monitoring points. Source: Graph by the authors

## 3.3. Simulation results

### *3.3.1. Luminous environment*

Figure 12 shows the indoor light environment before and after the Ecotect simulation of the renovation, and its data before the simulation of the renovation is the same as the monitoring data. In the simulation diagram, the light on

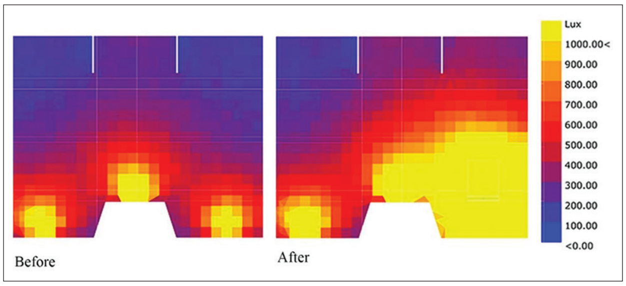



**Figure 12.** Indoor light simulation with and without light wells. Source: Diagram by the authors

the north side of the whole interior is relatively weak and needs to be improved. The model with additional light wells was simulated, and the results showed that the indoor light environment on the side with additional light wells was significantly improved after the addition of light wells, and the overall illuminance of the room met the illuminance standard for indoor reading and writing.

### *3.3.2. Thermal environment*

The simulation experiment was conducted using local meteorological data to analyze and simulate the indoor temperature of the selected sample dwellings throughout the monitoring period. Figure 13 illustrates the temperature variation curves for both indoor and outdoor spaces. The average outdoor temperature was 4.12°C, with a maximum temperature of 7.4°C and a minimum temperature of 0.07°C. The outdoor temperature exhibited a fluctuation of 7.47°C. In contrast, the average indoor temperature of the sample houses was 8.25°C, with a maximum temperature of 13.36°C and a minimum temperature of 9.54°C. The indoor temperature of the sample dwellings demonstrated a fluctuation of 3.82°C.

The simulation results indicate that the indoor temperature distribution exhibits a gradual transition and experiences less variability than the outdoor temperature, signifying a certain level of thermal stability within the residential houses. These findings suggest that the selected dwellings possess favorable thermal performance and provide a relatively stable indoor photothermal environment.

The heat energy loss of the building envelope was assessed before and after the renovation, as presented in Table 3. Before the renovation, the total energy consumption amounted to 2368.97 kWh. After the renovation, the total energy consumption was 793.04 kWh (Table 4). As a result of the renovation, the heat energy loss within the interior of the Miao traditional houses in the Xiangxi area decreased by 1575.93 kWh. Specifically, reductions in heat energy loss were observed in the wall

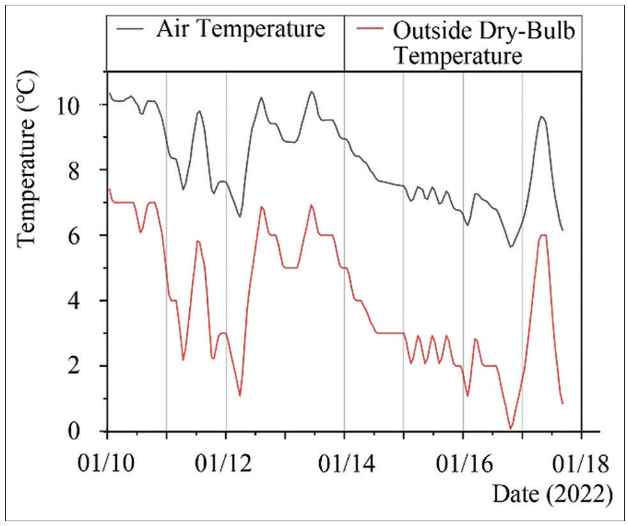



**Figure 13.** Simulated indoor and outdoor temperature results. Source: Graph by the authors

**Table 3. The energy consumption before renewal**

| | Heat balance (kW·h) | |
|---|---|---|
| **Energy outputs** | | **Total** |
| Envelope | | 2368.97 |
| Wall | 528.39 (22.3%) | |
| Ceilings | 656.17 (27.69%) | |
| Roofs | 647.27 (27.32%) | |
| Glazing | 14.23 (0.6%) | |
| External air | 522.91 (22%) | |

**Table 4. The energy consumption after renewal**

| | Heat balance (kW·h) | |
|---|---|---|
| **Energy outputs** | | **Total** |
| Envelope | | |
| Wall | 232.31 (29.29%) | 793.04 |
| Ceilings | 206.72 (26.07%) | |
| Roofs | 145.81 (18.39%) | |
| Glazing | 6.42 (0.01%) | |
| External air | 201.78(25.44%) | |

(296.08 kWh), ceiling (449.45 kWh), roof (501.46 kWh), and glass curtain wall (7.81 kWh).

## 4. Discussion

The architectural characteristics of traditional dwellings are intricately linked to the specific natural climate and geographic environment of a region. These variances encompass elements such as temperature and humidity, wind patterns and intensity, latitude and altitude, solar radiation, and precipitation. In the case of the Miao people residing in the western Hunan region, their traditional dwellings exhibit a remarkable synthesis of indigenous construction wisdom and techniques, effectively responding to the distinctive climatic conditions prevalent in the area. As a result, these locally adapted traditional dwellings not only embody the unique cultural characteristics of the region but also demonstrate exceptional adaptability to the prevailing climate.

The Miao traditional houses in western Hunan exemplify an architectural response to the regional variations in solar radiation intensity and duration, which differ between the southern and northern areas. This discrepancy allows for the strategic utilization of site elevation differentials to harness sunlight and elevates indoor temperatures during the winter months. In addition, owing to the higher solar altitude angle in the south, the design incorporates eaves to mitigate the intensity and duration of sunlight entering through south-facing windows during the summer. The case study of Zhushan village, which serves as the focal point of this research, showcases its favorable location between two south-facing mountains. The houses are arranged in alignment with the contour lines, featuring south-facing windows that facilitate natural ventilation, thereby reducing indoor temperatures during the summer. Simultaneously, the varying site elevations are leveraged to prolong sunlight exposure during the winter, effectively raising indoor temperatures. Furthermore, considering the influence of the cold northwestern monsoon prevalent in winter, the design avoids the inclusion of windows on the north side of Miao traditional houses in western Hunan to ensure optimal indoor comfort.

The spatial configuration of traditional dwellings exemplifies a responsive adaptation to the local natural environmental factors. The focus of this study is situated in Hunan Province, accompanied by hot and rainy summers and cold and humid winters. Consequently, traditional dwellings in this region uniformly adopt a two-story, square layout, whereby the ground floor is designated as the living area and the upper floor serves as storage space. The storage area on the upper floor incorporates a double-sloped roof design and ventilation apertures to foster efficient airflow, thereby mitigating indoor temperature and humidity levels. This design feature proves advantageous for long-term food preservation requirements. Simultaneously, the elevated storage area, functioning as a mezzanine, serves as a barrier against direct solar radiation, providing thermal insulation for the ground-floor living space, thereby reducing indoor temperature and ensuring a comfortable thermal environment. The primary areas of the dwelling, including the hall and the fire pit, are strategically positioned on the southern side of the ground floor, near windows and doors, to ensure optimal access to natural light and facilitate adequate ventilation. Conversely, the bedrooms are arranged along the northern side of the structure to minimize exposure to solar radiation.

The choice of construction materials for traditional Miao houses in western Hunan is influenced by factors such as the availability of local building materials, household income, and construction techniques. These dwellings utilize natural resources obtained from the nearby mountainous regions. The wooden frame materials are sourced from fir and pine trees harvested from the surrounding forests. This approach offers advantages such as convenience and affordability while also promoting environmental sustainability through the utilization of renewable, pollution-free, and breathable materials that are easily processed. The walls are constructed by layering shale obtained from the mountains and compacted earth bricks made from locally sourced raw soil. The base and lower portion of the walls are constructed using shale bricks, typically reaching a height of 900 – 1100 mm. The upper wall section comprises rammed earth bricks measuring 200 – 500 mm in thickness. This construction technique allows for moisture absorption in humid conditions and moisture release in dry conditions, facilitating effective air exchange and maintaining indoor comfort levels. For roofing, small green tiles made from mountain clay are employed, offering excellent heat insulation, water resistance, and air permeability. These tiles enable the transfer of solar heat and the discharge of hot air while preventing rainwater infiltration into the interior spaces. In Zhushan Village, double-sloped roofs with gentle to moderate slopes are predominant, featuring small green tiles that facilitate efficient rainwater drainage. In addition, the roof eaves extend approximately 450 – 650 mm, significantly reducing the potential corrosion of rammed earth walls caused by rainfall. The inherent characteristics of small green tiles contribute to balanced indoor temperature and humidity levels, smooth ventilation, and the creation of a comfortable indoor environment.

## 5. Questions and suggestions

A comparative analysis of monitoring and simulation data obtained from a representative sample of traditional Miao dwellings in the western Hunan region reveals the successful implementation of passive design strategies to adapt these dwellings to the local climate conditions. The traditional Miao houses in this region exhibit numerous technical adaptations that effectively respond to the climate. These include the incorporation of small windows and doors, high roofs, and broad eaves. The implementation of relatively compact window and door dimensions contributes to minimizing heat loss during the winter months. Moreover, the practice of not opening windows on the North, East, and West sides of the dwellings facilitates insulation against external climatic influences. The presence of upper storage spaces further aids in reducing temperature fluctuations within the lower living areas and provides a mildly heated environment during the winter. The wide eaves serve multiple purposes, including efficient rainwater drainage, protection against wood deterioration, and attenuation of excess heat absorption by the exterior walls. Additionally, during winter, the wide eaves provide shade for the residents. Despite these commendable design features, it is important to note that the indoor photothermal environment of traditional Miao dwellings in the western Hunan region still presents certain limitations and shortcomings, which require attention and improvement.

i. Due to the absence of active heat insulation equipment and measures, the Miao people have traditionally prioritized summer heat insulation over winter heat insulation in the design and construction of their dwellings. This choice may be attributed to the cultural practice of addressing the winter cold by adding layers of clothing. Consequently, the indoor photothermal environment of Miao traditional dwellings faces a significant challenge regarding winter heat insulation. Addressing this issue becomes an urgent imperative that necessitates prompt improvement measures.
ii. Furthermore, the inadequate indoor light in Miao traditional dwellings can be attributed to the design limitation of having only two small windows on the south side. This design consideration encompasses the requirements for summer ventilation, summer heat insulation, and winter insulation, as well as the constraints imposed by construction techniques. Consequently, the indoor light within the dwellings is significantly insufficient, with satisfactory illumination only observed in the vicinity of the doors and windows on the south side, while the North side experiences a severe lack of natural light.

This study employs a comprehensive approach, combining qualitative and quantitative analyses, to investigate the adaptive response of traditional dwellings to the local natural environment in the Miao region of western Hunan. It encompasses a thorough examination and analysis of the layout, form, materials, and structure of traditional dwellings in this region. Specifically focusing on Zhushan Village, the study examines the indoor photothermal environment characteristics of these traditional dwellings. The findings highlight the profound influence of the philosophical concept of harmony and unity between humans and nature on the design and construction of traditional dwellings in the Miao region of western Hunan. The study demonstrates that these dwellings effectively respond to the specific climatic characteristics of the region by incorporating appropriate dwelling forms, materials, and structural elements. Moreover, the study identifies and analyzes the existing challenges associated with Miao traditional dwellings in the western Hunan region and provides targeted recommendations for addressing these issues. The targeted recommendations are as follows:

i. In order to enhance the thermal performance of the exterior walls in traditional Miao dwellings, we suggest implementing an intervention by adding a composite wall on the inside of the existing exterior wall. This intervention involves incorporating a layer of 40 mm thick polyurethane foam and 10 mm cedar boards. By adopting this approach, we aim to improve the overall thermal insulation properties of the wall without compromising the traditional folk style while also providing opportunities for modern interior decoration.
ii. Considering the economic constraints and regional attributes of the Miao area, the windows installed in residential houses exhibit inadequate sealing properties due to the suboptimal design of their window frames and sills. To address this issue, we propose the adoption of 5 mm low-emissivity (low-e) glass for the windows. This intervention aims to enhance the thermal performance of the windows and promote improved interior light conditions. By implementing this measure, we can ensure that the aesthetic integrity of traditional dwellings remains intact while simultaneously enhancing their overall thermal efficiency.

## 6. Conclusion

This study employed a combination of field survey data and two simulation software programs, namely Designbuilder and Ecotect, to investigate the performance of Miao traditional dwellings in the western Hunan region with respect to the indoor photothermal environment. Our findings revealed that these dwellings demonstrate favorable responses to the local climate characteristics, exhibiting commendable adaptability in terms of architectural form, building structure, and building materials. The outcomes affirm the alignment of these dwellings with the prevailing trajectory of sustainable development in contemporary society, underscoring their efficacy in meeting the demands of environmentally conscious practices. The outcomes are elaborated as follows:

i. The analysis of the field monitoring data revealed that the mean indoor temperature of Miao traditional dwellings in western Hunan exhibited an approximate 1°C elevation compared to the outdoor temperature. Furthermore, the temperature fluctuations observed in the hall, fire pit room, and side room were measured at 4.5°C, 4.1°C, and 4.0°C, respectively, indicating a significant reduction of 11.5°C compared to the temperature fluctuations experienced outdoors. These findings provide empirical evidence that Miao traditional houses in western Hunan exhibit commendable thermal insulation performance.

ii. According to the field monitoring data, it was observed that the level of natural illumination within the interior of Miao traditional dwellings in the western Hunan region fell short of meeting the current standard requirements. To address this issue while preserving the regional characteristics of the dwelling façades, simulation techniques were employed using Ecotect software. The simulation results indicated that by implementing light wells on the roof, the overall indoor illumination levels were improved to meet the prescribed standards for activities such as reading and writing.

iii. Traditional dwellings of the Miao ethnic group in the western Hunan region exhibit a remarkable capacity for adaptation to the local geographic and climatic conditions, as evident in their spatial arrangement and material selection. The spatial layout of these dwellings effectively harnesses the prevailing southeast wind during the summer while mitigating the harsh northwest wind in the winter, thereby ensuring a comfortable indoor environment. Furthermore, measures such as the inclusion of eave projections serve to protect the walls from rainwater-induced corrosion. Moreover, the choice of building materials not only aligns with contemporary sustainable development principles but also corresponds harmoniously with the natural climate of the region.

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## Conflict of interest

The authors declare they have no competing interests.

## Author contributions

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*Data curation:* Zhezheng Liu, Xiang Lin
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*Writing – original draft:* Zhezheng Liu, Guanglei Yang
*Writing – review & editing:* Zhezheng Liu, Liang Xie

## Ethics approval and consent to participate

Not applicable.

## Consent for publication

Not applicable.

## Availability of data

The data presented in this study are available on reasonable request from the corresponding author. The data are not publicly available due to privacy considerations.

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ACCSCIENCE PUBLISHING

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ORIGINAL ARTICLE

# Building energy-saving mechanism for indoor cooling temperature set-point with different envelope: A case study in Guangzhou

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## Abstract

The temperature set-point of air conditioning system is a crucial parameter for behavior adjustment. Nevertheless, the thermal characteristics of building envelopes are different at varied construction ages. In this context, there are already several systematic studies demonstrating the differences in energy savings as a result of raising the same temperature set-point for air conditioning. In this study, an office building was used under four assumed envelopes representing different construction ages, and the characteristic temperature method was applied to simulate the hourly dynamic air-conditioning load before and after the set temperature rise of 1°C presenting monthly and annual cooling consumption. We then explored the energy-saving effect and difference in the mechanism of air conditioning with increasing indoor temperature set-point. The results showed that, provided that the temperature set-point is increased by 1°C under the same climatic conditions, the worse the thermal performance of the envelope, the higher the annual air-conditioning energy and the higher the annual energy-saving rate of air conditioning, which indicates that the behavioral energy-saving guidance for the groups with the poor performance of the older envelope has more immediate effects. The hourly load reduction of different envelopes at the outdoor temperature between 26°C and 27°C constitutes the behavioral energy-saving effect, which is the main contribution of air-conditioning energy saving (58 – 79%), while the energy-saving effect contribution of temperature difference reduction is secondary. The newer the construction age, the better the performance of the envelope, the smaller the hourly load reduction amount of the building, and the smaller the relative energy-saving rate, but its energy-saving behavior in the total energy saving ratio is greater, and the contribution of the energy-saving behavior is greater. The results of this study can provide a reference for guiding occupant energy-saving behavior and standard formulation.

***Keywords:*** Building simulation; Cooling load; Temperature set-point; Energy saving; Thermal performance

## 1. Introduction

Energy conservation, emission reduction, and environmental protection have always been hot issues in the world. The fifth report of the United Nations Intergovernmental

Panel on Climate Change indicates that the building construction sector has become the world's largest energy consumption sector, and the building industry is an important contributor to the world's energy consumption and greenhouse gas emissions. Building construction accounted for 32% of global carbon dioxide emissions in 2010. In recent decades, the proportion of global building energy consumption in total social energy consumption increased from 30% to 40% (Yu, 2017). According to the US Department of Energy (DOE) energy information account, the energy consumption of existing residential and commercial buildings accounts for about 40% of total energy consumption in the US, and the proportion of building energy consumption in total energy consumption of the society is higher than the world's average (Jin *et al.*, 2023). In all fields of Chinese society today, the building construction sector accounts for 40% of total energy consumption and 25% of greenhouse gas emissions (Li *et al.*, 2019). To reduce building energy consumption and greenhouse gas emissions, scholars from all over the world have put forward various technical measures, including adopting advanced system equipment and its operation and maintenance strategies, introducing smart grid systems to improve the energy efficiency of energy-using end, developing new net-zero-energy buildings, and carrying out energy-saving retrofits of existing buildings (Thomas *et al.*, 2018). However, these measures are all from the engineering and technical point of view of supplying and using energy equipment and systems and energy-consuming buildings, which require a large amount of investment, are easily restricted by market rules, and involve complex social and economic interests of various stakeholders, thus leading to great implementation resistance.

In recent years, with the development of people-oriented and passive building energy conservation concepts, discussions on building energy conservation from the perspective of occupants' energy use behavior, such as adjusting the temperature set-point of the air-conditioning system, reducing the use of lighting and equipment, and increasing the use of natural ventilation by opening windows, have been made (Papadopoulos *et al.*, 2019). These methods have the advantages of low cost, easy operation, and considerable energy savings. Among them, adjusting the temperature set-point is the most operable for users and managers, has grand energy-saving potential, and has received huge attention from around the world. As early as 2005, the Japanese government advocated that the national set-point of air-conditioners in summer should be raised to 28°C to achieve an indirect energy-saving effect, and then the British government also put forward the corresponding call due to this effect (Lakeridou *et al.*, 2012). In 2007, the state council of China issued the regulation that the indoor air-conditioning temperature in all public buildings should not be set below 26°C in summer. According to the indoor design parameters of comfortable air-conditioning stipulated in the Code for the Design of Heating, Ventilation, and Air-conditioning (HVAC) for Civic Buildings (GB50736-2012) (Ministry of Housing and Urban-Rural, 2012), the setting temperature of the long-term residence area of personnel in the cooling condition is 24°C – 28°C, and the temperature of the short-term residence area should be increased by 1°C – 2°C compared to that of the long-term residence area. ASHRAE 55-2013 (ASHREA, 2013; Office of Energy Efficiency & Renewable Energy, n.d.) stipulates that the temperature set-point of indoor air conditioning in summer should be 23°C – 27°C.

Some scholars have conducted relevant research combining temperature set-point and building energy conservation. For example, Liu *et al.* (2022) used orthogonal design and numerical simulation to explore the influence and adaptability of different thermal properties of university teaching office building envelopes on energy consumption in 12 typical cities (with different climates) in China. One of the results showed that when only the winter or summer conditions were considered, the optimized envelope coefficients resulted in energy savings of 49.97 – 100% for cooling loads, and 60.6 – 100% for heating loads. However, when optimized for annual operating conditions, annual load savings of 39.64 – 57.57% can be achieved for different climate zones. The results of this study can be used as a guide and data reference for energy-saving design and retrofit of office building envelopes in different climates. Aryal *et al.* (2018) pointed out that the majority of building energy consumption comes from air-conditioning and heating systems. To maintain a stable indoor environment for thermal comfort, the temperature set-point is often set as a fixed target value, ignoring the diversity of thermal comfort preferences of the occupants. On the one hand, the fixed set-point may not meet the needs of thermal comfort for most people; on the other hand, it may waste the energy-saving potential of equipment and systems. Therefore, the authors used big data analysis tools to study the relationship between the temperature set-point and human thermal comfort, to establish the thermal comfort model of the human body under different climatic conditions as the basis for adjusting the set temperature, and to study the energy-saving effect of adjusting the set temperature in 15 cities under four climatic conditions in the US using the DOE reference office building model. The results showed that, compared with the fixed 22.5°C, the temperature set-point of the system can be adjusted according to the characteristics of human thermal comfort in different climate zones, and the user requirements of different functional rooms, and the energy-saving effect can be achieved at different levels in different cities. In cities with a hot climate, the annual average relative energy-saving effect is 3.2%, and in cities with a cold climate, it is 1.6%. The hotter the region, the greater the energy-saving potential of adjusting the setting temperature of the air conditioner. However, due to the large number of cities selected by the author, and the lack of a unified standard for adjusting the set-point based on different climatic characteristics, the energy-saving effects in different cities after adjusting the set-point are too complex to compare, and it is difficult to deeply analyze the energy-saving mechanisms of different set-points. Moreover, the authors only give the research results of the relative energy saving rate but it lacks the research on the absolute energy-saving effect. Hoyt *et al.* (2015) believed that the temperature set-point adjustment range of HVAC systems equipped with office buildings in the US was too narrow, and there was a lack of quantitative research on the energy-saving effect of widening the range. Thus, the authors applied the widening of the system's temperature set-point range to office building models in seven US cities with different climate; the original narrow set temperature range of air-conditioning (21.1°C – 22.2°C) was used as the comparison baseline, and the building energy consumption under different ranges was simulated by Energy Plus software. The results showed that widening the set-point range has a significant energy-saving effect. For example, increasing the set-point of the air conditioner from 22.2°C to 25°C will achieve a 27% energy-saving rate for the equipment system. In addition, the authors compared the energy-saving effects after adjusting the temperature set-point in cities with different climates and concluded that increasing the setting temperature of air conditioning in hotter climate zones can obtain more significant energy-saving effects, which proves that adjusting the set-point of an air-conditioning system has a great impact on reducing energy consumption. However, the authors did not explore the energy-saving mechanism of adjusting the temperature set-point under the same climatic condition. For the same building type in the same city, the energy-saving effect, and the mechanism behind adjusting the temperature set-point, should be further studied.

As for the doubt that adjusting the settings in temperature will reduce occupants' thermal comfort, some scholars have carried out relevant research and proved that the environmental conditions for people's thermal comfort are not fixed. Through field surveys, questionnaires, physical metrology, simulation of a thermal comfort model, and other methods, a certain range of temperatures can be obtained based on the environmental conditions where people feel the thermal comfort, and an appropriate increase or decrease of temperature within this range will not significantly affect people's thermal sensation (Ghahramani *et al.*, 2014; Belazi *et al.*, 2019). The above research shows that adjusting the temperature set-point is an important behavioral energy-saving measure that attracts wide attention from scholars around the world, and many research results are emerging. However, China lacks a global perspective in the research field of building energy conservation, so more attention should be paid to temperature set-points and their energy-saving mechanisms. Therefore, this paper will focus on the energy-saving effect of raising the temperature set-point of air-conditioning in hot areas of China and study the behavioral energy-saving potential through a quantitative analysis method. In addition, the building envelope is a major focus of passive building energy conservation research. The thermal performance of the building envelope can significantly affect the energy consumption of the building. At present, there is abundant research on the energy-saving characteristics of the building envelope. Feng *et al.* (2010) simulated and calculated the air-conditioning cooling and heat load of office buildings with different heat transfer coefficients at the same temperature set-point through DeST software and found that the energy-saving effect of different envelope thermal characteristics was significantly distinctive in different seasons. Natephra *et al.* (2018) established an office building model on the building information modeling (BIM) platform and studied the automatic evaluation method of energy-saving building design based on BIM data by changing the information of the building envelope. The results showed that the thermal characteristics of the envelope structure had a significant impact on maintaining an indoor thermal environment and realizing the high energy efficiency of the building. Scholars all over the world regard envelope performance as an important factor affecting energy consumption and energy savings when studying the existing building's energy conservation retrofit and discussing how to improve the envelope of the building.

Existing buildings are built at different stages of social development, and the construction level is varied at different stages, which makes the performance of existing buildings' envelopes different. When the energy-saving measure of adjusting the temperature set-point of the air conditioner is applied to existing buildings, the influence of various envelope performances on the energy-saving effect must be considered (Liao *et al.*, 2022). To study the energy-saving effect of existing buildings in the US at different HVAC temperature set-points, Ghahramani *et al.* (2016) adopted the reference office building model of three sizes given by the US DOE standard. Each model is divided according to different construction ages (built before 1980, built from 1980 to 2004, and built after 2004). The authors selected 16 typical cities representing different climatic conditions in the US, calculated the optimal temperature set-point under various climatic conditions, and adjusted the HVAC system based on the optimal set-point. They then used the MATLAB program to simulate the energy consumption of the system. The research results show that under the three-size models, the construction age affects the characteristics of building energy consumption. The newer the construction age, the better the envelope performance, and the lower the energy consumption, the smaller the energy saving potential. The author applied different temperature set-points to three sizes of office building models in 16 cities under different climatic conditions. The results showed that compared with the baseline set-point of 22.5°C, the energy-saving effect varied to different degrees, and the energy-saving effect was significant in hot areas. However, due to the complexity of climate condition types, building size types, and optimal temperature set-point, the conclusions were not comparable. In addition, because of the complexity of the problem, the author only studied the difference in relative energy saving rate and did not study absolute energy saving, which significantly affected energy cost and emission reduction. In the same city or region, buildings with different envelope performances and different construction times coexist. The behavioral energy conservation policy that advocates raising the temperature set-point of air-conditioners is aimed at people living in buildings completed at different times. However, it is not difficult to find out from the above studies that under the same climatic conditions (the same city), there is little research on the differences in the relative and absolute energy-saving effect of buildings of different times with the same temperature set-point increase, and the profound revelation of its energy-saving mechanism is even more blank. Therefore, the temperature set-point and the thermal characteristics of a building envelope are coupled in this study. The thermal characteristics of building envelopes of different grades represent existing buildings built at different times. New constructions and high construction level often lead to better thermal performance of building envelopes (Feijó-Muñoz *et al*., 2019).

Aimed at office buildings, this paper selects Guangzhou, a typical Chinese city with hot summers and warm winters, to explore the relative and absolute energy-saving effect difference of increasing the temperature set-point of the air conditioner by 1°C for different grades of envelope performance, and further investigate the energy-saving mechanism, which has practical engineering significance and values. The research results can provide a theoretical reference for the revision of energy conservation standards and scientific guidance for the behavioral energy conservation of existing office buildings. The paper is structured as follows: Section 2 describes the research object (a model building) and research conditions (climate conditions, building parameters, temperature set-point, etc.) and introduces the quantitative analysis method used in the paper to analyze the mechanism of energy conservation. Section 3 gives the research results of the macroscopic energy-saving effect. Section 4 analyzes the difference between energy-saving effects and energy-saving mechanisms at the micro-scale. Section 5 discusses the comparison of the energy-saving effect after adding an internal heat source. Finally, Section 6 summarizes the research results and conclusions.

## 2. Research model and procedures

The research model in the paper is a typical three-story office building, whose plan and elevation are shown in Figures 1 and 2. The length of the building is 21.24 m, the width is 14.04 m, the height is 11.9 m, the total area of the building is 894.63 sqm, the total area of the envelope is 1065.96 sqm, the building volume is 3280.31 cubic meters, the shape coefficient is 0.3250, the window-wall ratio of the north and south external walls is 0.29, and the window-wall ratio of the east and west external walls is 0.07. For the other working conditions of building simulation, such as indoor air exchange rate (ACH) through mechanical ventilation system, internal heat gains from indoor lighting, occupations and devices, and so on, key parameters are obtained based on the benchmark values according to the US DOE Reference Building and ASHRAE AS (2013) Standard of thermal environmental conditions for human occupancy (building's daily office hours are 9:00 – 18:00) (ASHREA, 2013; Guo *et al*., 2019; Jin *et al*., 2023; Office of Energy Efficiency & Renewable Energy, n.d.).

To focus on the differences in the influence of a 1°C increase in air-conditioning temperature set-point on energy consumption of buildings of the same type in the same city but with different construction times under the condition of different envelope thermal characteristics, based on the general envelope structural requirements and related thermal engineering and energy-saving design standards of the outer envelope of civic buildings of different times in China, in this paper, we assume that the building envelope thermal characteristics are divided into lower-grade, medium-grade, high-grade, and top-grade. The envelope heat transfer coefficient of each grade is listed in Table 1. Some scholars have shown that the hotter the region, the higher the energy-saving potential (Feijó-Muñoz *et al*., 2019; Jin *et al*., 2023). Therefore, this paper focuses on the hottest region with hot summers

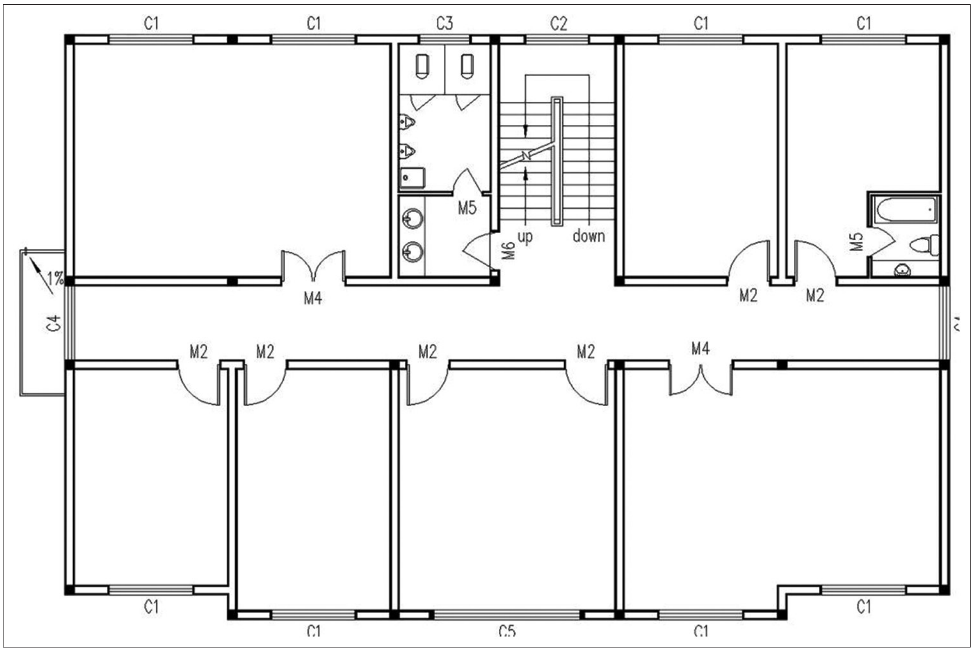


**Figure 1.** Building plan. Source: Drawing by the authors

**Figure 2.** Building elevation. Source: Drawing by the authors

**Table 1. Heat transfer coefficient of envelope of four grades**

| Grade of envelope | External wall heat transfer coefficient (W/(m2°C) | External window heat transfer coefficient (W/(m2°C) | Roof heat transfer coefficient (W/(m2°C) |
|---|---|---|---|
| Lower-grade | 1.9 | 6.18 | 0.93 |
| Medium-grade | 1.5 | 4.17 | 0.80 |
| High-grade | 0.80 | 2.5 | 0.50 |
| Top-grade | 0.18 | 1.55 | 0.1 |

Source: Ministry of Housing and Urban-Rural Development, 2012

and warm winters among China's five climate zones, and Guangzhou is a typical city with such a climate among the zones. The cooling consumption is an important component of the building operation consumption in the region. Hence, Guangzhou is selected as the case study city with the following main climate parameters: The annual average temperature is 22.5°C, the average temperature in the hottest month is 32.9°C, the annual maximum temperature is 36.1°C, and the annual total solar radiation is 1072.1 kWh/year.

The characteristic temperature method (CTM) based on building energy consumption theory is a dynamic simulation method used to calculate the heating (cooling) load and energy consumption of the building, which can reveal the relationship between the building load or energy consumption and various factors affecting solar radiation, indoor heat gains from lighting, and equipment, etc. (Long, 2005a). The reliability of this method has been verified by experiments and software comparisons in a large body of literature (Long, 2005b; Qian *et al.*, 2022; Qi *et al.*, 2023).

In this study, the CTM method was used to simulate and predict the hourly dynamic cooling load of buildings under the condition of four grades of envelopes with air-conditioning temperature setpoints of 26°C and 27°C, respectively, and then the hourly load of buildings was accumulated monthly and annually to obtain the cooling consumption on different time scales. By calculating the load difference before and after the set-point rises, the hourly cooling load reduction value or monthly and annual cooling consumption reduction value was obtained, that is, absolute energy savings. Based on the load or cooling consumption before set-point rise and divided by absolute energy saving, the hourly dynamic load reduction rate and the monthly and annual cooling consumption reduction rate were obtained, namely, the relative energy-saving rate. The simulation assumes that the cooling load is zero when the outdoor dry bulb temperature is lower than the temperature set-point. When the indoor characteristic temperature is lower than the setpoint, the cooling load is also zero. All the moments with an air-conditioning load were included in the analysis. To more significantly reveal the influence mechanism of the single factor of the envelope thermal characteristics on the energy-saving effect of the set-point rise and exclude the influence of secondary factors and personnel behavior uncertainty, in the simulation, the influences of internal heat sources such as personnel, equipment, and lighting were ignored, the air exchange rate was 0.5 $h^{-1}$, the shading coefficient of external windows was 1, and the transmission coefficient of solar radiation glass is 0.8 (Guo *et al.*, 2019). To ensure the integrity of the research results, the statistics included all moments when the set conditions were satisfied and a cooling load was needed.

## 3. Macroscopic comparison of energy saving

### 3.1. Annual energy saving

Figure 3 shows the comparison diagram of the annual absolute and relative energy savings of the same office building when the temperature set-point increases by 1°C from 26°C under an envelope of four grades. The result presented in Figure 3 shows that: (i) When the temperature set-point of air conditioning increases by 1°C, office buildings with different grades of envelope get different degrees of absolute energy savings under the same climate. A better insulation performance of the envelope structure results in the less energy saving throughout the year. The lower-grade envelope has the largest cooling consumption and energy saving, whereas the annual cooling consumption and energy savings of top-grade envelopes are the minimum. (ii) The annual energy-saving rate of air-conditioning decreases with the improvement of the insulation performance of the envelope structure because the annual cooling consumption and absolute energy-saving decrease with the improvement of the envelope performance, but the reduction range is different. Before the set-point rise, the annual cooling consumption of the top-grade envelope is 70% of that of the lower-grade envelope, but after the set-point rises, the annual absolute energy saving is only 50% of that of the lower-grade envelope, and the reduction in absolute energy saving is greater than the cooling consumption. This shows that after vigorously improving the thermal performance of the envelope, increasing the temperature set-point of the air-conditioner by 1°C does not achieve the same degree of energy savings. Therefore, the energy conservation retrofit of existing buildings should not pay too much attention to increasing the thermal resistance and reducing the heat transfer coefficient of the old building envelope but should comprehensively consider the potential of guiding the behavioral energy conservation of existing buildings of

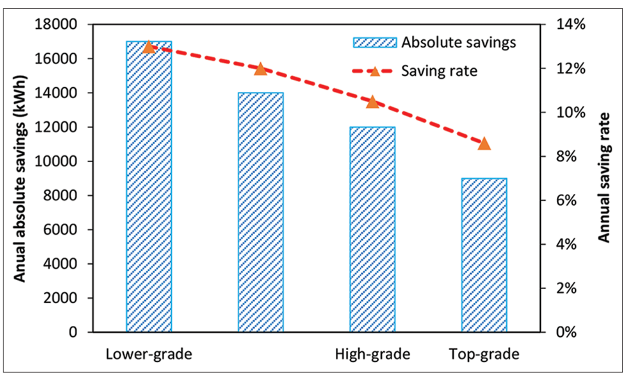


**Figure 3.** Comparison of annual energy saving of four grades of envelope. Source: Graph by the authors

all ages. The mechanism affecting energy savings is very complicated, which will be analyzed from the microscopic dimension of hours in the paper.

### 3.2. Monthly energy saving

Figure 4 shows the comparison of monthly absolute energy savings of four grades of the envelope when the temperature setpoint of the air conditioner increases by 1°C. It turns out that: (i) The monthly energy saving curve of different grades of the envelope has similar rules, and the peak energy saving occurs in the transitional season (May, June, and November). Compared with high-grade and top-grade envelopes, the changes in energy savings in hot months are gentler in lower-grade and medium-grade envelopes. (ii) In the cool winter months, the energy savings are very small. In February, because there is no cooling consumption, the energy savings are 0. (3) The change in thermal characteristics of the envelope has a greater impact on

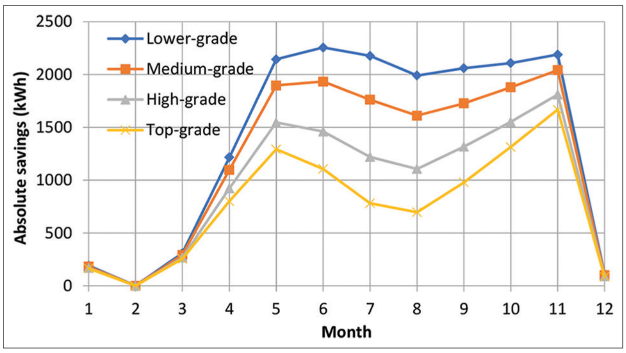


**Figure 4.** Monthly comparison of absolute energy savings. Source: Graph by the authors

energy savings in hot months (May–October) and a smaller impact in cool months (January, February, and December). This is reflected in the fact that the absolute energy savings decreases more in hot months than in cooler months as the performance of the envelope improves. (iii) With the improvement of the thermal performance of the envelope, the energy savings decreases month by month throughout the year, which is mainly reflected from May to October. This indicates that in hot months, the behavioral energy-saving potential of guiding old office buildings with poor envelope performance to increase the temperature set-point is greater. To express the whole picture more clearly, Table 2 shows the monthly cooling consumption before the set-point rise (i.e., when the set-point is 26°C) of the four grades of the envelope, as well as the monthly energy savings before and after the set-point rise. As we can see from Table 2, although the cooling consumption in July and August (the hottest months of the year) is much higher than that in May, June, and November (the transitional season), the energy savings in the transitional season months are higher than that in July and August. The mechanism of energy conservation is necessarily related to the coupling effect of climate conditions in different months and the increase of setpoints, which is worth further investigation.

Figure 5 shows the monthly comparison of relative energy-saving rate of four grades of envelopes when the temperature setpoint of the air-conditioner increases by 1°C. We can see from the diagram that: (i) In hot months, the relative energy-saving rate is relatively low, about 10%, while in cool months, the energy-saving rate is relatively high. The energy-saving rate is up to 100% in January, and nearly 100% in December, depending on the climate.

**Table 2. Monthly cooling consumption and energy saving (kWh)**

| Month | Lower-grade | | Medium-grade | | High-grade | | Top-grade | |
|---|---|---|---|---|---|---|---|---|
| | 26°C | Energy saving | 26°C | Energy saving | 26°C | Energy saving | 26°C | Energy saving |
| 1 | 191 | 191 | 183 | 183 | 170 | 170 | 165 | 165 |
| 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 3 | 552 | 309 | 524 | 292 | 481 | 267 | 464 | 256 |
| 4 | 6302 | 1216 | 5797 | 1097 | 5034 | 923 | 4534 | 801 |
| 5 | 15,072 | 2144 | 13,901 | 1896 | 12,161 | 1546 | 11,077 | 1292 |
| 6 | 20,388 | 2255 | 18,742 | 1933 | 16,065 | 1460 | 14,395 | 1107 |
| 7 | 25,532 | 2176 | 23,070 | 1762 | 19,547 | 1220 | 17,150 | 782 |
| 8 | 25,587 | 1991 | 23,104 | 1611 | 19,531 | 1107 | 17,002 | 697 |
| 9 | 22,869 | 2060 | 20,770 | 1727 | 17,873 | 1317 | 15,831 | 979 |
| 10 | 14,116 | 2108 | 13,022 | 1879 | 11,370 | 1552 | 10,290 | 1314 |
| 11 | 3947 | 2189 | 3687 | 2042 | 3277 | 1810 | 3027 | 1667 |
| 12 | 111 | 109 | 104 | 102 | 92 | 91 | 86 | 85 |
| Sum | 134,667 | 16,747 | 129,904 | 14,523 | 105,600 | 11,463 | 94,022 | 9146 |

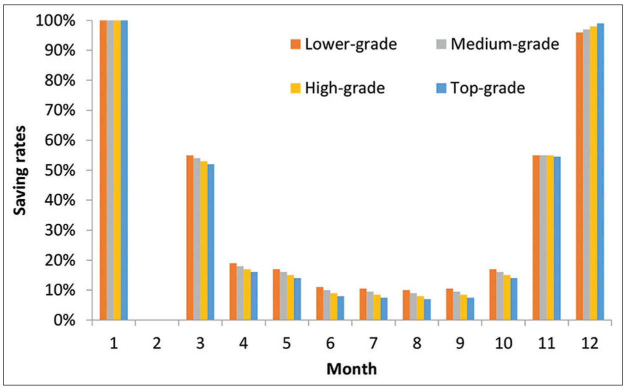


**Figure 5.** Monthly comparison of energy saving rate. Source: Graph by the authors

According to the statistics of climate data, only 3 h in January in Guangzhou have cooling demand before the set-point rises, and the dry bulb temperature of these three hours is between 26°C and 27°C. In these moments, when the set-point rises by 1°C, there will be no cooling load demand, so the energy-saving rate is 100%. The reason for the high energy-saving rate in December is similar. In February, the dry bulb temperature is lower than 26°C at all times. Therefore, energy savings in cool months are characterized by low cooling load demand, low absolute energy savings, and a high relative energy-saving rate, while in hot months, the hourly dry bulb temperature is higher, there is cooling demand almost all the time, and the cooling consumption base is large, so the relative energy-saving rate is relatively low. (ii) With the improvement of thermal performance of the envelope, the energy-saving rate decreases in hot months and changes little in cool months. However, due to the large cooling load demand in hot months, the base of cooling consumption is much larger than that in cool months, so the weighted average energy saving rate in hot months plays a macro-control role, and the common characteristics of the energy-saving rate in hot months are the characteristics of the annual energy-saving rate. (iii) The characteristic of the energy-saving rate in winter is different from that in summer. Even in December, the characteristic of the energy-saving rate is abnormal with the change in envelope performance. This shows that due to the complexity of building energy conservation issues, no energy-saving measure can have the same energy-saving effect at all times of the year. The monthly energy-saving rate can only reflect the annual energy saving law from the macroscopic perspective, but the deep-seated energy-saving mechanism of the thermal characteristics of the envelope coupling setpoint rise still needs to be further discussed at the microscopic level.

It is worth noting that by comparing the research results of the monthly absolute and relative energy-saving rates throughout the year, the conclusion drawn from the literature (Hoyt *et al*., 2015; Aryal & Becerik-Gerber, 2018) is that the hotter the climate, the more significant the energy-saving effect of increasing the set temperature of air-conditioning, has one-sidedness. In Figure 4, absolute energy savings in the hottest months of July and August are lower than that in the cooler months of May, June, and November. In Figure 5, the relative energy-saving rate in hot months is significantly lower than that in cool months, which is contrary to the conclusion of the literature (Hoyt *et al*., 2015; Aryal & Becerik-Gerber, 2018). Therefore, the conclusion is that the hotter the climate, the more significant the energy-saving effect of increasing the air conditioner set-point should be based on the annual energy-saving effect of different regions with different climatic conditions. However, in the same region, the climate conditions are the same all year round, but there are differences in the climate characteristics of different seasons and months, which lead to more abundant changes in the absolute energy-saving effect and the relative energy-saving effect. Therefore, an in-depth analysis, instead of a general summary, should be conducted.

## 4. Energy-saving mechanism

Ghahramani *et al.* (2016) applied the measures of adjusting the air-conditioning temperature set-point to the building models in different construction years and obtained the qualitative results that the newer the building, the lower the energy consumption after the temperature set-point is raised, but the absolute energy-saving potential is lower than the building models in the older construction years. Due to the higher building construction level in the newer construction period, the envelope performance of the newer building is better. Therefore, according to the research results in the previous section, the same qualitative conclusion is reached in the paper as in the literature (Feng *et al*., 2010), but there is no in-depth analysis of this energy-saving phenomenon in the literature. In this paper, to further reveal the mechanism of the above monthly and annual energy-saving effect of air-conditioning under different thermal performance envelope structures, the internal relationship between hourly load change and outdoor dry bulb temperature, solar radiation, and hourly cooling load demand is analyzed at the microscopic level.

### 4.1. Microscopic mechanism of absolute energy saving

Figure 6A and 6B show the comparison of hourly load reduction with the change of outdoor dry bulb temperature under the enclosure structure of lower-grade and top-grade when the air-conditioning temperature set-point increases by 1°C. We can see from the diagram

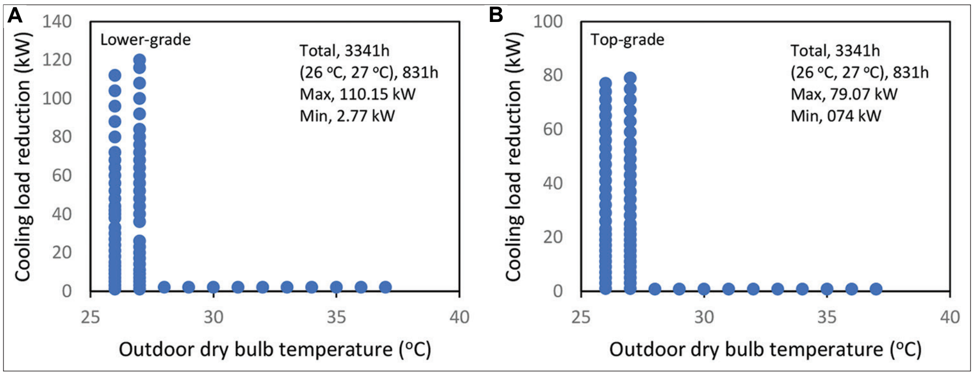


**Figure 6.** (A and B) Comparison of hourly load reduction based on outdoor dry bulb temperature. Source: Graph by the authors

that: (i) Due to the same climatic conditions, although the thermal performance of envelope vary greatly, the hourly load reduction has similarity with the variation of outdoor dry bulb temperature. (ii) When the outdoor dry bulb temperature is lower than 26°C, there is no cooling demand, and Guangzhou has the cooling demand for 3,341 h in the whole year, which has nothing to do with the envelope performance. The outdoor dry bulb temperature is between 26°C and 27°C for 831 h, and the absolute energy saving at these moments account for a large proportion of the total absolute energy saving in the whole year. For the lower-grade envelope, the total absolute energy saving at all times when the outdoor temperature is between 26°C and 27°C is 9763.01 kwh, accounting for 58.30% of the annual energy saving. For the top-grade envelope, the total absolute energy saving at these times is 7257.67 kWh, accounting for 79.35% of the annual energy savings. Therefore, in the time of annual cooling demand, the micro absolute energy saving of outdoor temperature between 26°C and 27°C always constitutes the main contribution of the total absolute energy savings after increasing the temperature by 1°C. (iii) Although from the perspective of macro energy consumption, the higher the performance of the envelope, the lower the absolute annual energy saving of the building. However, from the microscopic analysis results, buildings with better envelope performance have a larger percentage of behavioral energy savings in absolute annual energy savings, so their contribution is greater. Therefore, behavioral energy saving measures cannot be ignored for new buildings. (iv) For the moments when the outdoor temperature is between 26°C and 27°C, energy savings is resulted because the indoor temperature set-point is artificially raised from 26°C to 27°C, and indoor cooling is no longer needed, which saves all the cooling loads when the setpoint is 26°C. The hourly load reduction caused by set-point adjustment is much larger than the energy savings obtained by heat transfer due to temperature differences at other cooling moments. It can also be seen from the figure that the load reduction amount for 1 h within the range of 26°C – 27°C may be equal to 10 or even dozens of times of the hourly load reduction amount outside the range. Therefore, the key to the annual absolute energy saving effect is behavioral energy savings. (v) In the lower-grade envelope, the maximum hourly load reduction in the range of 26°C – 27°C is 110.18 kW, and only 79.07 kW in the top-grade envelope. This is because the improvement of the thermal performance of the envelope structure reduces the hourly cooling load demand of the building at 26°C. According to the above, the hourly load reduction of outdoor temperature between 26°C and 27°C is the hourly cooling load at the set-point of 26℃, which makes a great contribution to annual absolute energy savings. Therefore, the annual absolute energy saving scale with setpoint rise of 1°C shows a variation rule that decreases with the improvement of envelope performance. (6) For the time when the dry bulb temperature is >27°C, there is a minimum value of hourly load reduction, and the hourly load reduction values of all these moments are very close to this minimum value. The minimum hourly load reduction under lower-grade envelope is 2.77 kw, and it is only 0.74 kw under top-grade envelope. This is due to the decrease in K-value caused by the improvement in the performance of the envelope. According to the basic heat transfer formula of $Q = KF\Delta T$, the energy savings from heat transfer by temperature difference decreases. However, due to the large number of moments of heat transfer by temperature difference, the energy-saving effect brought by these still needs to be paid attention to.

Figure 7 shows the comparison of hourly load reduction of low-grade and top-grade envelope with hourly cooling load change before set-point rise. It can be seen from the diagram that: (i) Although the cooling load demand ranges of the two grades of envelope are different, the distribution rules of hourly load reduction have great similarity. (ii) With the increase of cooling load before set-point rise, the hourly load reduction presents two distribution rules. One is the gentle distribution near a minimum value; the other is the linear increase with the increase of cooling load. (iii) The load reduction with linear increase is the time when the outdoor temperature is between 26°C and 27°C. As the load reduction amount at these moments is equal to the hourly cooling load at 26°C, the figure shows a linear growth rule. The better the thermal performance of the envelope, the smaller the growth range of load reduction amount and the smaller the maximum value. (iv) The gently distributed load reduction occurs when the outdoor temperature is >27°C. The load reduction at these moments is generated by temperature difference heat transfer. The better the thermal performance of the envelope, the smaller the range of cooling load requirements before set-point rise, and the smaller the constant value of load reduction distribution, and the more concentrated the distribution.

From the above analysis of the load reduction at the micro level, the variation rule of the annual macro absolute energy savings mainly depends on the energy-saving effect obtained by the set-point adjustment behavior at the time when the outdoor temperature is between 26°C and 27°C.

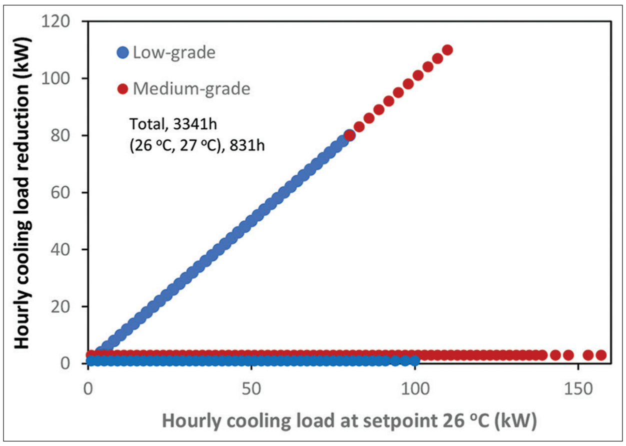


**Figure 7.** Comparison of hourly load reduction with hourly cooling load. Source: Graph by the authors

The worse the thermal performance of the envelope, the greater the energy savings potential of the act, and thus the better the energy savings of the act of increasing the temperature setting value, and finally the greater the absolute energy savings throughout the year. In addition, an outdoor temperature of between 26°C and 27°C is common in the transitional season of the year. From this point, it can be explained that the above monthly energy savings obtained the maximum distribution characteristics in the transitional season.

### 4.2. Micro mechanism of relative energy-saving rate

The cooling load caused by solar radiation is an important part of the total cooling load. Figure 8A and 8B show the comparison of annual hourly cooling load reduction rate with horizontal solar radiation under the envelope of lower-grade and top-grade when temperature set-point increases by 1°C. It can be seen from the diagram that: For envelope with different thermal performance, as the horizontal solar radiation increases, the hourly cooling load reduction rate has the same variation range and similar variation trend, which is the reason of the same climatic condition. The hourly load reduction rate is 100% for 831 h, when the outdoor temperature is in the range of 26°C – 27°C mentioned above. For other moments, hourly load reduction rate is mainly distributed in the range of <20%, the distribution points of top-grade envelope are more intensive, and the hourly load reduction rate point is lower than that of the lower-grade envelope under the same level of solar radiation intensity. Therefore, the annual weighted energy-saving rate of top-grade envelope is lower (9.73%) than that of lower-grade envelope (12.44%).

Figure 9 shows the comparison of hourly load reduction rate with the change of air-conditioning load before set-point rise under envelope of four grades and analyzes the energy-saving mechanism from another perspective. It can be seen from the diagram that: (i) The trend of hourly load reduction rate with the cooling load before set-point rise of

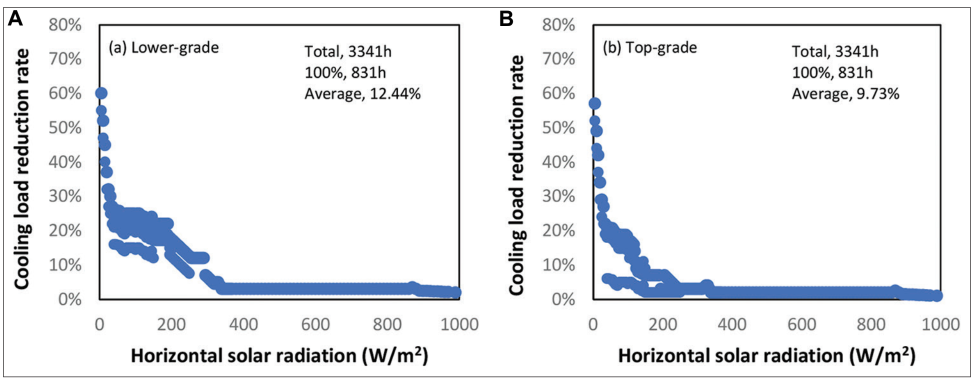


**Figure 8.** (A and B) Comparison of hourly load reduction rate based on horizontal solar radiation. Source: Graph by the authors

envelope with different performance is roughly the same. Its distribution trend is composed of two parts. The first part is the time when the outdoor dry bulb temperature is between 26°C and 27°C (831 h). The behavioral energy-saving effect brought by increasing temperature set-point makes the hourly load reduction rate of these scatter points all 100%, and the scatter points are distributed in parallel. The other part is that when the outdoor dry bulb temperature is higher than 27°C (2510 h), the hourly load reduction rate decreases rapidly with the increase of air conditioning load in an exponential curve, most of which are concentrated below 20% level and form a smooth curve. (ii) Although the hourly load reduction rate (100%) of scattered points in the first part is higher than that of scattered points in the second part, the latter has more corresponding moments and a larger load base before set-point rise, which plays a controlling role in the change trend of macro energy-saving rate. (iii) For the second part of scattered points, the cooling load demand range narrow results in the bigger curvature of the hourly load reduction rate curve (that is, the more concave to the origin), that is, the load reduction rate is smaller. From this microscopic distribution feature, the rule above can be proven that the monthly and annual absolute energy-saving and relative energy-saving rates decrease with the improvement of the thermal performance of the envelope.

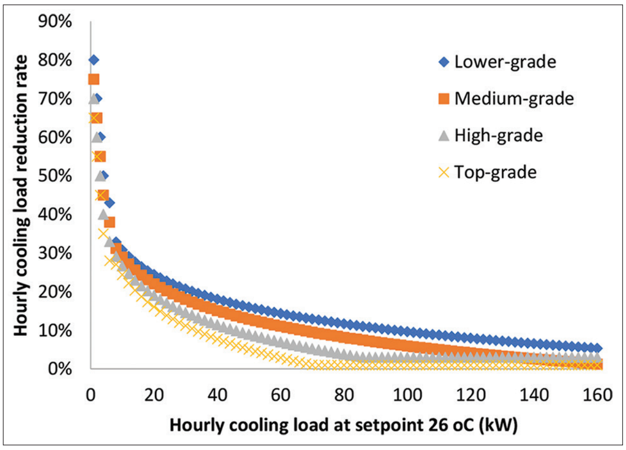


**Figure 9.** Comparison of hourly load reduction rate based on hourly load variation. Source: Graph by the authors

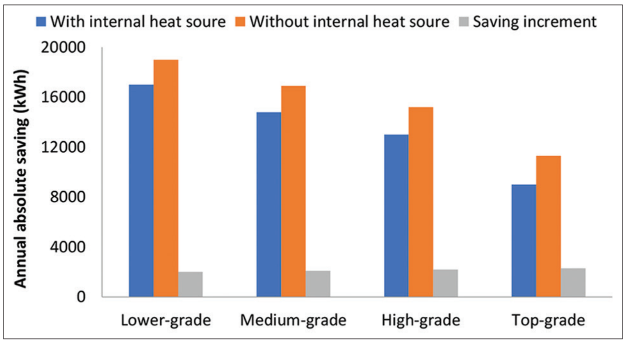


**Figure 10.** Comparison of annual energy savings before and after adding internal heat source. Source: Graph by the authors

## 5. Discussion

As mentioned above, when studying the energy-saving effect of 1°C increase in the temperature set-point of air-conditioning under different thermal performance of outer envelope of office buildings of the same size to better reveal the difference in the influence of a single variable of the set-point on the energy-saving effect, this paper disregards the influences of personnel, lighting, equipment, and other internal heat sources. However, in fact, the office building internal heat source is large, which will greatly increase the building cooling consumption, so that the energy-saving effect will change. In this section, the simulation results after considering the internal heat source are compared with the previous analysis. In the simulation, it is assumed that the office building can accommodate 35 office workers, the human load index is 136 W/person, the clustering coefficient is 0.96, the lighting load index is 11 W/m$^2$, the lighting couse coefficient during office hours is 0.6, the equipment load index is 20 W/m$^2$, and the equipment couse coefficient during office hours is 0.8.

Figure 10 shows the comparative diagram of annual energy-saving rate and annual cooling consumption before and after the addition of internal heat source in office buildings under the condition of four grades of envelope when the temperature setpoint of air conditioner rises by 1°C. It can be found that after considering the influencing factors of internal heat source, the annual cooling consumption of the four grades of envelope structures increases significantly before the set-point rise, but the annual energy saving rate does not change much. The energy-saving rate of top-grade and lower-grade envelope is slightly higher than that without internal heat source. The reason is that although the addition of internal heat source will increase the demand for cooling load of the building, the building is still in the same city with the same climatic conditions. After the addition of internal heat source, the number of hours of air-conditioning is almost unchanged, and the energy-saving mechanism has not fundamentally changed. Figure 10 shows the annual absolute energy savings and energy saving increment comparison of the four grades of envelope before and after considering the internal heat source as well. It is not difficult to find that the annual energy-saving rate is basically the same after adding the internal heat source, while the annual cooling consumption increases. Therefore, when there is an internal heat source, the absolute energy saving of the four grades of envelope increases to a similar degree, and the energy saving increment of the envelope with good performance is slightly larger than that of the envelope with poor performance. From the comparison and analysis in this section, it can be found that the relative energy-saving rate of increasing the temperature set-point by 1°C after adding internal heat source in office buildings has changed little, but the absolute energy-saving rate will increase significantly, and the value of energy savings will be improved.

## 6. Conclusion

This work takes the small office buildings in Guangzhou, a typical city with hot summer and warm winter, as the study site. Using the CTM method, four grades of envelope with assumed thermal performance are proposed to represent office buildings of different times. Under this condition, the energy-saving effect of air-conditioning when the temperature set-point increases by 1°C was studied, and the energy saving mechanism was explored from the micro perspective. The conclusions are as follows:

(i) The worse the thermal performance of the envelope of the same office building, the higher the absolute energy savings and the higher the relative energy-saving rate. This is because the annual cooling consumption and absolute energy savings decrease with the improvement of envelope performance, but the reduction range is not the same. Compared with lower-grade envelope, the annual cooling consumption of top-grade envelope decreases by 30% after the set-point rise, but the annual absolute energy savings decrease by 50%. The better the thermal performance of the envelope, the greater the reduction degree of absolute energy savings in the whole year relative to the cooling consumption; this indicates that the increase of air-conditioner's temperature set-point by 1°C, after envelope performance has been greatly improved, does not get the same degree of energy saving effect. Therefore, the energy conservation retrofit of existing buildings should not pay too much attention to improving the thermal resistance of the envelope of old buildings, but should pay attention to guide the occupants of office buildings in all construction times to conduct behavioral energy conservation.

(ii) Under the condition of the thermal performance of the four grades of envelope, the general rule of monthly energy savings is that: In the cool winter months, the relative energy saving rate is high but the absolute energy savings is small; in the transitional season, the absolute energy savings are the highest; in the hot summer months, although the cooling energy consumption is much higher than that in the transitional season, the absolute energy savings are lower than that in the transitional season. The difference between these rules is that, with the improvement of the thermal performance of the envelope, the monthly absolute energy savings decrease significantly from May to October, and it decreases more in hot months than in cool months. This suggests that there is greater potential for energy savings in the hot months by directing the behavior of old office buildings with poor envelope performance to increase their air-conditioning temperature settings.

(iii) The microscopic mechanism of the monthly and annual difference in absolute energy savings of air-conditioning with the temperature set-point rise always lies in the difference of load reduction when the outdoor temperature is between 26°C and 27°C. After increasing the temperature setpoint, there is no cooling demand at these moments, and the hourly load reduction is completely equal to the hourly cooling load at 26°C, with a large value. This kind of energy savings due to temperature-regulating behavior is regarded as behavioral energy-saving effect, which is the main contribution of macro air-conditioning energy savings. The annual and monthly absolute energy savings mainly depend on such behavioral energy savings. The better the thermal performance of the envelope, the smaller the hourly cooling load demand of the building when the temperature set-point is 26°C, thus reducing the behavioral energy savings. Therefore, the annual absolute energy savings with a set-point rise of 1°C shows a change rule that decreases with the improvement of the thermal performance of the envelope. Although better building thermal performance leads to lower behavioral energy savings and annual energy savings, it can contribute to higher overall energy-saving effect, which is also obvious for new buildings. In the transitional season, there are many moments when the outdoor temperature is between 26°C and 27°C, which greatly reduces energy consumption. Therefore, measures to increase the temperature set-point during the transitional season have a greater potential to behave in an energy-efficient manner.

(iv) The microcosmic mechanism of the difference between the annual and monthly relative energy-saving rates of air-conditioner with the set-point rise is that: The improvement of thermal performance of envelope reduces the range of cooling load requirements before temperature rise, and also reduces the microcosmic load reduction rate under the same solar radiation intensity, which changes the distribution rule of load reduction rate of envelope with good performance.

The load reduction rate of the envelope with good performance at the corresponding time is lower than that of the envelope with poor performance. From this microscopic distribution feature, it can be proven that with the improvement of the thermal performance of the envelope, the monthly and annual energy-saving rates of air conditioning temperature setpoint rise by 1°C and decrease on a macroscopic basis.

(v) After the addition of internal heat source, the annual cooling consumption of the four grades of envelope increases significantly, but the annual relative energy-saving rate is basically the same as before. The relative energy-saving rate of high-grade and top-grade envelope is only slightly higher than that without internal heat source, which is due to the same climatic conditions, the increase of internal heat source does not significantly increase the number of hours of air-conditioning, and the energy-saving mechanism does not fundamentally change. After the addition of internal heat source, the annual absolute energy savings increases significantly, the performance of envelope is improved, and the energy savings is increased by a greater degree, indicating that new buildings with a large internal heat source have greater energy-saving potential and higher absolute energy saving value by advocating to raise the temperature set-point of air conditioning.

In fact, building cooling energy consumption amounts are influenced by many factors, such as building types (residential, office, hotel, shopping mall, factory, etc.), since the human behaviors or occupants' habits vary widely in those buildings, resulting in different timely internal heat gains and dynamic load requirement changes for space cooling. For another example, even for building thermal grade of external envelopes, the age of the building may significantly impact practical heat transfer processes, since the heat insulation performance gradually decays with increasing years of usage, especially for those inserted wall insulation layers in retrofitting old building with limited lifespan of usage. Besides, practical energy usage amount depends on the types and thermal performance of indoor cooling equipment and systems, such as air-source heat pump, ground-source heat pump, and radiant air conditioner. In practical engineering, the building energy-saving potential and rate could vary widely with different air-conditioning devices, benchmarks, and reference systems, even in the same climatic zones. Although the specific results obtained in typical cases may not meet all the different conditions, the analysis methods used in this article are general and applicable to other occasions, which can provide references for energy-saving potential assessment for cooling system and building thermal design optimization.

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## Conflict of interest

The authors declare that they have no competing interests.

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*Writing – original draft:* Jianwu Xiong and Yin Zhang
*Writing – review and editing:* Meng Han, Jing Wu, and Zexuan Tian

## Ethics approval and consent to participate

Not applicable.

## Consent for publication

Not applicable.

## Availability of data

Climatic data for simulation are available on website: https://www.energyplus.net/weather.

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ACCSCIENCE PUBLISHING

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ORIGINAL ARTICLE

# Troglodyte settlements on the Loess Plateau of China: Challenges to sustainable tourism-oriented development

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## Abstract

Troglodytism is one of the most representative cultural expressions of geo-architecture. On the Loess Plateau of China, several significant examples of this approach to urban development can be found. Sometimes abandoned, sometimes still inhabited, cave settlements are precious examples of living heritage in rural and internal areas, which are at the risk of disappearance. Tourism is one of the strategies to revitalize these settlements, but it might be both an opportunity and a risk. A balance between conservation and development must be found, and a paradigm change is needed. Chinese cases can serve as a reference for solutions for this type of cave heritage, on which a debate has only recently begun at a global scale. This study introduces the classification of cave settlements based on the Underground Built Heritage theoretical approach. Chinese cases in Shanxi and Shaanxi provinces are illustrated on a comparative level. Tourism-oriented reuse and enhancement practices are analyzed and discussed in the context of national and international scenarios. In addition, criticalities and opportunities for the future are illustrated.

***Keywords:*** Troglodyte settlements; Yaodong cave dwellings; Rural and remote areas; Underground Built Heritage; Tourism; Sustainable development

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## 1. Introduction

Troglodytism has been one of the most widespread practices of living in the world for thousands of years. This method of approaching the territory is peculiar to the desert and semi-arid regions, with easily accessible natural cavities or easily excavated soil, generally on plateaus and in karst-fluvial areas. Many typologies have been tested and perfected from place to place, resulting in an extraordinary variety of features, thus defining a cultural landscape with a strong identity.

In the Loess Plateau area of northern-central China, this traditional building practice constitutes a broad phenomenon (Knapp, 2000; Wang, 2016; Fan, 2019; Zhang *et al.*, 2021). Especially between the Yellow River and the middle and lower reaches of the Yangtze River, where there are primarily plains, gullies, rivers, and lakes, underground spaces were used to fortify villages, store water and food, or for burial functions since the Bronze Age. Troglodytism has remained as the basis of urban experience and lifestyle to this day. Yaodong, literally "cave house," is a distinctive symbol of the folk culture in remote and rural areas, from both the tangible and intangible points of view (Liu, 2014; Varriale & Genovese, 2021, Li *et al.,* 2021).

Unfortunately, many folk settlements are at the risk of disappearance. Multiple natural and anthropogenic factors depress their survival and/or development, it is even tough to generalize the phenomenon. These geo-architectures are fragile and affected by climatic and environmental conditions that heavily impact their conservation (Feng, 2011; Li & Sun, 2013; Han & Li, 2014; Fan, 2019; Zhang *et al*., 2021). Furthermore, vernacular villages are "vulnerable in the face of pressure including urban, rural development, infrastructural development, tourism or changes in agricultural practices" ("Silk Roads," 2014). Since the 1990s, various government initiatives have been promoted for rural development to avoid some of these risks. Initiatives have also been launched for the protection of traditional villages and their landscape, thus changing the conception of cultural heritage within the country, and strengthening Chinese historical and cultural identity (Li, 2009; Wang, 2016; Zhang *et al.,* 2016; Liu, 2014; Wang *et al.,* 2021). In this context, tourism has entered as a practice for economic development. As highlighted during pre-COVID time, some yaodong villages with a poor farming-based economy faced the challenge of conversion into tourist attractions so as not to lose their vitality (Varriale *et al.,* 2019; Genovese *et al.,* 2021). Other villages or small towns have already invested in tourist development, having been promoted as tourist destinations at the national or international level.

Tourism is both an opportunity and a risk. On the one hand, it could be the driver for heritage-led economic development, thus straightening local communities' sense of identity. On the other hand, the mirage of short-term economic interest and tourist pressure may drive local policies toward unsustainable solutions in terms of physical conservation, urban regeneration, livability, loss of authenticity, and a sense of place. A balance between conservation and development must be found, and a paradigm change is needed, which considers the peculiarities of the yaodong settlements. It is a matter of rural heritage in remote areas and underground settlements developed with peculiar logic. From this perspective, the study of Chinese cases can offer solutions in this cultural heritage category – that of the underground settlements in a rural context – on which a debate has only recently begun globally.

This study introduces a general survey of a series of reuse strategies for tourism in some Chinese cave settlements. Fourteen cases were selected based on predefined criteria to offer the widest range of typologies and functions. The research is based on the classification of the cave heritage introduced with the Underground Built Heritage (UBH) theoretical approach (Varriale, 2021). This work is still an ongoing part of a broader comparative research between Western and Eastern countries, aimed at identifying elements supporting the creation of a general framework of heritage-led strategies for developing sustainable troglodyte settlements in rural areas (Genovese *et al*., 2019).

## 2. Literature review: Analysis of the global scenario

The conservation and sustainable development of folk villages in rural and remote areas, along with the management of underground spaces both in rural and urban contexts, has become a global issue today. Troglodyte villages are a peculiar kind of heritage, as each settlement is an expression of climate, geomorphology, geography, technical culture, belief, economics, politics, and so on. (Wang, 2016, vol. 4). Thus, the number, variety, and potential of troglodyte villages still need to be fully investigated and explored.

Rarely, an adequate understanding of the high potential and value, both tangible and intangible, of underground settlements, as well as calibrated protection and management actions, have determined the success of some cases. This was witnessed by the inclusion in the World Heritage List of cases such as the "Göreme National Park and the Rock Sites of Cappadocia," Turkey, in 1985; "The Sassi and the Park of the Rupestrian Churches of Matera," Italy, in 1993, and the "Cultural Landscape of Maymand" Iran, in 2023.

Based on these successful cases, the attention and appreciation for underground cultural heritage have gradually spread. Today, based on 1157 assets included in the UNESCO List, 175 cultural and mixed sites bear the word "rock" and 108 have the word "cave," that is, approximately 15 percent and 9% of the total. As a result, all over the world, old mines, temple grottoes and rocky sanctuaries, underground wineries, underground military sites, and cave settlements. The list can continue, – are recovered and musealized, becoming points of interest for tourism (Edwards & i Coit, 1996; Varriale, 2019; Pace & Salvarani, 2021; Varriale *et al*., 2022).

In the past few years, such geo-architectures have been equipped to become tourist attractions and accommodations, particularly in Europe and the Middle East. Only sometimes these structures were created as living spaces. Frequently, they were transformed and reused for tourism purposes. On a macro scale, it has also happened in many urban contexts. The tourism market has stimulated local policies toward adopting practices to make places attractive to tourism. However, the mirage of short-term economic interests related to tourism has pushed both private owners and local policymakers toward unsustainable solutions in terms of physical conservation, quality of life – that is, availability of services for residents, overcrowding, pollution, and safeguarding the sense of place and cultural memory.

In this perspective, the international community pushes toward models for sustainable development and responsible tourism, respectful of livability and place identity, as recommended by Agenda 2030 for Sustainable Development (Agenda 2030; "Tourism in the 2030 Agenda," n.d.) and the ICOMOS International Charter for Cultural Heritage Tourism 2022 (ICOMOS, 2022). The UNESCO Commission is also proceeding in this direction in evaluating sites with living heritage connotations to be included in the Cultural Heritage List. It has recently been demonstrated by the nomination of the Iranian case – above-mentioned – and by the submission of new candidatures, such as for the candidacy of "Cave dwellings and the world of ksour in southern Tunisia," in 2020. Nonetheless, each country is approaching the conservation, recovery, and enhancement intervention efforts in these settlements on the basis of what it deems most relevant to the interests of the country itself (i.e., social, economic, etc.).

## 3. Methodology

The present study introduces a preliminary overview of a series of reuse strategies for tourism in some Chinese cave settlements within the context of an ongoing project. The research was based on the design of various cases and employed both quantitative and qualitative methods of data collection. Documentation and information were collected during the on-site visits of the corresponding phases of the project since 2018 before the COVID-19 outbreak had started. The methodology adopted in this paper was organized into five different stages, according to the theoretical approach employed as follows:

(i). Adoption of UBH approach to Chinese cultural heritage;
(ii). Selection of Chinese yaodong as case studies;
(iii). Selection and adoption of significant data for the analysis of case studies;
(iv). Analysis of results from the comparative study;
(v). Discussion of results: Contextualization of Chinese troglodyte settlements in the national and international scenarios and opportunities for the future.

Concerning stage one, the UBH (Varriale, 2021) theoretical approach is taken as a reference. It provides parameters for the classification of all elements included in the class and allows both static and dynamic analysis of all cases, introducing several criteria also to evaluate historical reuses that can be considered within dedicated enhancement processes.

With reference to the second methodological step, we decided to focus on Chinese yaodong as an expression of the UBH class – Living Space. Case studies were selected based on the following criteria:

(i) Availability of the widest variety of typologies: a single village or clusters of interdependent villages in a contiguous area with historical functions, such as rural, commercial, and military/fortified;
(ii) Selection according to different levels of reuse and enhancement;
(iii) Inspection of all case studies considered during on-site visits.

Regarding the third methodological step, the parameters considered were as follows: name, GPS coordinates, province, county, date, typology of settlement, typology of geo-architecture, architectural quality, inhabited or not, prevailing economy, historical/cultural/natural connections in or around the settlement, infrastructural connections, level of protection, enhancement policies, tourism development, promotion, brief description, year of visit, sitography, and references. Then, a systematization of data was done to allow for subsequent comparative analysis. Parameters considered were as follows: settlement typology, presence of historic remains in or around the settlement, level of protection of each site, and type of tourism development. With reference to the fourth step, a comparative analysis of case studies was carried out.

The fifth phase consisted of the discussion of results. The analysis considers the level of tourism-oriented reuses adopted in China. It is based on the UBH reuses scale, which has been recently updated, encompassing interpretation, protection, abandonment, reuse, and rebuilding. Results are contextualized in the scenario of interventions for the conservation and revitalization of rural heritage and then in the international one.

### 3.1. Adoption of UBH approach to Chinese cultural heritage

The UBH (Varriale, 2021) theoretical approach is taken as a reference for the study and classification of troglodyte contexts. It considers the elements of cultural heritage that can be included in the newborn homonym class, providing several instruments for the functional classification, and the static and dynamic analysis of all those artifacts coherent with the given definition while introducing several criteria for their reuse and the evaluation of connected enhancement process as well. Thus, all typologies considered are expressions of the local and national history and culture, potentially leading to both heritage-led economic development and the straightening of the places' identity.

This method has been utilized and refined during several ongoing projects; thus, some categories were re-elaborated and/or modified concerning the already published methodology. At this stage, the method provides a functional analysis (Figure 1).

The functional classification points out eight UBH functions – sanitary, water, living space, religion, defense, economy, food, and transport, each connected to the underground management of correspondent environmental conflicts, social interactions, or both.

The methodology can also be adapted to study historical reuses, both from one function to another and about different uses within the same function.

At a theoretical level, concerning the current situation after dismissing the UBH elements regarding their primary function, the protocol defines four possible alternatives: interpretation, protection, abandonment, and reuse. A fifth hypothesis, that is, re-building, refers to the construction of new UBH elements by adopting the same technology for the construction of UBH elements.

(i). Interpretation: it refers to UBH elements at the core of enhancement projects.
(ii). Protection: it refers to UBH elements included in protected areas but not exploited as cultural heritage elements.
(iii). Abandonment: it refers to abandoned elements of UBH.
(iv). Reuse: it refers to UBH elements that have been dismissed regarding their primary function but reused within another function.
(v). Re-building: it refers to new cave elements built following the historical techniques adopted for the construction of UBH, responding to the same functions as the new ones.

In China, interpretation, protection, abandonment, reuse, and re-building were all adopted from case to case regarding different elements included in the UBH class.

### 3.2. Selection of Chinese yaodong as case studies

The present study was based on field research carried out in the pre-COVID period. The latest data collection was conducted between 2017 and 2018.

Initially, the research focused on an overview of the most representative Chinese elements from the UBH class (Figure 2). The religious function, Buddhist caves, rupestrian churches, and necropolis were classified. The defense and escape tunnels were listed. The economic and historical mines were studied. The food preparation and historical granaries were considered. For sanitary, we focused on historical sewers. For the water study, we selected buried channels. Finally, for living space, cave villages known as yaodong were studied.

Yaodong forms, while showing common elements, reveal the broad range of housing-type solutions. Each has emerged from specific environmental and social conditions characteristic of the plateau area at different times in the past (Golany, 1992; Knapp, 2000; Wang, 2016).

In general, a yaodong is an artificial cave created by excavating the earth and transformed into a living space

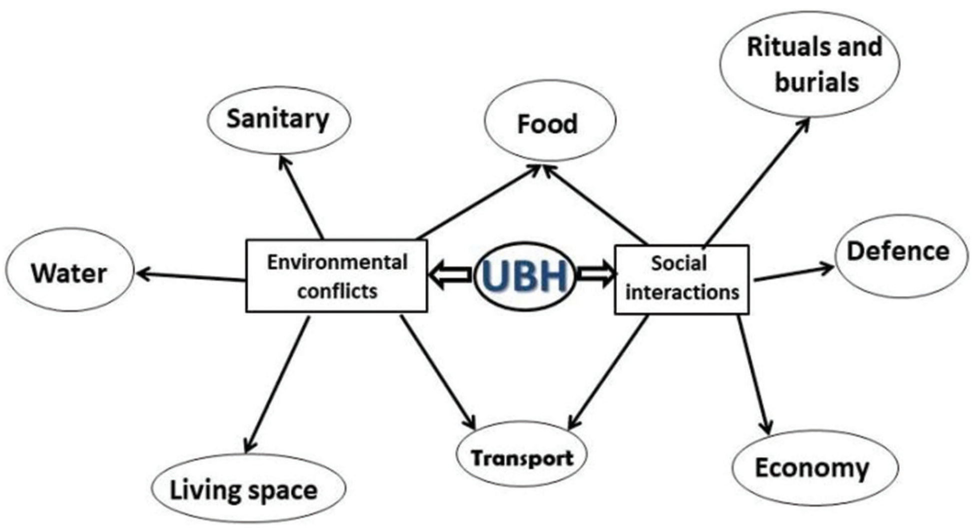


**Figure 1.** The Underground Built Heritage chart. Source: Diagram by Roberta Varriale

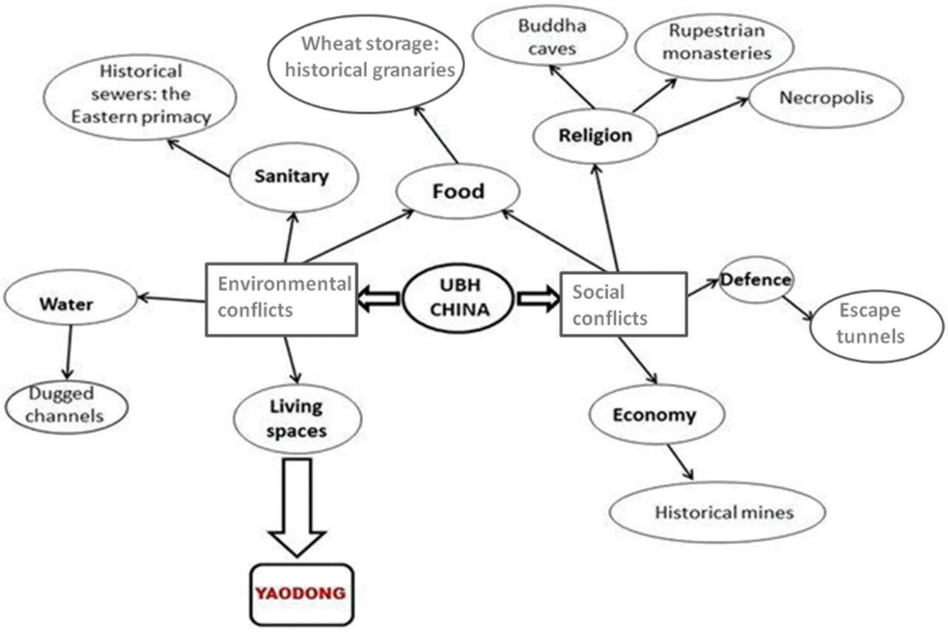


**Figure 2.** The Underground Built Heritage functional chart in China. Source: Diagram by Roberta Varriale

by enclosing the entrance with walls constructed from fired bricks, earthen bricks, stones, or wood, depending on the specific site. The interior space usually has mixed use: the main living room doubles as the kitchen and bedroom. Typically, multiple dwellings are built adjacent to or on top of one another and are connected to form a multitiered village, often for a single clan or an extended family (Figures 3A and 4). Terrain and semi-terrain elements are combined with a structure built above ground to form an integrated complex connected by a path. Yaodong settlements are isolated or form part of clusters of interdependent villages in a contiguous area. This last case depends on the original function of the settlement. For example, if it arose for the agricultural exploitation of the land, as an extension of a military post, or as an economic and commercial exchange center. Some are very old, it is even difficult to define their age. In this, only the documentation offers support because yaodongs are fragile geo-architectures requiring continuous maintenance. Their conservation depends on natural and anthropogenic factors (Feng, 2011; Li & Sun, 2013; Han & Li, 2014; Fan, 2019; Zhang *et al.*, 2021). On the one hand, environmental and climatic conditions, such as desertification, climate change, hydrogeological instability, and seismicity, heavily impact places' livability. On the other hand, reuse, rebuilding, abandonment, and demolition are common phenomena linked to the needs of local communities or the country's modernization and infrastructure policies (Hsing, 2010) (Figure 3).

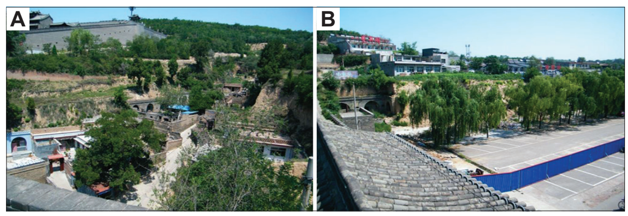

**Figure 3.** Jingsheng village, Lingshi County in Shanxi, 2017. The old yaodong village overlooks the Wang Family Compound (the gray brick walls). (A) Part of the old yaodong recovered and/or rebuilt in yaodong style. (B) Old yaodongs are being demolished to make room for the new tourist car park and urban development. Source: Photos by Laura Genovese

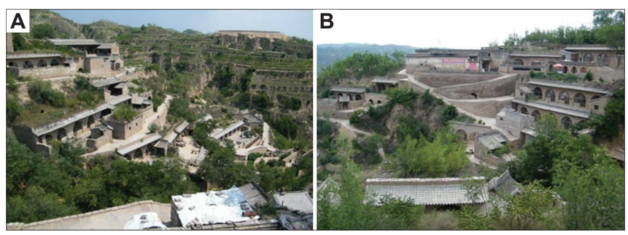

**Figure 4.** Lijiashan, Lin County Shanxi province, 2018. The photos show the characteristic layout of the village on overlapping terraces, which also find its counterpart in the agricultural management of the landscape, with terraces reserved for cultivation (A). There is a guest house at the top of the village (B). Source: Photos by Laura Genovese

Cases have been selected to offer the broadest range of typologies and functions, and the reuse of cave houses in the Lesbian area guarantees diversification as much as possible. In this sense, the selection only exhausts part of the range of possibilities, considering the significant number of potential cases. Case studies were selected based on the following criteria:

(i) Availability of a wide variety of typologies: A single village or clusters of interdependent villages in a contiguous area with traditional functions, such as rural, commercial, and military/fortified;
(ii) Selection according to different levels of reuse and enhancement;
(iii) Inspection of all case studies considered during on-site visits.

### 3.3. Selection of significant data for the analysis of case studies

Case studies were analyzed based on predefined criteria, already tested in other contexts using the UBH method, which have been perfected for the type of asset considered in the Chinese context. The use of these criteria is aimed at making the results of the data collection and subsequent analyses comparable with those already organized in the database concerning cave settlements, which was created using data collected in other countries and has been operational for some time. In this perspective, as a first step, information on each selected case was collected and organized thanks to a predefined datasheet – structured precisely on these criteria – as shown in Table 1.

**Table 1. Criteria for data collection and systematization**

| Criteria | Description |
|---|---|
| Name | |
| GPS coordinates | |
| Province | |
| County | |
| Date | |
| Typology of settlement | |
| Typology of geo-architecture | |
| Architectural quality | |
| Inhabited or not | |
| Prevailing economy | |
| Historical/cultural/natural connections in or around the settlement | |
| Infrastructural connections | |
| Level of protection | |
| Enhancement policies | |
| Tourism development | |
| Promotion | |
| Brief description | |
| Year of visit | |
| Sitography | |
| References | |

Table shows the criteria defined for data collection and the organization of the datasheets. Source: Table by Laura Genovese

Some of these criteria are intuitive, and others require a brief comment. Concerning the settlement location, the parameter "County" is considered valuable, not only to point out the administrative competence but also to specify the geographical context; if the surveyed settlements are too small to be found on the map; if GPS coordinates are not available, or if a settlement system is considered within a broad territorial context. Finally, this geographical indication can offer qualifying elements on the geo-climatic characteristics and local geo-architectural typologies.

"Typology of geo-architecture" refers to identifying possible architectural declinations of the yaodong, depending on the soil morphology and composition, the local building culture, and so on. "Architectural quality" criterion refers to the harmony and homogeneity of the materials; the façades and roofs; the openings; the presence of symbolic decorative elements; the state of conservation of the historic building, for example, due to the effect of restorations, or that of abandonment, or modern destruction.

"Historical/cultural/natural connections in or around the settlement" refers to the presence of historic/cultural relics and natural scenic spots or attractions in and/or around the settlement, which may constitute an identitarian asset for the local community and/or a tourist attraction.

"Infrastructural connections" concerns the problem of accessibility and reachability of sites from important centers.

"Level of protection" refers to the presence of measures for protection at the provincial or national level or whether the site is a UNESCO property.

"Enhancement policies" criterion concerns interventions supporting the conservation and enhancement of the site and/or the surrounding environment, embellishing façades, presence of elements of modern urban furniture, care for public parks, and presence of signs.

"Tourism development" refers to the enhancement of tourist exploitation and the site's national and international promotion. The relevant parameters are reflective of tourist attendance, presence of accommodation, availability of food catering and recreational activities, presence of art craftsmen and services, presence of commercial activities, presence of cultural activities/institutions (i.e., museums), and the reuse of folk spaces for new activities.

"Promotion" refers to the level of promotion of the site, thus including the presence of a tourist office or information centers; partial or total closure of the town after ticketing; organization of guided tours; editions of guides and/or promotional brochures, websites, and communication tools (including digital); and presence of directional and information signs.

In the second step, relevant information was organized to simplify the subsequent comparative analysis phase, as shown in Table 2. In this phase, the parameters considered were as follows:

(i). The codification of settlement typology concerning historic functions;
(ii). The presence of historical remains and relevant points of interest in or around the settlement;
(iii). The level of protection of each site;
(iv). The type of tourism development detected.

## 4. Analysis of results from the comparative study

The study focuses on a particular tourist-oriented reuse approach for yaodong settlements. With regard to the analysis carried out with the UBH approach, it can be assumed that if the primary use of the yaodong settlements

**Table 2. Synoptic table of selected cases**

| Name | Province | Settlement typology | Historic remains in or around the settlement | UNESCO-National-Provincial | Tourism development |
|---|---|---|---|---|---|
| Beiying village (北营村委会) and Shanzhou district – Sanmenxia city (Guancaitou village, etc.) | Henan | Rural system | Shanzhou is renowned for its historical heritage sites of Yang-shao culture | N: listed in the third batch of China's national intangible cultural heritage in 2011 | Many residences in the Shanzhou district have been renovated and turned into tourist attractions |
| Jingsheng village (静升镇) – Lingshi County | Shanxi | Rural village | Wang Family Compound "Historic Residences in Shanxi and Shaanxi Provinces" UNESCO tentative list 2008 | n.d. | The residential village has been partially rebuilt to host tourist facilities related to Wang Family Compound |
| Laoniuwan village (老牛湾) | Shanxi | Fortified village | Castle and boundary walls as part of the military system of the Great Wall UNESCO site | N: Great Wall Protection Ordinance 2006 | Some residences have been renovated and turned into tourist attractions |
| Lijiashian village (李家山) | Shanxi | Rural village | | N: Historical and cultural towns and villages (HCTVs) | Bottom-up initiatives for tourism attraction |
| Pinglu County (平陆县) (Jidu, Yaoli, Shijianian villages) | Shanxi | Rural system | | N: Included in People's Republic of China: Yellow River Basin Green Farmland and High-Quality Agriculture Development Project, 2022 | Many of residences in Pinglu County have been renovated and turned into tourist attractions |
| Qikou town (碛口镇) | Shanxi | Merchant town | Offshore terminal of Yellow River, rich in artistic and cultural relics | N: Since 2004 subject of international projects for the protection of historic architecture | The city core has been renovated and turned into a tourist attraction |
| Snail Valley, in Tongchuan city | Shaanxi | Rural system | | P: Provincial government initiative for recovering and converting into tourist accommodation | Many of the residences have been renovated and turned into tourist accommodations |
| Yan'an town (延安) | Shaanxi | Fortified village | Yan'an Revolution Memorial Hall | N: List of Major National Historical and Cultural Sites as Yan'an Revolutionary Site | Mao's yaodongs have been renovated and musealized |
| Zhangbi village (张壁古堡) | Shanxi | Fortified village | Underground tunnels | | Underground defensive network has been recovered and musealized |

Table summarizes some selected cases, which are significant for typology, traditional functions, level of protection, and tourism reuse. Source: Table by Laura Genovese as a living space was interrupted and the function of the economy came in, three possible transformations can be found in the Chinese scenario.

Spaces are transformed into hotels, shops, and exhibition centers. Among the selected cases, transformations into B&B or charming hotels (blue in Figure 5) and commercial activities (violet in Figure 5) are more frequent in abandoned sites. In the Snail Valley Country Hotel, Tongchuan city, central Shaanxi, some abandoned vernacular villages were turned into tourist accommodations. The Snail Valley Country Hotel project aimed to attract tourists and develop the economically depressed area. The project dealt with the renovation and conversion of abandoned cave dwellings into hotel rooms and the architectural addition of connection to the old underground spaces to create the tourist center (Xu *et al.,* 2019). Nonetheless, this kind of reuse can also be found in inhabited villages. This is the case of Lijiashan, a historic Ming village in Lin County, west of Shanxi province (Yu, 2008; Wang, 2016), which is still partially inhabited. Even if it is well known and promoted by various international guides and tour operators, tourist reuse is limited to the reconversion of a yaodong courtyard into a family guest house – the Qikou Li Jianxin Farmstay (Figure 4). During the field visit in 2017, many renovation interventions on cave dwellings were seen, and we pointed out the techniques and solutions that were respectful of vernacular architecture, which came with excellent results (Genovese *et al.,* 2019).

Another possible reuse is the musealization or the transformation into a tourist and/or exhibition center (orange in Figure 5). In the country, culture and economic/tourist development are generally considered together. This is why this function is considered a subset of the economy concept in Figure 5.

Furthermore, musealization has been found in sites both inhabited and not. Laoniuwan village, Pianguan County, Datong City in Shanxi, is historic. Since the Ming dynasty (1368 - 1644), Laoniuwan fortress was erected as a fundamental garrison in support of the Great Wall and control of an essential landing on the Yellow River to Mongolia, thus playing a strategic role in the defense of borders and trade with the Tartars, on the Mongolian side of the river. The village was developed under the Qing dynasty (1636 - 1911) around the castle when it lost its military functions and troops became farmers. Recently, the village is almost deserted, and the local people have moved to new settlements close to the historic one. Some cave dwellings have been recovered in the context of the Great Wall Protection Ordinance 2006 – regarding the conservation and protection of the Deshengbao Fortresses network – and few have been turned into photographic exhibition spaces. Others have been recovered and opened to the public as tourist attractions that display the folk lifestyle in vernacular cave dwellings. On the other hand, Yan'an is a thriving town in Shaanxi. The city hosts the most famous Chinese cave dwellings, which are an important historical symbol, having been inhabited by Mao Zedong and some comrades of the Party between 1935 and 1948. Here, they headquartered and elaborated the ideology that later became known as "Maoism." Today, Yan'an Revolutionary Site is listed as a Major Historical

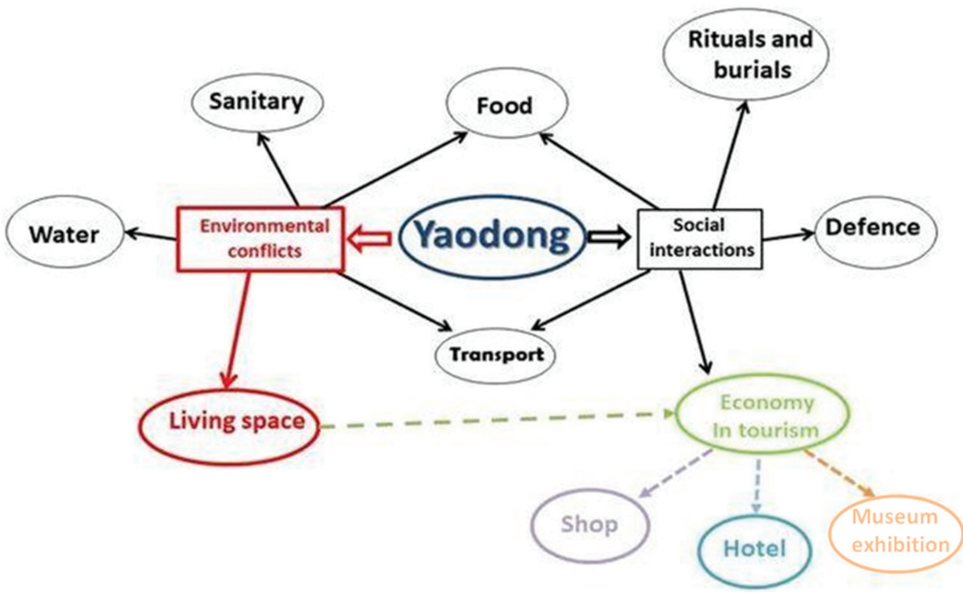


**Figure 5.** Underground Built Heritage chart of yaodong functions transformations. At the bottom part, the transformations from living space to economy are represented. Source: Diagram by Roberta Varriale

and Cultural Site protected at the national level, and all historic cave dwellings have been recovered and enhanced, becoming a must-see for red tourism.

Musealization is the approach also for underground spaces with hybrid functions, such as those initially built for military and defensive functions. This is the case of the Zhangbi fortified village, Jiexiu City in Shanxi (Figure 6). The ancient village, from the Sui (581 – 618) and Tang (618 – 907) dynasties, stands on steep rocky cliffs, having been pierced by an intricate tunnel system. The tunnels were created for military and defense purposes and have been connected to dwellings and spaces with varied uses. Nowadays, the village is still vital, and the underground system has been recovered and turned into a museum. The ticket gives access to three tunnel levels, including mangers, furnaces, wells, grain silos, flood prevention structures, and wall communication facilities.

In all these tourist-oriented reuses, interpretation action represents the first step as the basis for the reconversion projects.

Re-building and destruction are other actions adopted in the tourist-oriented development strategy. In truth, these practices are widespread in variable proportions in almost all cases and are considered part of modernization and urban development. Nonetheless, "developmental destruction and constructional destruction" seem to have a more significant impact on vital centers, if they arise near the famous tourist attractions (Zhang *et al.*, 2021). This is the case of the Jingsheng village, Lingshi County in Shanxi (Ping & Chunyang, 2022), an old yaodong village from Yuan (1271 – 1368) to the early Ming (1368 – 1644) dynasties. It overlooks the Wang Family Compound, which is a well-known tourist attraction as it is one of 123 residences of the "Historic Residences in Shanxi and Shaanxi Provinces" submitted in 2008 for inclusion in the UNESCO World Heritage Tentative List, for the cultural category (Ancient Residences, 2008). Modern urban development, on the one hand, and the tourist pressure related to the Wang Courtyard, on the other, are crushing the historic housing fabric, endangering the survival of traditional folk villages (Figure 3). Furthermore, vernacular architecture has mostly been restored or rebuilt with new materials in the traditional style. Modernizing the structures with different colored plasters, cables, water heaters, and antennas creates a truly chaotic and confusing effect.

Similar problems affect Qikou town, Lin County, Luliang city in Shanxi (Wang, 2016). As a prosperous historic land-and-water port along the Yellow River since the Ming dynasty, the town lost its strategic role around the 1930s due to the introduction of rail transport and fell into decline. After years of almost total abandonment, starting from 2004, the city has been the subject of an international debate for the conservation of traditional architecture, aspiring for the candidacy for UNESCO site (Chen, 2004; Ma, 2006; Yan, 2018). Nonetheless, recent tourism – both cultural and ecological – development started, triggering a process of urban and infrastructural transformation, which can put the historic town and its cultural landscape at risk. On the one hand, particularly in the outlying areas, some cave dwellings have been abandoned and filled in, left for collapse or demolition (Figure 7A). In some cases, they have been rebuilt with modern materials according to traditional typologies, adapting to the needs of modern lifestyle (Figure 7B). On the other hand, the threat of highway access to Qikou and the creation of the highway along the river call for disrupting its historic waterfront access. For these reasons, since 2006, the site has been under observation by the World Monument Fund (World Monument Fund, n.d.).

Regarding the abandonment action, it must be stated that abandoned spaces have been identified in almost all the cases evaluated. This practice is regular in urban development and generally concerns spaces no longer relevant or usable


**Figure 6.** Zhangbi village, Jiexiu City, Shanxi province, 2018. (A) A diorama illustrating the structure of the hill, with the city built on top of the network of underground tunnels. (B) An old yaodong, along the slope of the hill facing the valley, used as a tourist shop. (C) Renovation of a yaodong connected directly to the tunnel network. Source: Photos by Laura Genovese

for various reasons. However, in the specific case of the effects of tourism on practice, we cannot say that we have encountered gentrification phenomena at the moment.

Table 3 offers a summary of the reuse highlighted in selected cases.

### 4.1. An overview of cave settlement development initiatives in the Chinese scenario

The protection practice deserves a different treatment and a classification in the broader national scenario. As explained above, it should be emphasized that yaodong villages and their territorial context are very fragile, and the consequences of their abandonment of vernacular architecture are multiple. Depopulation means the deterioration and destruction of earthen heritage, which is made from highly perishable materials, thus requiring constant maintenance and protection from atmospheric agents (Genovese *et al.,* 2021). Looking at the problem from a micro- to macroscale, it is the loss of local architectural typicality and craftsmanship, the loss of cultural and social integration of communities, and the loss of the sense of place. More generally, it impacts the conservation of the historical and cultural landscape.

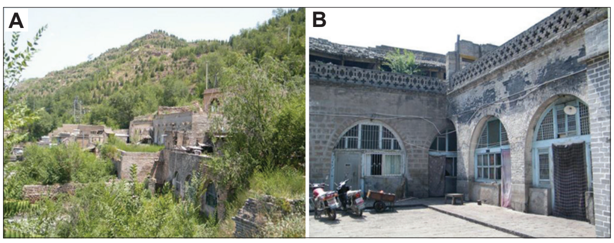


**Figure 7.** Qikou town, Lin County, Shanxi province, 2017. (A) A complex of yaodong, which is almost degraded and partially abandoned. (B) A yaodong courtyard, at the basis of the monumental complex, having been rebuilt many times in traditional style with modern materials. Source: Photos by Laura Genovese

The abandonment phenomenon has undergone an acceleration since the 1980s, during the period of reform and opening-up of China, after which residents in Loess terrace-like plains gradually moved to new or more significant settlements or, simply, from cave dwellings to aboveground architectures, searching for more comforts and modern standards. The vernacular architecture was filled, collapsed, or abandoned almost in all Loess areas. To avoid these risks, since the 1990s, various government initiatives have been promoted, basically dedicated to two areas of intervention: (i) The revitalization and rural development that seeks to address and alleviate poverty, and (ii) the conservation of traditional settlements and their productive landscape, seeking to promote the development of rural tourism (Li, 2009; Wang, 2016; Zhang *et al.*, 2016; Liu *et al.*, 2019; Wang *et al.,* 2021). Among the initiatives, the Loess Plateau Watershed Rehabilitation project, which is concentrated in the northwest of Shanxi, including Pianguan County and Laoniuwan village, was initiated to avoid desertification and support the survival of farms in the plateau area (World Bank, 2006). Very recently, China's new Rural Revitalization has entered a new stage, and a Promotion Law to advance the work of rebuilding the rural economy came into effect in June 2021 (*Rural Revitalisation Promotion Law*, 2021). Furthermore, in 2022, the Ministry of Agriculture launched a project supported by the Asian Development Bank, aiming to strengthen sustainable green agricultural production systems and agricultural value chain, to revitalize rural areas in six provinces, such as southern Shanxi, particularly the Pinglu County ("Yellow River Basin Green Farmland," 2022).

In the long run, this trend of protecting and enhancing rural assets has acted as a tool to articulate the country's urbanization and modernization project. At the same time, this initiative has made it possible to preserve and strengthen the Chinese historical and cultural identity. The inclusion of many rural settlements in the national or

**Table 3. UBH analysis and RE-USE classification**

| Name | Interpretation | Protection | Reusing | Rebuilding | Abandonment |
|---|---|---|---|---|---|
| Beiying village (北营村委会) | x | x | | x | |
| Jingsheng village (静升镇) | | | | x | |
| Laoniuwan village (老牛湾) | x | x | x | | x |
| Lijiashian village (李家山) | | x | x | | x |
| Pinglu County (平陆县) (Jidu, Yaoli, Shijianian villages) | x | | x | x | |
| Qikou town (碛口镇) | | x | | x | x |
| Snail Valley, in Tongchuan city | x | | x | x | x |
| Yan'an town (延安) | x | x | x | | |
| Zhangbi village (张壁古堡) | x | | x | | |

The table summarizes cases illustrated above, in relation to the type of action detected for the adaptation of historic underground architecture to the site's tourism development strategy. Source: Table by Laura Genovese provincial lists of historical and cultural towns and villages, and that of traditional villages, starting from 2003 (Yan *et al.*, 2017; Zhang *et al.,* 2021), such as the case of Lijiashan, fits into this scenario. Likewise, the National List of Intangible Heritage of Pinglu technological culture and craftsmanship in building silo-houses in 2021 ("Cave Building Technique," 2021), as well as the candidacy and inclusion in UNESCO Lists of numerous architectural and cultural expressions of various ethnic groups linked to regional and rural, might be considered (Chinese Paper-cut, 2009). In this context, although conservation and enhancement practices are mainly seen in the function of tourist-oriented economic development – the aim is to support and increase the "lost" national cultural identity (Zan *et al.,* 2018; Varriale *et al.,* 2019) – relevant cases emerged, in which the communities have been involved in preserving details that give meaning and quality to yaodong's lifestyle and in testing solutions for sustainable development (Yong *et al.,* 2019). Rarely, bottom-up initiatives were found, which were subsequently supported by local policies, as found for various types of rural settlements affected by tourism development (Yin & Wu, 2008; Huang, 2021; Li *et al.*, 2021; Qi, 2023).

On the other hand, early attention of the country toward underground heritage should be noted, highlighting the importance of the troglodyte culture, which is part of the national identity. In this perspective, of the 56 sites inscribed in the UNESCO World Heritage list, 18 include the word "rock" in its description, and 14 have the word "cave". Between the cultural and mixed sites (cultural/natural), there is evidence of prehistoric settlements, rock sanctuaries, and Buddhist cave temples. Among these kinds of underground heritage, yaodong is included: the serial site "Silk Roads: the Routes Network of Chang'an-Tianshan Corridor" ("Silk Roads," 2014) includes, which remains of terrain and semi-terrain settlements. In this regard, a 20-year tradition of academic study has been focused on yaodong settlements. The interest was concentrated on deepening technical and performance characteristics in internal insulation and environmental sustainability, evaluating solutions to replicate cave dwellings in a contemporary way (Golany, 1992; Li & Sun, 2013; Wang, 2014; You *et al.,* 2019).

Nonetheless, a recent attitude has spread toward considering the intangible values that they represent, such as those on the cultural landscape. Thus, solutions for conserving livability, historical memory, and the sense of place have been explored (Qi, 2023). In this context, social participation in recovery processes and enhancement cases was individuated.

Concerning selected cases, the analysis evidenced three principal scales of intervention for tourism-oriented strategies for rehabilitation and reuse:

(i) Bottom-up initiative. This is the case of Lijiashan village, historically devoted to a farm-based economy and developed due to the economic influence of the nearby Qikou town. Recently, it has been attempting to attract tourists visiting Qikou in a bid to improve local tourism. The first form of promotion was through word of mouth among visitors. Then, the increasing number of visitors motivated the conversion of a yaodong courtyard at the top of the village into a family guest house (Figure 7B). Nonetheless, occasionally, ordinary people offer hospitality to trippers. Nowadays, it is recognized as one of the historical and cultural towns and villages (HCTVs).

(ii) Provincial/local government initiative. Several villages in the Shanzhou district, Sanmenxia city of Henan province have been included in the national or provincial traditional village list since 2012, including Beiying, Qu, and Liusi villages in the Zhangbian township. More than 80 silo-caves in the Beiying village have been renovated and turned into tourist attractions that display the folk lifestyle and craftsmanship. The village is a famous tourist attraction (Li & Li, 2018; Zhang *et al.,* 2021).

(iii) Central governmental initiative. This is the case of the Laoniuwan Deshengbao fortress and village mentioned above, having been restored in the context of the national project on the protection of the Great Wall zone, together with other Deshengbao villages close to the Great Wall, and enhanced to attract tourism (Genovese *et al.,* 2021).

## 5. Discussion of results: Contextualization of Chinese troglodyte settlements in the national and international scenario and opportunities for the future

Nowadays, the conservation and sustainable development of folk villages in rural and remote areas, as well as the need to manage underground spaces in rural and urban contexts, have become a global issue. Chinese yaodong settlements combine two issues that are not simple to deal with. Settlement pattern, plan layout, façades, and internal organization of the artificial cavities express local human abilities and craftsmanship in dealing with the Plateau's physical and climatic characteristics (Wang, 2016).

Yaodong settlements express an entire vulnerable complex territorial system comprising geographical, economic, political, social, and cultural elements. Let's call this system Historic Underground Landscape (Genovese, 2021). Investigating this complex system has many challenging aspects and criticalities, which do not strictly depend on China itself. However, one of the main critical issues is the lack of a study protocol that allows for an adequate understanding.

The lack of a study approach so far has been the basis of the lack of recognition of the high value and potential of most of these sites. In fact, where there has been an adequate understanding and interpretation of this heritage, there have been cases of successful conservation and enhancement, as demonstrated by the few cases of troglodyte settlements included in the UNESCO List. More commonly, these precious treasure nests of information and examples of living heritage are completely undervalued and left abandoned or sacrificed to urban development.

Our research highlights that, at a global level, there are still many fundamental steps to go through to approach the topic and define a framework for heritage-led sustainable strategies for underground rural settlements. More specifically, a universally recognized and shared glossary, a universally recognized classification for troglodyte architecture, the census and systematization of troglodyte settlements on every national scale are all necessary steps in a first phase of both a quantitative and qualitative analysis of this kind of heritage. In the second phase, the improvement of the interpretation, communication, educational, enhancement, and management practices will provide bases for elaborating conscious strategies for protecting and developing these contexts. In this scenario, the comparative analysis of international cases is very complicated. Attempts have been made in this direction, for example, in the context of the project Underground for Value (COST ACTION 18110, 2019-2023), leaded by the National Research Council of Italy (CNR) and involving the authors. This project involved more than 200 members from 32 countries. It has experienced the interdisciplinary approach for promoting the UBH methodology as a valuable resource to celebrate and preserve and, when sustainable, to reuse and enhance, realizing its full potential to support local community development (Pace & Salvarani, 2021).

Cave dwellings in the Mediterranean basin are better-known, thanks to historical and comparative studies (Laureano, 1993; Urdiales & Maccarone, 2011; Horden & Kinoshita, 2014). Furthermore, the project Vernacular Knowledge for Sustainable Architecture (VerSus) gave a big input toward their knowledge. It was a European initiative developed in the framework of Culture 2007–2013 program, which partners with CRAterre-Ecole Nationale Supérieure d'Architecture de Grenoble (France), Escola Superior Gallaecia (Portugal), DIDA (Department of Architecture, University of Florence-Italy), DDICAAR (Department of Civil Engineering, Environment, and Architecture, University of Cagliari-Italy), and Escuela Técnica Superior de Arquitectura of Polytechnic University of Valencia, Spain (Vegas *et al.*, 2014).

Hence, a partial comparison is presented below between a Chinese case and some worldwide famous underground settlements, mostly in the Mediterranean area, some of which have already been studied according to the UBH methodology (Varriale, 2014; Varriale, 2021).

The comparison is summarized in Table 4. All examples are located on plateaus at a latitude between 32° (the Libyan case) and 40° (the Italian case). Differences were found in current uses: only Gharyan (Tripoli), Matmata (Tunisia), Kandovan (Iran), and Lijiashan (China) are still inhabited by the locals, while in the other cases, underground settlements are mostly interpreted as examples of traditional lifestyle, protected in natural areas, or inscribed in protection lists or reused.

**Table 4. UBH RE-USE classification in cases from different countries**

| Site | Country | Data and information | | | | |
|---|---|---|---|---|---|---|
| | | Name of the plateau | Meters o.s.l. | Latitude | Inhabited | Interpretation |
| Gharyan | Libya | Jabal Nafüsah | 700 o.s.l. | 32°10' N | x | x |
| Matmata | Tunisia | Matmata Plateau | 600 o.s.l. | 33°32 N | x | x |
| Sassi Matera | Italy | Murge Plateau | 401 o.s.l. | 40°40' N | | x |
| Kandovan | Iran | Iran/Persian Plateau | 2300 o.s.l. | 37°47 N | x | |
| Derinkuyu | Turkey | Anatolian Plateau | 1300 o.s.l. | 38°37 N | | x |
| Ürgup | Turkey | Anatolian Plateau | 1050 o.s.l. | 38°38 N | | x |
| Göreme | Turkey | Anatolian Plateau | 1104 o.s.l. | 38°38 N | | x |
| Avanos | Turkey | Anatolian Plateau | 920 o.s.l. | 34°42 N | | x |
| Lijiashan | China | Loess Plateau | 2628 o.s.l. | 36°52 N | x | |

This table illustrates the UBH RE-USE classification tested in cases from different countries. Abbreviation: o.s.l., over the sea level. Source: Table by Roberta Varriale

As anticipated, Lijiashan village is still inhabited, with a traditional farming-based economy. It is a protected site, listed as a historical and cultural town and village, and a well-known tourist destination. Nonetheless, tourist-oriented reuse is limited to the guest house, which was created inside a courtyard cave dwelling.

The comparative study showed how the Chinese village is one of the few still inhabited cave villages worldwide, together with some villages in Libya, Tunisia, and Iran. However, its peculiarity is that even though it is a protected and reused site, its interpretation as a typical expression of local cultural heritage is inferior. This aspect, which is fundamental in communicating both tangible and intangible values of the caved settlement of Lijiashan, can influence its future preservation as a cultural site. The establishment of a museum dedicated to traditional troglodyte cultures, like those dedicated to Italian Sassi in Matera, Tunisian Matmata, and Turkish Göreme, could support both the conservation and the divulgation of those value and support the sustainable development of those elements, also in the touristic sector.

## 6. Conclusions

At a global level, rural and remote areas' sustainable development and reuse of underground spaces are two heartfelt issues. In China, these two topics are synthesized in the yaodong villages of the Loess Plateau. From the analyzed cases, numerous suggestions for the interpretation, reuse, and enhancement – also in the touristic sense – can be derived, which can be included in a more general census of options. The authors are committed to this direction, seeking the creation of standard guidelines for the sustainable enhancement of UBH, to explore all the potential of these forms of heritage, whose variety and complexity have yet to be fully understood. In this regard, the research on Chinese cases form part of a broader comparative research by the authors and their multidisciplinary team, extended to Eastern and Western countries.

As declared, many criticalities hinder research development because there is no recognition of a single glossary and a shared classification globally. The improvement and experimentation of the UBH method are pushing in this direction. Good results are being achieved, thanks to the European project Underground for Value (COST ACTION 18110), led by CNR and involving the authors, which brings together 32 countries for the experimentation of the method. In the same direction, bilateral projects between Italy and individual European and non-European countries such as Georgia, Iran, Armenia, Tunisia, Turkey, Jordan, and Israel are under evaluation by the authors and are trying to stimulate a census of underground settlement in each country.

Among the challenging goals to be achieved in the future is the improvement of the interpretation, communication, education, enhancement, and management practices related to this kind of asset to elaborate conscious strategies for its protection and development. As the international experience shows, the only possibility to avoid Disneyfication and contrasting with the gentrification processes, already experienced in worldwide famous caved settlements having been transformed into popular tourist destinations, is to integrate them in scientific and educational tourism and therefore expand the interest in society. In this sense, social participation in the development process could be a way to share responsibility between local institutions and communities. It would require building a shared strategy and undertaking the responsibility for developing a plan, allocating resources, and implementing and evaluating development activities that would better cater to local needs (Huang, 2021). Engaging local citizens mean strengthening and preserving local identity, ensuring that increased tourism does not become an agent of destruction.

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## Conflict of interest

The authors declare they have no competing interests with any institutes, organizations, or agencies that might influence the integrity of results or objective interpretation of their submitted works.

## Author contributions

*Conceptualization:* Laura Genovese
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*Methodology:* Laura Genovese, Roberta Varriale
*Formal analysis:* Laura Genovese
*Writing – original draft:* Laura Genovese
*Writing – review & editing:* Laura Genovese

## Ethics approval and consent to participate

Not applicable.

## Consent for publication

Not applicable.

## Availability of data

Raw data can be shared with readers upon reasonable request to corresponding author.

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ACCSCIENCE PUBLISHING

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ORIGINAL ARTICLE

# Esthetic characteristics of Mount Jingfu's "Grotto-Heavens and Blissful Lands" landscape based on the cultural and regional disposition theory

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## Abstract

To inherit the essential characteristics of regionality, diversity, and artistry of the landscape "Grotto-Heavens and Blissful Lands," this study takes Mount Jingfu, a model of that in the Lingnan Region, as the research object. It is based on the Cultural and Regional Disposition Theory under landscape architecture esthetics and summarizes the esthetic features of Mount Jingfu from three dimensions: (i) regional and technical characteristics of adaptation to local conditions, elaborately utilizing and arranging the space, and drawing on local materials; (ii) social milieu of seeking inner pleasure and integrating different cultures, worshipping numeral immortals and benefiting the folks, and embracing simplicity and bold innovation; (iii) artistic and human qualities of clarity and quiescence, exquisiteness and elegance, and morality and righteousness. The study is conducive to promoting the regional conservation and living inheritance of Lianzhou's culture of blissful lands and presenting the esthetic characteristics of renowned mountain landscape resources.

***Keywords:*** Landscape architecture esthetics; Grotto-Heavens and Blissful Lands; Mount Jingfu; Cultural and Regional disposition theory

## 1. Introduction

The cultural landscape of Mount Jingfu's "Grotto-Heavens and Blissful Lands" (*Dongtian fudi*, 洞天福地), built on Daoism, first appeared in the *Palaces and Bureaus of the Grotto-Heavens and the Blissful Lands* (*Tiandi gongfu tu*, 天地宫府图) painted by Sima Chengzhen (司马承祯 647 ‑ 735), an eminent Daoist during the Tang dynasty (618 ‑ 907). In the painting, Mount Jingfu's "Grotto-Heavens and Blissful Lands" are ranked 49$^{th}$ among the 72 Blissful Lands. Developed over a millennium, it holds great value and significance for research in cultural landscape heritage, esthetics, and culture not only in China but also globally (Roe, 2007; Lee, 2009; Suzuki, 2019; Wan, 2012). As shown in Figure 1, Mount Jingfu lies in Bao'an Town, Lianzhou City, Guangdong Province, adjacent to the Bao'an River. During the Wei (220 ‑ 265), Jin (265 ‑ 420), and Southern and Northern dynasties (420 ‑ 581), the Daoist Liao Chong sought a natural cave in a mountain to create elixirs, and later, Chong ascended in flight (a way to become

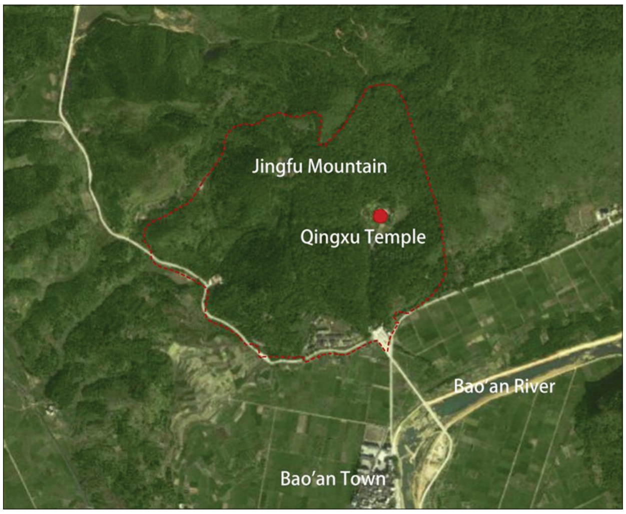


**Figure 1.** Research area (red line). Source: Map adapted from Google Map

a divine immortal in Chinese Daoism). The locals built a Taoist temple named Qingxu Temple, "*Qingxu guan* (清虚观)" to worship him. Simple and crude as the temple was, it laid the foundation for the formation of Mount Jingfu's "Grotto-Heavens and Blissful Lands" landscape. The Tang dynasty witnessed the peak of the expansion of Mount Jingfu's landscape. The local people and officials greatly admired Daoism, and therefore, Qingxu Temple was restored and expanded, significantly contributing to the spread of Daoist culture in southwest China. However, Mount Jingfu suffered repeated damages due to the outbreak of wars in modern China. Although, in the 1970s, the Chinese government tried to restore its "Grotto-Heavens and Blissful Lands" landscape by protecting the natural ecology and repairing palace buildings, the renovated landscape looked different from the original one. The root of the problem lies in the fact that although the landscape is shaped by the natural geography of the mountain, it possesses unique esthetic traits influenced by Daoist and regional esthetic cultures. Furthermore, the restoration efforts using modern technologies under contemporary esthetic cultures risk compromising the effective inheritance of traditional esthetic features. Therefore, this paper explores the impact of different esthetic cultures on Mount Jingfu's "Grotto-Heavens and Blissful Lands" landscape, which is a vital guarantee to maintain the inherent esthetic essence of the landscape as a living cultural heritage.

To date, the research on the esthetic characteristics of Mount Jingfu's landscape has mainly been focused on religious thoughts (Park, 2016; Maxime, 1967), artistic features (Gesterkamp, 2019), cultural dissemination (Tsuchiya, 2019; Suzuki, 2019), spatial layouts (Li, 2014; Wan, 2012), landscape elements (Zheng *et al.*, 2020; Wang, 2013), and environmental features (Li, 2014; Yuan *et al.*, 2022). There have been some research achievements from the viewpoint of one specific factor. However, it is essential to further explore and study the combination of different landscape elements influenced by various types of esthetic cultures from a holistic perspective. This approach will help reveal the logical relationship between the esthetic characteristics of Mount Jingfu's "Grotto-Heavens and Blissful Lands" landscape. For this purpose, the article delves into three research questions regarding the esthetic features of Mount Jingfu's landscape:

i. How to develop a research framework based on the Cultural and Regional Disposition Theory?
ii. What types of esthetic cultures have had the greatest influence on shaping the landscape's esthetic characteristics?
iii. What is the primary mechanism behind the creation of different esthetic features of the landscape?

## 2. Data and methods

This article adopts the Cultural and Regional Disposition Theory to build the foundational framework for the study. It employs various research methods, including literature review, on-site investigation, expert interviews, and graphic analysis, to examine esthetic cultures embodied in the landscape. The Cultural and Regional Disposition Theory holds significant value in the realm of landscape esthetics. It has found extensive application in the exploration of settlement landscape esthetic culture and has been embraced by scholars in the fields of landscape esthetics and landscape studies (Wang, 2017; Peng & Tang, 2017; Chen, 2018. Lu *et al.*, 2020).

This theory has been summarized and refined by one of the authors of the present study, Tang Xiaoxiang, who is also a professor from the Department of Architecture at South China University of Technology. Through his long-term and extensive research on the cultural and esthetic aspects of Lingnan regional settlement landscapes (Tang, 2010), he concluded that "the essence of Lingnan settlement landscape can be attributed to the "cultural and regional disposition" that defines Lingnan esthetic culture." He further elaborated, "The spiritual aspect of Lingnan esthetic culture is nurtured by the natural, social, and humanistic environment of the Lingnan region. This environment also impacts the formation and development of the Lingnan settlement landscape, shaping its cultural and regional disposition, and ultimately determining the unique technical features and humanistic qualities of the area." Professor Tang believes that "the ultimate measure of landscape beauty is the harmonious blend of regional and cultural characteristics from different eras." The significance of the "Cultural and Regional Disposition

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Theory" lies in its comprehensive exploration of the above-mentioned three key aspects. He summarizes these aspects as the regional and technical characteristics, the social milieu, and the artistic and human qualities.

Figure 2 presents the research framework employed in this paper, illustrating the analysis of the esthetic characteristics of Mount Jingfu's landscape based on the Cultural and Regional Disposition Theory under landscape esthetics. This framework aids in identifying the logical structure of the landscape. According to the psychological process of appreciating a landscape, the esthetic perception of Mount Jingfu can be attributed to two factors. First, it arises from the material form of the landscape. Second, it is influenced by the social spirit and motive that the landscape embodies. These factors contribute to a more subjective, internal, and rational perception, resulting in a primary esthetic experience (Scruton, 2009). By exploring the cultural connotation and esthetic ideals of the villages, a more profound esthetic experience can be attained. Therefore, this article primarily focuses on studying the esthetic qualities of Mount Jingfu's landscape and delving into its cultural and regional disposition. The key to studying the esthetic characteristics of the mountain lies in the analysis of its regional and technical characteristics, the social milieu, and the artistic and human qualities.

### 2.1. Material form

As a significant subject of esthetic research, Mount Jingfu's "Grotto-Heavens and Blissful Lands" landscape is a spatial form that comprises visible, tangible, and perceptible elements based on existing material entities. Moreover, it can be interpreted from the perspectives of regional and technical characteristics. People's perceptions of the "form" of Mount Jingfu are what creates its beauty. According to Zhu Guang-qian (one of the founders of the study of esthetics in 20th-century China), the "form" refers to an image or graphic of independence and self-sufficiency. He asserted that people's perceptions and experiences of beauty stem from their intuitions toward the "form," and as a result, people primarily sense the beauty of the landscape through their vision of its specific "material form" (Yu, 1998). When it comes to the esthetic structure of Mount Jingfu's landscape, the exploration of internal form is closely intertwined with the external form, which encompasses not only the overall outline and shape of the Qingxu Temple complex but also external beauty presented by various elements such as mountains, waters, fields, forests, and residences within the Mount Jingfu area (Zhou, 2006). As humans, we can perceive the beauty of nature and artificial landscapes of unique features through the five senses and appreciate breathtaking scenery, melodic natural sounds, and the changing of seasons. Based on their visual scope, these elements can be categorized as the environmental design, spatial layout, and material utilization in Mount Jingfu's landscape.

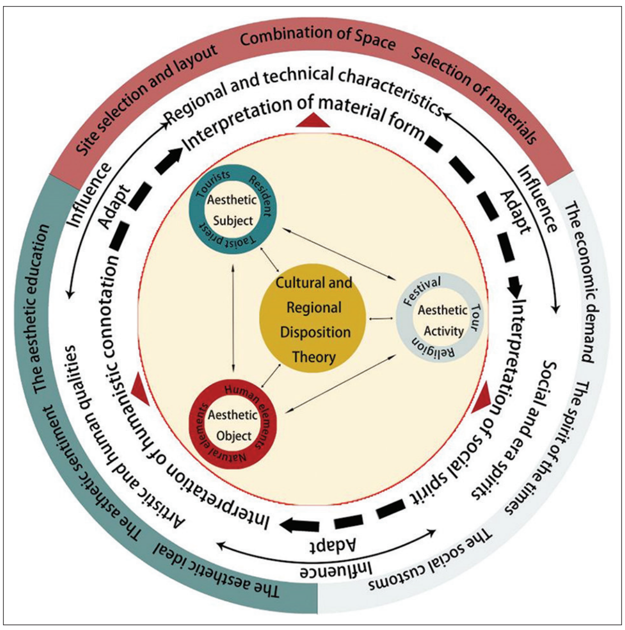

**Figure 2.** Research framework. Source: Drawing by the authors

### 2.2. Social ambiance

Exploring the social esthetic drives and implications behind the material form is the second dimension of Mount Jingfu's "Grotto-Heavens and Blissful Lands" landscape's esthetic culture, which also corresponds to the social milieu under the Regional and Cultural Disposition Theory (Tang, 2017). In esthetic activities related to the landscape, people's esthetic preferences are influenced by multiple factors, including diverse mountain formations, water flows, spatial layouts, and distinctive architectural designs. To further enhance the appreciation for the beauty of Mount Jingfu and fully engage in the esthetic experience, we must explore the understanding and interpretation of the "social esthetic implications and drives" of the landscape. Mount Jingfu's landscape is primarily rooted in Daoist esthetics, but it also incorporates other coexisting esthetic cultures. As a result, its esthetic structure is not solely dominated by Daoist esthetic ideology but also encompasses a diverse range of folk and highbrow esthetic content. The esthetic features of this landscape are shaped by religious Daoist practices, including adherence to the Rules of Purity and Observances (*Qinggui jielv*, 清规戒律), *zhai* and *jiao* rituals (*Zhaijiao keyi*, 斋醮科仪), and self-cultivation. It also manifests in social gatherings and festivals attended by literati and travelers at Mount Jingfu's landscape.

### 2.3. Humanistic connotations

Esthetic activity is an emotional and subjective experience deeply ingrained in human life. It serves as a reflection of an individual's spiritual essence. The same is true of the esthetic experience of Mount Jingfu. The esthetic subject observes the landscape's surrounding environment, the spatial structure, and the architectural style of Qingxu Temple. Then, it interprets the spirit of the social milieu, which, in turn, evokes the subject's emotional experience and pleasure, allowing one to engage with the world of the spirit and meaning. One of the authors of the present study, Tang Xiaoxiang, believes that "people's esthetic experience of architecture is always based on such sequences of time and space, as well as emotional process. The emotional process starts with the visual impact and continues with the emotional pleasure generated from admiring the architectural form. Furthermore, the central focus of the sequences and process is the recognition and attention to the oriented value and cultural spirit conveyed by the appearance, layout, spatial combination, and environmental landscape of the architecture." The appreciation and comprehension of the spiritual value of Mount Jingfu's landscape also follow this temporal and spatial sequence, accompanied by an emotional journey (Wu & Jin, 2021), which is also the process of generating its images beauty. It reveals that the study on cultural connotation should emphasize esthetic ideals, emotions, and psychology.

## 3. Results

### 3.1. Regional and technical characteristics

The landscape's regional and technical characteristics stem from its consistent and stable natural geography and topography, which have significantly influenced the creation and growth of Daoist esthetic culture.

#### *3.1.1. Site selection and layout based on local conditions*

The location and layout have been carefully chosen to blend the mountainous features with Daoist geomantic omen esthetic culture. The landscape is nestled against the mountain and overlooks the river, creating a harmonious balance of *yin* and *yang*, a feature of a well-selected location. Regarding the layout, the landscape is encircled by "Azure Dragon on the left, White Tiger on the right, Vermilion Bird in the front, and Black Tortoise at the back" (Chen, 2011). It was pointed out that "yearning for returning to the harmonious unity of heaven and earth, The Daoist searched for caves or used geomantic omen to discover "caverns," and setup palaces and temples to cultivate immortals with a wish to return to the original state, thus achieving immortality" (Jiang, 2003). The Daoist survey the terrain and use geomantic omen or hemerology (*Kanyu*, 堪舆术) to determine the optimal site for constructing Daoist buildings (Wang, 2013). Figure 3 illustrates the site selection and layout of the Qingxu Temple. It features the historic map of Mount Jingfu from the Qing dynasty and the traditional Chinese "geomantic omen (*Fengshui*, 风水)" map, depicting the reasons behind the site selection based on the geomantic omen principles. Qingxu Temple nestles in a basin in the northeast of Mount Jingfu with mountains on the east, south, and west, respectively, representing Azure Dragon, Vermilion Bird, and White Tiger, and also with water on the south representing Black Tortoise which is beneficial in gathering wind and *qi* (气) and nurturing spirits. In addition, its spatial layout also ingeniously incorporates the mountainous terrain and effectively embodies the esthetic culture of Daoist geomantic omen through the "journey to heaven." Mount Jingfu symbolizes heaven, its foot represents earth, and the first archway is "*Changhe* (阊阖)," the boundary between heaven and earth. Mount Jingfu has been further divided into three tiers by the setting of rest platforms, namely, the lower tier "*Fantong* (樊桐)," the middle tier "*Xuanpu* (玄圃)," and the upper tier "*Tianting* (天庭)" (Li, 2014). Therefore, in Daoist esthetic culture, the process of ascending to heaven involves entering through the southern gate of the mountain, ascending and passing the three tiers through Zhushen Path, and finally arriving at Qingxu Temple.

#### *3.1.2. Skillful combination of space borrowed from reasons*

Mount Jingfu's landscape expresses the magnificent and mysterious esthetic ideals of Daoism by skillfully intertwining architecture, courtyards, and gardens in an interdependent manner (Li, 2014). The main axis connects different elements such as palaces, courtyards, pavilions, and the surrounding landscape at Qingxu Temple, creating a sequence of spaces with varied sizes. Within the temple, the sizes of these spaces are continuously changing, and the elements are skillfully placed to alternate between being visible and concealed, which is well-placed.

Figure 4 shows the main topographical sequence of Mount Jingfu's landscape on an adapted Google Map. As one approaches the landscape's main axis, the spatial sequence begins with an archway and leads to a transition in the form of pavement. The space gradually narrows down before finally arriving at the mountain gate. The entrance plaza and Fangsheng Pond (a pond to liberate captive animals) create an open space that cleanses the mind and soul of the people from the mundane world, acting as a transitional zone for immersing oneself in the

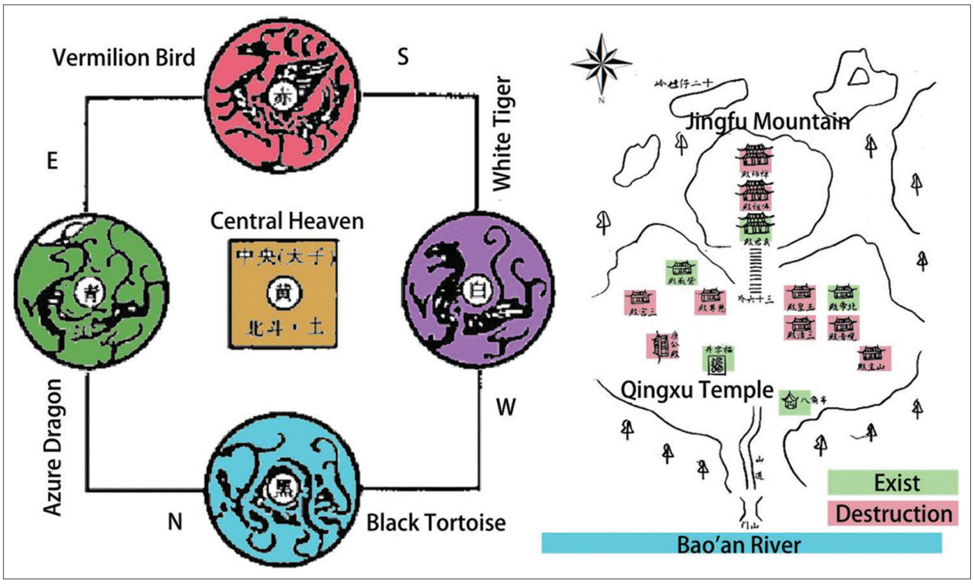


**Figure 3.** Site selection and layout influenced by the geomantic omen. Right: the traditional Chinese "geomantic omen (*Fengshui*, 风水)" map; left: the Qing-dynasty historic map of Mount Jingfu. Source: Drawings adapted from *Chronicles of Lianzhou*

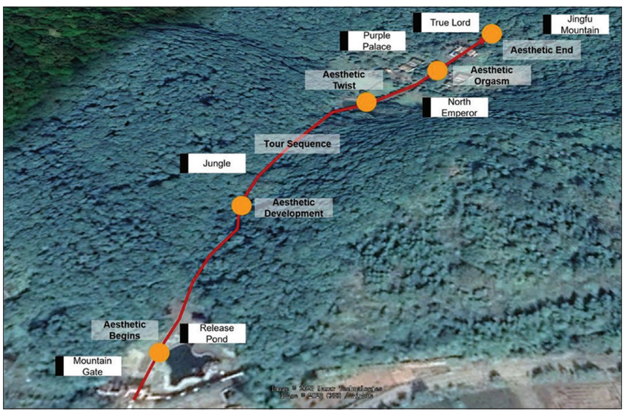


**Figure 4.** Landscape sequence. Source: Map adapted from Google Map

esthetic culture of Daoism. After experiencing a narrow and dim space between the entrance and Qingxu Temple, there comes a turning point where people can glance at and behold the Qingxu Temple nestled on the mountainside, bathing in sunshine. This majestic sight inspires a profound sense of reverence (Temper & Martinez-Alier, 2013). Climbing up the mountain path, people reach the pinnacle of the spatial sequence, where Qingxu Temple stands on a high platform, majestic and solemn in the bright sunlight, and the Purple Palace (*Ziwei dian*,紫微殿) and North Emperor Palace (*Beidi dian*,北帝殿) on both sides of the mountain path, further enhance the grandeur and majesty of Qingxu Temple.

As people pass through the mountain gate of Qingxu Temple, the space narrows again within their sight, and the imposing statue of "*Wang Lingguan* (王灵官)" comes into view, inspiring the worship of immortals in Daoist esthetic culture. After making the way through the largest and most impressive Real Lord Hall, "*Zhenjun dian* (真君殿)," a narrow corridor comes on the eastern side, and their minds gradually calm down with the space opening again. The architectural arrangement leads to the final segment of the main path. Thus, the spatial sequence development of the main axis of Qingxu Temple includes three cycles of change, transitioning from open spaces to narrow ones, during which people experience gardens, courtyards, and architecture. As a result, the people, namely, the esthetic subjects, sublimate their religious faith in a string of emotional changes when admiring the well-placed combination of open and narrow spaces.

#### *3.1.3. Selection of materials using locally sourced resource*

The distinctive local materials found at Mount Jingfu are utilized to create a distinct regional style and features, thus conveying the esthetic concept of Daoism's natural and harmonious esthetic culture. As the landscape is in a forested and mountainous region, materials are typically selected from the surrounding natural environment, which is readily accessible and renewable. This concept is reflected in the selection of construction and gardening materials, as well as the arrangement of plants.

As to the selection of wooden materials, the climatic and geological conditions of the forested areas in Mount Jingfu are ideal for the growth of Chinese fir, which has a quick shaping process and a short harvesting cycle. Therefore, Chinese fir becomes the primary material for building the palaces and temples of the landscape and is specifically used as columns in Qingxu Temple. While slowly-growing trees such as ginkgo, oak, and Chinese yew offer superior quality as building materials compared to Chinese fir, they are often protected in Daoist culture due to their association with concepts such as longevity (Tao, 2015). For example, pine and cypress represent youth and longevity, and hence, the landscape prioritizes the selection and appropriate planting of slow-growing trees as the landscape foundation, inspired by the Daoist culture's appreciation for natural and harmonious esthetics.

Regarding the selection of stone, the Mount Jingfu area offers a variety of stone resources such as weathered stone, cut stone, and rounded stone, which are commonly used for building house foundations, retaining walls, and column bases, or for paving garden paths (Xu & Wang, 2019). Natural stones without excessive carving or decoration often serve as visual focal points in landscape design. These stones are either collected from Mount Jingfu or left in their original location instead of being intentionally transported from other places, which is the exact manifestation of a Daoist esthetic concept-conformity to nature.

### 3.2. Social milieu

The second dimension of the esthetic characteristics of Mount Jingfu's landscape is determined by economic development, the spirit of the time, and social customs, which reflects that both the Daoist esthetic culture and folk culture have an integrated influence on the land transformation.

#### *3.2.1. Demands for seeking pleasure, enjoying leisure, and embracing diversity*

The esthetic concept of seeking pleasure and leisure in Lingnan culture is particularly strong in the journey to Mount Jingfu's landscape. Meanwhile, the urban middle class tends to prioritize the pursuit of material enjoyment and recreational sentiment (Eliade, 2008). The combination of the sacred Daoist culture and the lifestyle of Lianzhou, with some adjustment, demonstrates the characteristics of inclusiveness. Figure 5 shows the cordial relationship between people in Qingxu Temple and the gardens. The landscaping of Qingxu Temple is influenced by commercial awareness and the mindsets of merchants. Therefore, it emphasizes practicality, making the garden landscape straightforward and easily comprehensible and promoting a close conversation between people and the garden (Duan, 1994). The Qingxu Temple gardens feature open transitional spaces, which reduce the perceived distance and thus make them more approachable. Such a layout aligns with the merchants' psychology to foster social bonds and engage in conversations, and it manifests a way of enjoying life through the garden. The psychology and thought can be found in examples such as the Linglong Water Pavilion of Panyu Yuyinshan House and the Baiyue Pavilion of Dongguan Ke Garden.

From the viewpoint of landscape elements, Mount Jingfu's landscape sets up Fangsheng Pond (a natural water-flowing pond) at the entrance, seamlessly integrating with the surrounding mountains and forests and coordinating the differences between artificial and natural scenery. The pond itself also reflects people's pursuit of life and enjoyment. A pond is not only visually appealing but also serves practical purposes, such as matching a landscape to the hot climate of Lingnan by adjusting the microclimate and creating a pleasant and comfortable environment (Ren, 2019). At the garden, in terms of plant configuration, one can observe a diverse range of fruit trees, including loquat, papaya, and longan. The Daoist also utilize the available area in the garden for cultivating small plots of farmland and growing fruits, vegetables, and melons for decorative elements and as a food source. Folk esthetics manifests itself significantly when economic needs are considered as a way of plant decoration.

#### *3.2.2. Spirit of the time that values natural simplicity and innovative exploration*

Through its pioneering, innovative, and decorative themes, and its natural, simple color schemes, the Mount Jingfu's "Grotto-Heavens and Blissful Lands" landscape has formed a Daoist temple garden with a unique Lingnan

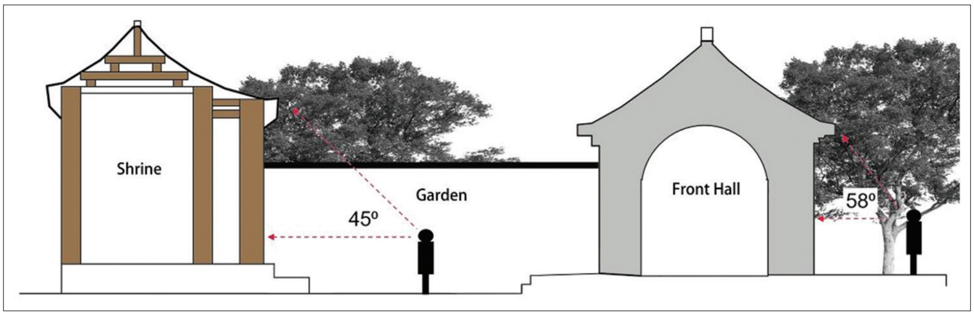


**Figure 5.** Architectural scale creates a sense of intimacy and closeness among people. Source: Drawing by the authors

style. The landscape highlights the esthetic and folk cultures of Daoism in response to the demands of the time. Figure 6 displays the architecture's interior decorations, brick carvings, roof decorations, and garden adornments. The landscape's decoration themes emphasize meaningful content and expressive forms. Similarly, Daoist cultural themes often depict the figures through stories from Daoist ideologies. For example, there are depictions of the Eight Immortals crossing the sea, searching for the Blue Gauze Cap, facing tigers alone, and slaying the Dragon Prince. Furthermore, Daoist cultural themes portray the Daoist immortals worshiped in Qingxu Temple (Yuan *et al.*, 2022). The story of "Liao Chong ascending in flight" describes the protagonist's deification at the Real Lord Hall. Through his story of attaining immortality and teaching the profane people, the Daoist aspiration to help himself and others attain immortality is conveyed.

Besides Daoist cultural themes, many Lingnan local decorative motifs have been incorporated into the design, including flowers, fruits, plants, folk production, living scenes, the 24 Filial Exemplars, the 12 Zodiac Animals, and auspicious birds and beasts. These mythical creatures have been inspired by ancient Chinese legends, such as the Two Dragons Fighting for the Pearl, and the Turtle and Fish on the roof of the main sacrificial building. The decorations reflect the best wishes, beliefs, and esthetic preferences of the people in Lingnan. The creative integration of folk esthetics with the sacred world in the temple design embodies the pioneering and innovative spirit of Qingxu Temple.

The architectural decorations here boast a rich and diverse array of decorative themes. Moreover, they are influenced by the Daoist esthetic concept of "embracing simplicity and plainness." The use of natural or light colors rather than bright colors on the exterior walls imbues the temple with a simple and plain style (Kuang, 2021). Furthermore, the wooden structure is mostly black. However, influenced by the distinctive architectural style of Lingnan, the sacrificial buildings of Qingxu Temple have employed bright hues for decorating and embellishing key parts, such as the roof. Consequently, the architectural color palette of Qingxu Temple is characterized by light colors as the keynote, with vibrant decorations on specific parts. The combination of local natural and simple architectural decorative art with the simple yet elegant Daoist temple gardens embodies the Daoist esthetic concept of "great skill in the use of plainness" (*Daqiao ruozhuo*, 大巧若拙). The concept suggests that truly exquisite and beautiful things do not necessitate excessive embellishment.

#### *3.2.3. Social customs of polytheism and the pursuit of practicality and usefulness*

The Daoist culture and folk beliefs of Mount Jingfu's landscape are intricately interwoven, exhibiting the


**Figure 6.** Decoration integrated with different esthetic cultures found in Qingxu Temple. Source: Photos by the authors

characteristics of worshiping multiple immortals. As long as it is beneficial, people will worship gods devoutly, which reflects a strong utilitarian esthetic value. It is the innate characteristics of folk esthetics that have triggered the utilitarianism of polytheistic worship and Daoist immortals. Qingxu Temple venerates a variety of deities with distinct abilities, catering to the spiritual needs of different individuals. This is a key factor in understanding why the temple holds great appeal among the local folks. For example, Real Lord Temple in Mount Jingfu is one of the temples that worship the Real Lord, a Daoist immortal. According to Daoist beliefs, Real Lord has possessed incredible divine powers and magical abilities after becoming an immortal. These powers can bless believers with peace and success. Therefore, for believers, the blessings of the Temple include good health, family harmony, a successful career, prosperity, and so on. Meanwhile, devotees can pray for Daoist items such as talismans (*Fu*, 符), which ward off malevolent influences and augment their spiritual energy. *Ziwei dadi* (紫微大帝) is worshiped in the Purple Palace. In traditional Chinese culture, he is regarded as the god of constellations who oversees the fortunes and misfortunes of the world, blessing people with peace, happiness, and health. In addition, drowning accidents involving children occur in rural areas every year, and as the North Emperor (*Beidi*, 北帝) oversees water, people will visit the North Emperor Temple during traditional festivals to pray for protecting children from harm (Tang *et al.*, 2021). Other Daoist immortals such as "*Yuanchen* (元辰)," "*Tudi gong* (土地公)," and "*Doumu Yuanjun* (斗姆元君)" are also revered at Qingxu Temple. The worship of these deities reflects the pragmatic and utilitarian mindsets of the people who seek help from specific immortals based on the nature and type of problems they encounter. This practice is influenced by the esthetic consciousness of practicality and utility of people in the Lingnan region.

### 3.3. Artistic and humanistic qualities

The artistic and humanistic qualities are manifested as symbolic representations of both Daoist and folk esthetic cultures that have been materialized. They are endowed with the concept and significance that Daoist culture pursues originality, and Lingnan people pursue self-realization. These cultural expressions represent the regional characteristics, the relationship between people and the land with its humanistic qualities.

#### *3.3.1. Esthetic ideal of reversion to peace and truth*

A positive attitude toward life constitutes an essential part of the Lingnan people's esthetic system and lays a significant foundation of the Daoist one, which highlights the pursuit of balance between nature and the inner world and respect for nature and others. It also emphasizes the harmonious relations between humans and nature, as well as humans and society. Due to this esthetic concept, people face their lives more positively and improve their personal qualities and self-cultivation. Specifically, Daoism stresses self-cultivation and advocates the idea of "governing by doing nothing" (*Wuwei erzhi*, 无为而治), that is, maintaining a balance and health in mind and body through inner calmness and tranquility (Liu & Liang, 2020). Daoism also advocates the idea of "boundless love" (*Daai wubian*, 大爱无边), which values caring for others and society and establishing good interpersonal relations through selfless dedication and helping others. These concepts and values of Daoism contribute to maintaining a calm and stable mentality, improving self-awareness and self-management, and establishing healthy interpersonal relations and social harmony. Therefore, Daoist esthetics enable people to face life more actively and pursue a higher realm in life. Simultaneously, Mount Jingfu's landscape forges a spiritual cohesion through the medium of couplets, plaques, inscriptions, and stone carvings that convey meanings with words. It gathers relevant elements into an organic and continuous artistic conception to express the esthetic ideal of tranquility and simplicity (Du & Wang, 2018). On the two pillars of Binyu Pavilion (*Bingyu ting*, 宾于亭) in Qingxu Temple is a couplet titled "Previously, no one knew about Meng Binyu's reputation, but now his poetry is very popular in Jiangnan." (昔日声名喧洛下，近来诗价满江南). This line comes from the poem "To Meng Binyu" (*Ji Meng Bingyu*, 寄孟宾于) by Li Fang, who excelled in the imperial examinations in the same year as Meng Binyu (904 – 991). It was erected to commemorate Lianzhou's local poet Meng Binyu for praising his low-key or modesty. The couplet inside the Real Lord Temple reads, "The landscape saves the crowd with pursuing tranquility, and the palaces demonstrate the Daoist spirit of nihility" (清静无为洞天福地行济世，虚无自然宫观坛堂展道风), while the outside couplet reads "With sincerity, one can visit the magical places of Penglai; Without fortune, it is difficult to reach the blessed land and famous mountains" (蓬莱胜迹真心诚意自可游，福地名山无缘随便难到此). These sayings inspire people to forge ahead and follow the good toward the noble esthetic ideals of purity and truth.

#### *3.3.2. Simple and natural esthetic sentiment*

The cultural and artistic decorations of Mount Jingfu enhance its simple and natural esthetic sentiment. These decorations depict the humanistic scenery within it, allowing people to cultivate their sentiments while experiencing them. Mount Jingfu's landscape stimulates the emotional response of the esthetic subject through inscriptions, paintings, mythological legends, poetry, and couplets and guides people to process their emotions on their own. Driven by emotions and through imagination and association, they further enrich their esthetic experience (Peng & Tang, 2017). Through psychological mechanisms such as emotions, imagination, and comprehension, the subject projects themselves into the object to achieve integration of the subject with the object and obtain esthetic pleasure, evoking the spatial-temporal perception of the esthetic subject, leading to a harmonious esthetic concept with nature.

The inscriptions and paintings at Mount Jingfu are vivid imageries, but the esthetic meanings of them are subtle. Therefore, when appreciating them, people often need esthetic associations, relying on other things to produce a corresponding image to the esthetic object (Zhou, 1996). More importantly, the appreciation of inscriptions and murals develops people's perception, imagination, and rhetorical skills and helps them attain self-cultivation and tranquility. Furthermore, the landscape, as a sacred religious place, contains a wealth of mythological legends that reflect people's life experiences and aspirations in a joyful and magical way. To some extent, these legends are derived from historical facts and are the product of cultural accumulation. These legends are presented through simple natural carriers such as stones, flowing water, and old trees, continuously imbuing Mount Jingfu with a divine and mysterious color, expanding people's esthetic imagination, and nurturing a natural and simple esthetic sentiment, especially for Daoist disciples and visitors.

#### *3.3.3. Esthetic education of promoting the way of righteousness and nurturing integrity*

Mount Jingfu's "Grotto-Heavens and Blissful Lands" landscape promotes excellent Daoist traditional esthetic ideas and moralities by engaging people in worshiping the immortals and nourishing inner tranquility. People participate in charitable activities, promoting a favorable social climate, and educating the public. The moral and esthetic education here serves as an indispensable means of cultivating the cognition, sentiments, and moralities of the people, mainly in three aspects.

First, it is the spiritual education of Daoist basic tenets. Through various ways, such as promoting Daoist classical discourses and delivering discourse lectures, people are directly educated on thoughts and commandments. Different Daoist buildings on the landscape hold different religious activities. For example, the Daoist practice activities in the Real Lord Temple are divided into morning and evening classes (Wang, 2021). The Daoist conduct of religious rituals and practices can benefit health and longevity in their daily studies. These activities reveal the desire of Lingnan people for a better life.

Second, the behavioral enlightenment of Daoism in religious activities is provided. People gain indirect enlightenment from religious activities in the landscape, such as worshiping gods and self-cultivation. People carry the "Great God" (*Dashen*, 大神, the most popular figure in the local area) along the street, which means that everyone will ward off evil spirits and welcome good luck.

Third, it is the social education achieved by Daoism through charitable practices to educate the public. The renovation funds for Mount Jingfu's landscape come not only from the daily entrance fees of tourists but also, even much more, from donations of surrounding residents. On special occasions, such as the birthday of an immortal, the residents gather spontaneously to make donations in Chongxu Temple. Such charity activities are not only due to the residents' need to pray for blessings but also illustrate the crucial role of the landscape in esthetic education.

## 4. Discussion and conclusions

In the study, we found that the formation of esthetic characteristics of the "Grotto-Heavens and Blissful Lands" landscapes was not only dominated by Daoist esthetics but also under the joint influence of multiple ones, such as folk esthetics and highbrow esthetics. Accordingly, in the study of the esthetic characteristics of such landscapes in different regions, Daoist and regional esthetics must be equally emphasized. More importantly, their esthetic connotations and characteristics must be examined from the perspective of regional identity so that people can better understand their status and values. Besides, the study also found that Daoist, Confucian, and Buddhist esthetics integrate themselves into such landscapes. For example, Fangsheng Pond originates from Buddhist culture but is still adopted in the landscape construction of Mount Jingfu's "Grotto-Heavens and Blissful Lands." This finding confirms that more esthetic and cultural factors have influenced the construction of the "Grotto-Heavens and Blissful Lands" landscapes, and further in-depth research is needed in the future.

The unique combination of religion and amusement in Mount Jingfu's "Grotto-Heavens and Blissful Lands" landscape determines the distinctiveness of its esthetics. This article, based on the Cultural and Regional Disposition Theory and with methods such as text analysis and architectural diagrams, elucidates the landscape's distinctive esthetic characteristics whose formation has been influenced by natural conditions, social milieu, and the local culture. The research results indicate that the regional and technical characteristics mainly reflect the influence of Daoist esthetics on mountainous landscapes, which serve as tangible representations of sacred spaces in Chinese traditional culture in the mountains. The social milieu reflects the common effect of Daoist and Lingnan folk esthetics on the transformation of the land based on its natural characteristics. This aspect reveals the influence of economic development, the spirit of the time, and social customs on the landscape's esthetics. The artistic and humanistic qualities concentrate on Daoist philosophical thoughts and the concepts of folk culture, specifically manifested in the esthetic ideals of tranquillity and truth, the refined and elegant esthetic sentiments, and the esthetic enlightenment of promoting the Way of Truth. By exploring the esthetic characteristics of the "Grotto-Heavens and Blissful Lands" landscape, this article not only enriches the academic research on China's famous mountain landscapes but also discovers the unique cultural and regional disposition from a new perspective.

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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

Not applicable.

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## Availability of data

All data are incorporated into the article.

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ORIGINAL ARTICLE

# Changes in land use or land cover and ecosystem service values in Wuhan city, China, from 1996 to 2018

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## Abstract

Despite rapid development in response research of land use to ecosystem service values (ESV), there is little attention to the influence of ecological construction at a local scale with an empirical study. Based on land use data from two Chinese land surveys, this study attempted to assess ESV from the dual perspectives of urbanization and ecological protection with the primary data-based approach from 1996 to 2018 in Wuhan, central China. We found that the ESV increased from 119.32 billion yuan to 220.29 billion yuan during 1996 – 2018, with an average annual growth rate of 1.27%, 3.86%, 3.49%, 2.97%, and 1.87% during the periods 1996 – 2000, 2000 – 2005, 2005 – 2010, 2010 – 2015, and 2015 – 2018, respectively. The conversion of other land use types to forest and water bodies was the main reason for the increase in ESV. The analysis results could be helpful to provide a new way to create policies pertaining to city development and ecological environment protection in typical rapid urbanization regions.

***Keywords:*** Ecosystem service values; Land use; Urbanization; Ecological protection

## 1. Introduction

Ecosystems furnish a variety of services that are of critical importance to human well-being, health, survival, and development (Costanza *et al.*, 1997; Xie *et al.*, 2008; de Groot *et al.*, 2012). The continuous population growth and urbanization around the world have brought increasing pressure to ecosystems (Xie *et al.*, 2017). Thus, to alleviate the pressure on ecosystems and improve ecosystem services, estimating the ecosystem service values (ESV) has become an urgent necessity (Costanza *et al.*, 2014).

Since the 1990s, exploratory studies of ecosystem services have grown rapidly (Xie *et al.*, 2017). Costanza *et al.* (1997) estimated the value of global ecosystem services, which was seen as a major milepost in this topic (Xie *et al.*, 2017). In 2005, ecosystem services were divided into four categories: production functions, supporting service, regulation service, and cultural service, by the Millennium Ecosystem Assessment (MEA), which was a 4-year, 1300-scientist study for policy formulation (Millennium Ecosystem Assessment, 2005). Studies on ecosystem services of various ecosystems at various scales have been carried out, ranging from global (Costanza *et al.*, 1997; de Groot *et al.*, 2012), regional (Schirpke & Tasser, 2021), urban ecosystem (Li *et al.*, 2017; Ye *et al.*, 2013), to a single ecosystem, such as forest (Zhao *et al.*, 2004), grassland (Zhao *et al.*, 2004), wetland (Jiang *et al.*, 2015), and farmland (Miu *et al.*, 2016), or individual ecological service functions, such as biodiversity. Previous evaluations of the ESV in China were varied, most of which have found a moderate to significant decrease in ESV. For example, Li *et al.* (2010) found a total decline of 8% (US$34.16 million) in Shenzhen between 1996 and 2004 (Li *et al.*, 2010), and Dai *et al.* (2021) found an overall decrease of 30.92% (CNY7.446 billion) in Chengdu from 2003 to 2018 (Dai *et al.*, 2021). Some studies such as Cai *et al.* (2013) found that the ESV decreased significantly by 55.3% from 1989 to 2009 in Fuzhou city (Cai *et al.*, 2013). However, others found almost no change (Han *et al.*, 2016), and some have noticed increases in value due to various reasons (Wang *et al.*, 2014). For example, Li *et al.* (2018) found that the ESV in Chengdu increased by 75.46% (CNY21.6 billion) from 2000 to 2015 (Li *et al.*, 2018). Due to different ecological environments and different stages of development, the ecosystem services in different regions may vary. Therefore, it is necessary to analyze in detail the changes in the value of ecosystem services in different regions to formulate management policies that are in line with the actual local situation.

Evaluating ESV generally involves two kinds of methods: one is referred to as the unit value-based approach using economic value per unit area of ecosystem plus land use/land cover proxy (Costanza *et al.*, 1997; Xie *et al.*, 2008; Xie *et al.*, 2017; Costanza *et al.*, 2014); the other is referred to as the primary data-based approach. ESV is evaluated in two steps: (i) quantifying the biophysical supply of ecosystem service based on a series of ecological models (e.g., photosynthesis equation for gas regulation), and (ii) estimating ESV using economic valuation techniques (e.g., market price method, replacement cost method, and travel cost method) (Wang *et al.*, 2013; Zhao *et al.*, 2013; Li *et al.*, 2018).

The value transfer method, which belongs to the unit value-based approach, was proposed by Costanza *et al.* (1997) to assess the global ESV (Costanza *et al.*, 1997), and was then developed by Xie *et al.* as the equivalent per-unit-area following the same methodology to meet Chinese situation (Xie *et al.*, 2008; Xie *et al.*, 2017). This method assumes an equivalent value per unit of land area and multiples the value by the area of each ecosystem type to assess the total ESV. The value transfer method is a process to estimate the ESV by transferring available value information from an existing study site to a new unstudied site (Costanza *et al.*, 2014; Richardson *et al.*, 2015). The unit value-based approach is not an empirical study (Jiang *et al.*, 2021), and provides more convenient solutions to aggregate comprehensive spatial-temporal distribution of ESV, which has made it widely used in larger spatial studies, such as regional and global scales (Ida *et al.*, 2013; Tolessa *et al.*, 2017; Song & Deng, 2017).

The primary data-based approach commonly demands many input parameters and presents detailed accounting processes, and then requires calculating biomass and economic values one by one, which results in the difficulties of unifying calculation approach and standardizing parameters for the assessment of each ecosystem service of each ecosystem (Xie *et al.*, 2017). Thus, this method is seldom applied to the comprehensive ESV owing to the intensive parameterization and is suitable for the evaluation of a single service or a single ecosystem (Li *et al.*, 2010), otherwise on the small spatial scale (Xie *et al.*, 2017). However, the primary data-based approach generally provides only a static evaluation that ignores spatial and temporal changes of the ecosystems, thus the conclusions cannot represent the spatial and temporal dynamic transformation of ecosystem services (Xie *et al.*, 2017; Sun, 2011). The intensive parameterization and static evaluation restricted the practical application of ESV in environmental research and management, especially for some cities under much ecological environment protection pressure, such as Wuhan city.

To address this gap, this paper aims to present a case study to assess comprehensive ESV on the local scale. The study focuses on Wuhan City, one of the rapidly urbanizing megacities in central China that is in contradiction with ecological protection. Different from other works, we adopted the national land survey data whose resolution ratio is no less than 2.5 m, which is of high precision and can improve the accuracy of land use classification and valuation. In addition, with the primary data-based approach, evaluating the ESV of representative cities through parameter updates can establish knowledge over time through case studies, and thus promote the iteration of research methods.

In this study, we aimed to: (i) estimate land use changes in Wuhan during the period of 1996 – 2018; (ii) assess the dynamic changes in ESV in response to land use changes; and (iii) discuss the relationship between the change in ESV and the economic development and ecological protection policies. Therefore, this case study will produce significant practical impacts to support the management of urban development and ecological protection for other similar cities worldwide.

## 2. Materials and methods

### 2.1. Research area

Wuhan, located in the central part of China, is the capital of Hubei Province and one of the sub-provincial cities in China. Geographically, Wuhan lies where the Yangtze River and Han River meet and is located between 29°58' – 31°22'N and 113°41' – 115°05'E (Figure 1). The total area was about 8569 sqkm and the resident population of Wuhan reached 11.08 million with an urbanization rate of 80.29%. The gross domestic product (GDP) of Wuhan ranked 3rd among China's sub-provincial cities in 2018, at 1484.7 billion yuan. Wuhan has 13 districts, among which 7 are in the downtown districts and 6 are in the new urban districts. The city is the transportation hub of China, one of the four central cities of science and education, and was once rated by National Geographic as one of the three cities with the richest inland wetland resources in the world.

The elevation in the city ranges from 19.2 m to 873.7 m, mostly below 50 m. The primary geomorphic type is plain, with a proportion of 39.3%. Wuhan has a typical subtropical monsoon climate. The annual average temperature is 15.8 – 17.5°C, and the frost-free season lasts for 211 – 272 days. The annual precipitation is 1150 – 1450 mm, and the rainfall concentrates in July and August. The annual duration of sunshine is 1810 – 2100 h, with a total annual radiation of 104 – 113 kcal/cm$^2$.

### 2.2. Data sources

This study includes three kinds of data: land use data, socioeconomic data, and natural resources data. Multi-temporal data are needed for the ESV assessment of dynamic analysis.

#### *2.2.1. Land use data*

In the study, the land-use data in 1996, 2000, 2005, 2010, 2015, and 2018 were collected from Wuhan Natural Resources and Planning Bureau (WNRPB). Since 1984, two land surveys have been conducted nationwide in China; both of which were approved and organized by the State Council of China. The WNRPB implemented Wuhan's land survey and established the land use database in 1996 and 2009. Based on the two national land surveys, the change of annual dynamic renewal mechanism of land resources was established.

The source data adopted in the article is different from the data obtained from remote sensing images in other articles in terms of core technology, spatial resolution, and rendering methods. First, the national land survey data in China not only used remote sensing but also utilized geographic information systems (GIS) and Global Navigation Satellite System (GNSS). Second, the spatial resolution is higher. The resolution of general remote sensing images in other papers is generally 30 m, with some reaching up to 15 m. Yet, the spatial resolution of the images adopted by the national land survey in China is no <2.5 m. Further, the data used in this article has been validated through human-computer interaction and has a wider field investigation scope. Other articles are limited by manpower and can only be conducted through sampling surveys, while the data verification in this article was carried out across the country using an overall survey, with hundreds of thousands of technicians organized

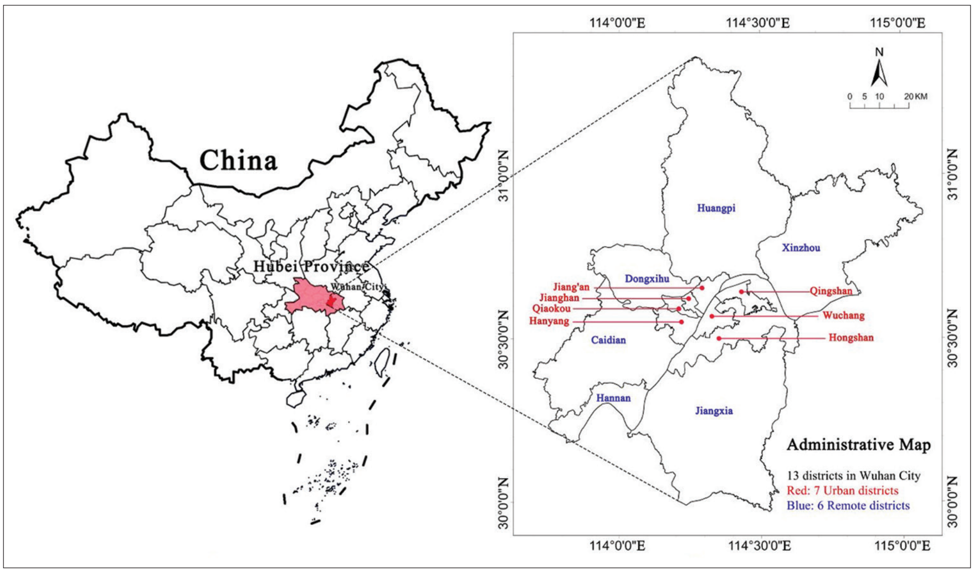


**Figure 1.** The geographical location of Wuhan. Source: Map by the authors

nationwide to participate in field surveys on a plot-by-plot basis. Thus, this method ensures that the database was authoritative, accurate, and intact.

In the study, we divided the land based on six types of land use, such as cultivated land, forestry area, grassland, water body, built-up land, and unused land. Due to the large water area and high ESV of water bodies in Wuhan, the study subdivided water bodies into two subcategories: rivers/lakes and wetland. It was the first time that such data were used for research in the ESV assessment at an urban scale in China.

*2.2.2. Socioeconomic data*

The socioeconomic data were largely sourced from statistical data. The total value of agricultural products, population, GDP, and other social and economic data sets were sourced from Wuhan statistical yearbooks. To enhance comparability, the economic data in 1996, 2000, 2005, 2010, 2015 were converted to 2018 benchmark.

*2.2.3. Natural resources data*

Natural resources data mainly pertain to the natural environment and biological conditions. The natural environment conditions included soil, water, and climatic conditions. Biological conditions are concerning vegetation, aquatic organisms, and ecosystem types. Water resources data were obtained from Wuhan Water Affairs Bureau and Wuhan Lake Bureau. Climatic data, including annual precipitation and mean temperature from 1996 to 2018, were downloaded from China Meteorological Data Sharing Service System. Others were sourced from related databases and literature.

### 2.3. Analysis of land use change

Single land use dynamic degree was used to reveal the changes of a certain land use type in the study area over a period (Wang & Yang, 2021). The formula is as follows:

$$K=\frac{Afinal-Ainitial}{Ainitial}\times\frac{1}{T}\times 100\% \quad \text{(I)}$$

Where K represents the land use dynamic index for a single land use type, $A_{final}$ and $A_{initial}$ are the area ($hm^2$) of land use category at the final and initial year of the studied period, respectively, and T is the period studied (year). If T is one year, K refers to the annual change rate.

### 2.4. Analysis of ESV

According to the relevant research of Costanza *et al.* (1997; 2014) and Xie *et al.* (2008; 2015), the evaluation indexes selected in the study included production provision, water resource supply, gas regulation, climate regulation, environmental purification, hydrological regulation, soil retention, nutrient cycling, biodiversity conservation, and esthetic landscape. According to the types and attributes of different evaluation indexes of ecosystem in Wuhan, the market value method, shadow project method, alternative project method, and travel cost method were mainly applied to evaluate the ESV of Wuhan. To eliminate the impact of inflation, the study adopted the corrected consumer value index (CPI) of residents to adjust the price to 2018 to make the results comparable. The specific formulas and processes used to estimate the ESV in Wuhan are shown in Table 1.

*2.4.1. Agricultural production*

Nature provides renewable biotic resources and non-renewable abiotic resources. Generally, production functions are limited to renewable biotic resources, the so-called "agricultural products," including "forest products" (e.g., fruits, leaves), "other agricultural products" (e.g., rice and corn), and "aquatic products" (e.g., fish, shrimp). The values of production functions were evaluated by market price method (Miu *et al.*, 2016). The formula is as follows:

$$V_P=\sum M_i\times P_i \quad \text{(II)}$$

Where $V_p$ is the total value of agricultural products; $M_i$ is the annual output of the i-th agricultural products (kg); and $P_i$ is the price of this agricultural product in that year (yuan/kg).

Based on the land use data and statistical yearbook (Wuhan Statistics Bureau, 1997, 2001, 2006, 2011, 2016, 2019), the value of agricultural product can be obtained.

*2.4.2. Water supply*

The water supply function focuses primarily on the capacity of water storage, and the ecosystem of services related to water supply refers to the consumption of water (by households, agriculture, and ecological environment). The water supply value was evaluated by the market price method (Ye *et al.*, 2013; Deng *et al.*, 2019; Zhang *et al.*, 2017). The formula is as follows:

$$V_{ws}=\sum Q_i\times P_i \quad \text{(III)}$$

Where $V_{ws}$ is the water supply value (yuan/a); $Q_i$ is the water consumption for the i-th purpose ($m^3$/a); and $P_i$ is the market price of water for the i-th purpose (yuan/$m^3$), in which the price of water consumption was the price of water in Wuhan from 1996 to 2018.

According to Wuhan Water Affairs Bureau and Wuhan Lake Bureau, the unit water consumption for agriculture,

**Table 1. Methods to calculate ecosystem service values in Wuhan**

| Ecosystem service functions | | Valuation index | Valuation method | Calculation formula | Indices |
|---|---|---|---|---|---|
| Type | Sub-type | Indicator | | | |
| Provisioning service | Agricultural products | Fruits, rice, fish, and so on | Market price method | $V_p=eM_i\times P_i$ | $V_p$ is the total value of agricultural products; $M_i$ is the annual output of the i-th agricultural products (kg); and $P_i$ is the price of this agricultural product in that year (yuan/kg) |
| | Water supply | Freshwater supply | Market price method | $V_{ws}=sQ_i\times P_i$ | $V_{ws}$ is the water supply value (yuan/a); $Q_i$ is the water consumption for the i-th purpose ($m^3$/a); and $P_i$ is the market price of water for the i-th purpose (yuan/$m^3$) |
| Regulating service | Gas regulation | $CO_2$ fixation | Replacement cost method-afforestation cost method | $V_q=P_c\times A\times(1.63\times NPP+D_c)+1.19\times P_o\times A\times NPP$ | $V_q$ is the total value of gas regulation; NPP is the net primary productivity of ecosystem (t/$hm^2$·a); $D_c$ is carbon density of soil (t/$hm^2$); $P_c$ is the price of carbon sequestration (yuan/t); $P_o$ is the price of $O_2$ production; and A is the area of ecosystem ($hm^2$) |
| | | $O_2$ emission | Replacement cost method-oxygen production method | | |
| | Climate regulation | Plant transpiration and water surface evaporation | Replacement cost method | $V_{cr}=E\times L\times P_e/\alpha$ | $V_{cr}$ is the climate regulation value; E is the transpiration (J/$hm^2$·d); L is the evaporation heat consumption coefficient (J/g); $P_e$ is the current electricity price (yuan/kWh); and α is the air-conditioning efficiency ratio |
| | Environmental purification | $SO_2$ treatment and dust retention | Replacement cost method of air pollutant reduction | $V_{pe}=Q_S\times P_S+Q_d\times P_d$ | $V_{pe}$ is the value of environmental purification; QS is the annual $SO_2$ absorption (kg); Qd is the annual dust reduction (t); $P_S$ is the investment cost per unit SO2 reduction (yuan/kg); and $P_d$ is the investment cost per unit dust reduction (yuan/t) |
| | Hydrological regulation | Water conservation | Replacement engineering method | $V_{wc}=A\times(P-E)\times P_r$ | $V_{wc}$ is the value of water conservation; A is the ecosystem area ($hm^2$); P is the annual precipitation (mm); E is the average evapotranspiration (mm/a); and $P_r$ is the cost of reservoir per unit storage capacity (yuan/t) |
| | | Flood regulation | Replacement engineering method | $V_{fr}=Q\times P_r$ | $V_{fr}$ is the flood regulation value; Q is the flood regulation volume ($m^3$/a); and $P_r$ is the reservoir cost per unit storage capacity (yuan/t) |
| Supporting service | Soil conservation | Prevention of soil erosion | Replacement cost method | $V_{se}=A\times P_{et}\times (X_2-X_1)/\rho$ | $V_{se}$ is the annual reduced soil erosion value; A is the ecosystem area ($hm^2$); Pet is the cost of earthwork excavation and transportation per unit volume (yuan/$m^3$); $X_2$ is the potential erosion modulus (t/$hm^2$·a); X1 is the actual erosion modulus (t/$hm^2$·a); and ρ is the soil bulk density (g/$cm^3$) |
| | | Maintenance of soil fertility | Replacement price method of fertilizer | $V_{sf}=A\times(X_2-X_1)\times(NC_1/R_1+PC_1/R_2+KC_2/R_3+MC_3)$ | $V_{sf}$ is the annual fertilizer conservation value; N, P, and K are the average content of nitrogen, phosphorus, and potassium in soil (%); $R_1$ and $R_2$ are the content of nitrogen and phosphorus in standard fertilizer, respectively (%); $R_3$ is the potassium content in standard fertilizer (%); $C_1$, $C_2$, and $C_3$ are the prices of $(NH_4)_2HPO_4$, KCl, and organic matter, respectively (yuan/t); and M is the content of soil organic matter (%) |

*(Cont'd...)*

**Table 1.** ***(Continued)***

| Ecosystem service functions | | Valuation index | Valuation method | Calculation formula | Indices |
|---|---|---|---|---|---|
| Type | Sub-type | Indicator | | | |
| | | Reduction of sediment deposition | Replacement cost method of reservoir engineering | $V_{sd}$=24%×A×($X_2$-$X_1$) $P_w$/ρ | $V_{sd}$ is the value of reducing sediment deposition; A is the area of ecosystem ($hm^2$); $P^w$ is the cost of sediment cleaning (yuan/t); and ρ is the soil bulk density ($g/cm^3$) |
| | Nutrient cycling | Fixation of N, P, and K | Replacement cost method | $V_{nc}$=A×NPP×($NC_1$/$R_1$+$PC_1$/$R_2$+$KC_2$/$R_3$) | $V_{nc}$ is the annual value of nutrient maintenance; N, P, and K are the contents of nitrogen, phosphorus, and potassium in plants (%) |
| | Biodiversity maintenance | Biodiversity conservation function | Shannon–Wiener index method | $V_{bc}$=$P_s$×A | $V_{bc}$ is the value of biodiversity conservation; and $P_s$ is the conservation value of species resources per unit area (yuan/$hm^2$·a) |
| Cultural service | Aesthetic landscape | Travel | Travel cost method | $V_{al}$=MTE×$T_p$ | $V_{al}$ is the value of aesthetic landscape; MTE is per capita tourism expenditure (yuan); and $T_p$ is the annual number of travelers |

industry, domestic, and ecology water in 1996, 2000, 2005, 2010, 2015, and 2018 was based on the current water consumption unit price in Wuhan city. The agricultural water consumption unit prices were 0.03, 0.035, 0.04, 0.04, 0.16, and 0.16 yuan/$m^3$, respectively; the unit prices of industrial water were 0.55, 0.79, 1.51, 1.65, 2.35, and 2.35 yuan/$m^3$, respectively; the unit prices for domestic and ecological water were 0.67, 0.85, 1.51, 1.65, 2.28, and 2.28 yuan/$m^3$, respectively.

### *2.4.3. Gas regulation*

The main services associated with gas regulation are to maintain clean, breathable air, which depends on the chemical balance in the atmosphere maintained by bio-geochemical processes that regulate the $CO_2$/$O_2$ balance, $SO_x$ levels, and so on. The current research only studied the function of release of oxygen and carbon sequestration, which was estimated according to the photosynthesis equation, that is, 1.63 tons of $CO_2$ can be fixed and 1.19 tons of $O_2$ can be released for each ton of dry matter formed. Soil carbon sequestration was calculated by different soil carbon densities. The values were calculated by the afforestation cost method and industrial oxygen production method, respectively (Zhao *et al.*, 2004; Miu *et al.*, 2016; Wang *et al.*, 2013; Chen & Zheng, 2021). The formula is as follows:

$$V_q = P_c \times A \times (1.63 \times NPP + D_c) + 1.19 \times P_o \times A \times NPP \quad (IV)$$

Where $V_q$ is the total value of gas regulation; NPP is the net primary productivity of the ecosystem (t/$hm^2$·a); $D_c$ is carbon density of soil (t/$hm^2$); $P_c$ is the price of carbon sequestration (yuan/t); $P_o$ is the price of $O_2$ production; and A is the area of ecosystem ($hm^2$).

According to the average NPP and $D_c$ of Wuhan (Zhang *et al.*, 2011; Ke & Tang, 2019), the total annual carbon fixation and oxygen release of Wuhan could be calculated. Then, assuming that the cost of forestation and average price of oxygen were 260.90 yuan/t and 1000 yuan/t, respectively (Ouyang *et al.*, 2011), the value of gas regulation by the ecosystem of Wuhan between 1996 and 2018 can be calculated.

### *2.4.4. Climate regulation*

Climate regulation mainly refers to the maintenance of a pleasant climate, both at local and global scales, and the value of which was estimated through the transpiration of plant leaves and evaporation of water by alternative cost method (Xiao *et al.*, 2014; Zhang *et al.*, 2012). The formula is as follows:

$$V_{cr} = E \times L \times P_e / \alpha \quad (V)$$

Where $V_{cr}$ is the climate regulation value; E is the transpiration (J/$hm^2$·d); L is the evaporation heat consumption coefficient (J/g); $P_e$ is the current electricity price (yuan/kWh); and α is the air-conditioning efficiency ratio.

The evaporation heat consumption coefficient can be calculated from the monthly average temperature of July, August, and September in Wuhan. The first-tier electricity price in Wuhan, which were the prices of 0.523 yuan/kWh in 1996, 2000 and 2005, and 0.573 yuan/kWh in 2010, 2015 and 2018, adopted as the electricity price (P). The conventional average value of 3.25 was taken as the air-conditioning efficiency ratio (Deng *et al.*, 2019).

### *2.4.5. Environmental purification*

The main services provided by environmental purification are to purify the air and prevent human respiratory diseases caused by the excessive accumulation of harmful substances, such as $SO_2$, $NO_x$, HF and dust. The paper mainly considers the functions of $SO_2$ and dust reduction (Fang *et al.*, 2011; Bai *et al.*, 2010; Bai *et al.*, 2011). The formula is as follows:

$$V_{pe} = Q_S \times P_S + Q_d \times P_d \qquad \text{(VI)}$$

Where $V_{pe}$ is the value of environmental purification; $Q_S$ is the annual $SO_2$ absorption (kg); $Q_d$ is the annual dust reduction (t); $P_S$ is the investment cost per unit $SO_2$ reduction (yuan/kg); and $P_d$ is the investment cost per unit dust reduction (yuan/t).

Based on other research achievements (Xiao *et al.*, 2009; Bai *et al.*, 2011), the annual $SO_2$ absorption and the annual dust reduction can be adopted. The annual dust reduction and the investment cost per unit dust reduction are from the Standards and Calculation Methods for Collecting Pollution Discharge Fees in China.

### *2.4.6. Hydrological regulation*

The natural ecosystem plays an important role in water conservation and flood regulation by adjusting hydrological paths.

(A) Water conservation
The services derived from water conservation relate to the regular distribution of hydrological flows at the earth's surface, which is manifested in the functions of vegetation interception of precipitation, enhancement of soil infiltration, mitigation of surface runoff, and so on. The value of water conservation can be determined according to the storage cost of the reservoir project (alternative project method) (Tang *et al.*, 2016; Zhang *et al.*, 2016).

$$V_{wc} = A \times (P-E) \times P_r \qquad \text{(VII)}$$

Where $V_{wc}$ is the value of water conservation; A is the ecosystem area ($hm^2$); P is the annual precipitation (mm); E is the average evapotranspiration (mm/a); and $P_r$ is the cost of reservoir per unit storage capacity (yuan/t).

According to Wuhan Water Affairs Bureau and Wuhan Lake Bureau, the average annual precipitation in Wuhan in 1996, 2000, 2005, 2010, 2015, and 2018 year was 1166.00 mm, 1051.81 mm, 1096.1 mm, 1494.8 mm, 1391.6 mm, and 1304.3 mm, respectively. The runoff coefficients of different types of land are derived from the the "Guidelines for Planning and Design of Sponge Cities in Wuhan" (Wuhan Water Bureau, 2015). In the 1990s, the unit cost for a reservoir was 2.17 yuan/t (Bai *et al.*, 2011), and has been revised to as 2.74 yuan/t, 6.11 yuan/t, 7.28 yuan/t, 8.44 yuan/t, and 8.80 yuan/t according to the price increase index in 2000, 2005, 2010, 2015, and 2018, respectively (Wuhan Statistical Bureau, 1997; 2001; 2006; 2011; 2016; 2019).

(B) Flood regulation
The main function of flood regulation is to store and release excess water slowly, and redistributes water in time and space to avoid and reduce flood disasters. The alternative project method was adopted in this study (Dai *et al.*, 2021; Li *et al.*, 2018; Ida *et al.*, 2013; Deng *et al.*, 2019; Zhang *et al.*, 2017), and the formula is:

$$V_{fr} = Q \times P_r \qquad \text{(VIII)}$$

Where $V_{fr}$ is the flood regulation value; Q is the flood regulation volume ($m^3$/a); and $P_r$ is the reservoir cost per unit storage capacity (yuan/t).

According to relevant research (Chen & Zhang, 2021; Pan *et al.*, 2018), the flood storage capacity is calculated based on the unit area flood storage capacity and maximum submergence depth of the relevant land types. The reservoir cost per unit storage capacity is the same as above.

### *2.4.7. Soil retention*

Soil retention deals with the impact of nature on vegetation cover and root system, which stabilize the soil and intercept the rainfalls to prevent the erosion of soil. Soil retention is mainly reflected in reducing soil erosion, maintaining soil fertility, and reducing sediment deposition in rivers and lakes.

(A) Prevention of soil erosion
According to the difference between potential and actual erosion modulus (Zhang *et al.*, 2016; Han *et al.*, 2021; Ouyang *et al.*, 1999), the value of soil erosion reduction is calculated as follows:

$$V_{se} = A \times P_{et} \times (X_2 - X_1)/\rho \qquad \text{(IX)}$$

Where $V_{se}$ is the annual reduced soil erosion value; A is the ecosystem area ($hm^2$); $P_{et}$ is the cost of earthwork excavation and transportation per unit volume (yuan/$m^3$); $X_2$ is the potential erosion modulus ($t/hm^2 \cdot a$); and $X_1$ is the actual erosion modulus ($t/hm^2 \cdot a$); and $\rho$ is the soil bulk density ($g/cm^3$).

According to the consumption quota of relevant engineering projects in Hubei province ("Hubei Provincial Construction Engineering," 2008, 2018), the cost of earthwork excavation and transportation per unit volume could be obtained. The potential erosion modulus and the actual erosion modulus were obtained from relevant research (Han *et al.*, 2021; Ouyang *et al.*, 1999). The soil bulk density in Wuhan was taken as the average value of 1.35 $g/cm^3$ (Wang *et al.*, 2020).

(B) Maintenance of soil fertility
The value of maintaining soil fertility can be expressed by the market value of chemical fertilizer with the same fertility in soil (Ye *et al.*, 2013; Miu *et al.*, 2016; Wang *et al.*, 2013; Chen & Zheng, 2021;

Zhang *et al.*, 2011; Ke & Tang, 2019), and the formula is as follows:

$$V_{sf} = A \times (X_2\text{-}X_1) \times (NC_1/R_1 + PC_1/R_2 + KC_2/R_3 + MC_3) \quad (X)$$

Where $V_{sf}$ is the annual fertilizer conservation value; N, P, and K are the average content of nitrogen, phosphorus, and potassium in soil (%); $R_1$ and $R_2$ are the content of nitrogen and phosphorus in standard fertilizer, respectively (%); $R_3$ is the potassium content of standard fertilizer (%); $C_1$, $C_2$, and $C_3$ are the prices of $(NH_4)_2HPO_4$, KCl, and organic matter, respectively (yuan/t); and M is the content of soil organic matter (%).

Data on the average content of nitrogen, phosphorus, and potassium in soil were obtained from Wang *et al.* (2020) and Xiong *et al.* (2005). The content of nitrogen, phosphorus, potassium, and organic matter was taken as the conventional average value of 18%, 46%, 60%, and 45%, respectively. The prices of different fertilizers in different years could be obtained from China Fertilizer Network (http://www.fert.cn/). Thus, the value of maintaining soil fertility could be calculated using Equation X.

(C) Reduction of sediment deposition
According to the law of sediment movement in China, about 24% of the sediment lost through soil erosion is deposited in rivers and lakes, resulting in the decline of water storage, and increasing the chance of drought and flood disasters (Miu *et al.*, 2016). The value can be calculated by shadow engineering method according to water storage cost as follows:

$$V_{sd} = 24\% \times A \times (X_2 - X_1) \times P_w/\rho \quad (XI)$$

Where $V_{sd}$ is the value of reducing sediment deposition; A is the area of ecosystem ($hm^2$); $P_w$ is the cost of sediment cleaning (yuan/t); and ρ is the soil bulk density ($g/cm^3$).

The parameter values in this section are the same as the part in section 2.4.7. (A).

### *2.4.8. Nutrient cycling*

Life depends on the cycling of chemical elements in nature, among which nitrogen, phosphorus, and potassium are the most important (Ida *et al.*, 2013; Ye *et al.*, 2013; Ouyang *et al.*, 2011). The value can be calculated as follows:

$$V_{nc} = A \times NPP \times (NC_1/R_1 + PC_1/R_2 + KC_2/R_3) \quad (XII)$$

Where $V_{nc}$ is the annual value of nutrient maintenance; and N, P, and K are the contents of nitrogen, phosphorus, and potassium in plants (%).

The average NPP of Wuhan was also obtained from Zhang *et al.* (2011). The other parameter values in this section are consistent with those in section 2.4.7. (B).

### *2.4.9. Biodiversity conservation*

Biodiversity conservation function can be expressed by means of the Shannon–Wiener index, which is divided into different levels and given corresponding value parameter (Richardson *et al.*, 2015; Ye *et al.*, 2013). The formula is as follows:

$$V_{bc} = P_s \times A \quad (XIII)$$

Where $V_{bc}$ is the value of biodiversity conservation; and $P_s$ is the conservation value of species resources per unit area ($yuan/hm^2 \cdot a$).

The conservation values of species resources per unit area were obtained from the "People's Republic of China Forestry Standard: Forest Ecosystem Service Valuation Norms" (State Forestry Administration, 2008; State Administration for Market Regulation & Standardization Administration of the People's Republic of China, 2020).

### *2.4.10. Aesthetic landscape*

Nature provides people with opportunities for recreation, tourism, scientific research, and education. The paper mainly considered the value of recreation and tourism. The travel cost method was used to assess the value of aesthetic landscape (Wang *et al.*, 2014; Li *et al.*, 2018; Deng *et al.*, 2019).

$$V_{al} = MTE \times T_p \quad (XIV)$$

Where $V_{al}$ is the value of aesthetic landscape; MTE is per capita tourism expenditure (yuan); and $T_p$ is the annual number of travelers.

Based on the data of Wuhan Statistical Yearbook (Wuhan Municipality Bureau of Statistics, 1997; 2001; 2006; 2011; 2016; 2019), the values of aesthetic landscape could be obtained.

### *2.4.11. The whole ESV*

The ESV of the four major categories and ten subcategories above constitutes the whole ESV, and the calculation formula is as follows:

$$V_w = V_p + V_{ws} + V_q + V_{cr} + V_{pe} + V_{wc} + V_{fr} + V_{se} + V_{sf} + V_{sd} + V_{nc} + V_{bc} + V_{al} \quad (XV)$$

Where $V_w$ is the whole ESV; the meaning of other codes can be found in the explanation of the above-mentioned formulas.

## 3. Results

### 3.1. Changes of land use

The change of land use in Wuhan during the 1996 – 2018 periods is shown in Table 2 and Figure 2. Cultivated land was an important factor, with the greatest proportions (49.40% in 1996, 48.63% in 2000, 42.01% in 2005, 37.94% in 2010, 35.75% in 2015, 35.12% in 2018), followed by water area and built-up land. These three land use categories accounted for approximately 87% of the total area, while the other three land use categories (forestry area, grassland, and unused land) together covered almost 13% of the total area.

Land use in Wuhan underwent drastic changes from 1996 to 2018, a period characterized by a decrease in cultivated land, unused land, and grassland, and an increase in built-up land, forestry area, and water area (Figure 3). The cultivated land declined from 49.40% (422322.06 $hm^2$) in 1996 to 35.12% (300987.73 $hm^2$) in 2018, unused land from 2.14% (21043.81 $hm^2$) in 1996 to 0.44% (3774.80 $hm^2$) in 2018, and grassland from 2.14% (6901.47 $hm^2$) in 1996 to 0.0002% (2.14 $hm^2$) in 2018. On the contrary, built-up land increased from 14.96% (127917.35 $hm^2$) in 1996 to 24.41% (209182.2 $hm^2$) in 2018, water area from 23.29% (199132.27 $hm^2$) in 1996 to 28.05% (240394.99 $hm^2$) in 2018, forestry area from 9.08% (77583.57 $hm^2$) in 1996 to 11.97% (102572.73 $hm^2$) in 2018.

The single land use dynamic degree (K) is shown in Table 3. The K of the cultivated land and unused land were negative, meaning their areas declined continuously during the period of 1996 – 2018. While the area of built-up land increased continuously because the K of the built-up land was positive. The forestry area and water area increased first in 1996 – 2010 and then decreased in 2010 – 2018 in that K>0 first and then K<0. The grassland varied greatly with the largest K, and the area of grassland approached zero in 2018, but the change area was the smallest because of its minimum absolute area.

In 1996 – 2000, the K of each type was the smallest; only the K of farmland and unused land decreased, while the K of other land types increased. After 2000, most of the cities in China, including Wuhan, have successively entered the era of speeded urbanization with the accelerated economic growth. The characteristics of land use in Wuhan were a rapid expansion of built-up land and a sharp decline in cultivated land. Forestry area and water area increased and reached the peak in 2010 and then decreased slightly. Grassland continued to decline to close to zero in 2010 and then remained unchanged.

**Table 2. Area changes of land use in Wuhan**

| Land use categories | Area ($hm^2$) | | | | | | Change rate (%) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1996 | 2000 | 2005 | 2010 | 2015 | 2018 | 1996 – 2000 | 2000 – 2005 | 2005 – 2010 | 2010 – 2015 | 2015 – 2018 | 1996 – 2018 |
| Cultivated land | 422322 | 415766 | 359118 | 325073 | 306327 | 300988 | −1.55 | −13.63 | −9.48 | −5.77 | −1.74 | −28.73 |
| Forestry area | 77584 | 77784 | 101566 | 105739 | 103585 | 102573 | 0.26 | 30.58 | 4.11 | −2.04 | −0.98 | 32.21 |
| Grassland | 6901 | 6901 | 283 | 2 | 2 | 2 | 0.00 | −95.90 | −99.24 | 0.00 | 0.00 | −99.97 |
| Water body | 104530 | 104621 | 112853 | 110734 | 110255 | 110117 | 0.09 | 7.87 | −1.88 | −0.43 | −0.13 | 5.34 |
| Wetland | 94602 | 96114 | 114734 | 139547 | 132641 | 130278 | 1.60 | 19.37 | 21.63 | −4.95 | −1.78 | 37.71 |
| Built-up land | 127917 | 132954 | 153111 | 171266 | 200218 | 209182 | 3.94 | 15.16 | 11.86 | 16.91 | 4.48 | 63.53 |
| Unused land | 21044 | 20768 | 13244 | 4554 | 3885 | 3775 | −1.31 | −36.23 | −65.62 | −14.68 | −2.85 | −82.06 |

**Table 3. Changes in land use in Wuhan during the period of 1996 – 2018**

| Land use categories | Percentage of land use type (%) | | | | | | Land use dynamic index K (%) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1996 | 2000 | 2005 | 2010 | 2015 | 2018 | 1996 – 2000 | 2000 – 2005 | 2005 – 2010 | 2010 – 2015 | 2015 – 2018 | 1996 – 2018 |
| Cultivated land | 49.40 | 48.63 | 42.01 | 37.94 | 35.75 | 35.12 | −0.39 | −2.73 | −1.90 | −1.15 | −0.58 | −1.31 |
| Forestry area | 9.08 | 9.10 | 11.88 | 12.34 | 12.09 | 11.97 | 0.06 | 6.12 | 0.82 | −0.41 | −0.33 | 1.46 |
| Grassland | 0.81 | 0.81 | 0.03 | 0.00 | 0.00 | 0.00 | 0.00 | −19.18 | −19.85 | 0.00 | 0.00 | −4.54 |
| Water area | 23.29 | 23.48 | 26.62 | 29.21 | 28.35 | 28.05 | 0.20 | 2.68 | 1.99 | −0.59 | −0.34 | 0.94 |
| Rivers/lakes | 12.23 | 12.24 | 13.20 | 12.92 | 12.87 | 12.85 | 0.02 | 1.57 | −0.38 | −0.09 | −0.04 | 0.24 |
| Wetland | 11.07 | 11.24 | 13.42 | 16.28 | 15.48 | 15.20 | 0.40 | 3.87 | 4.33 | -0.99 | −0.59 | 1.71 |
| Built-up land | 14.96 | 15.55 | 17.91 | 19.99 | 23.37 | 24.41 | 0.98 | 3.03 | 2.37 | 3.38 | 1.49 | 2.89 |
| Unused land | 2.46 | 2.43 | 1.55 | 0.53 | 0.45 | 0.44 | −0.33 | −7.25 | −13.12 | −2.94 | −0.95 | −3.73 |

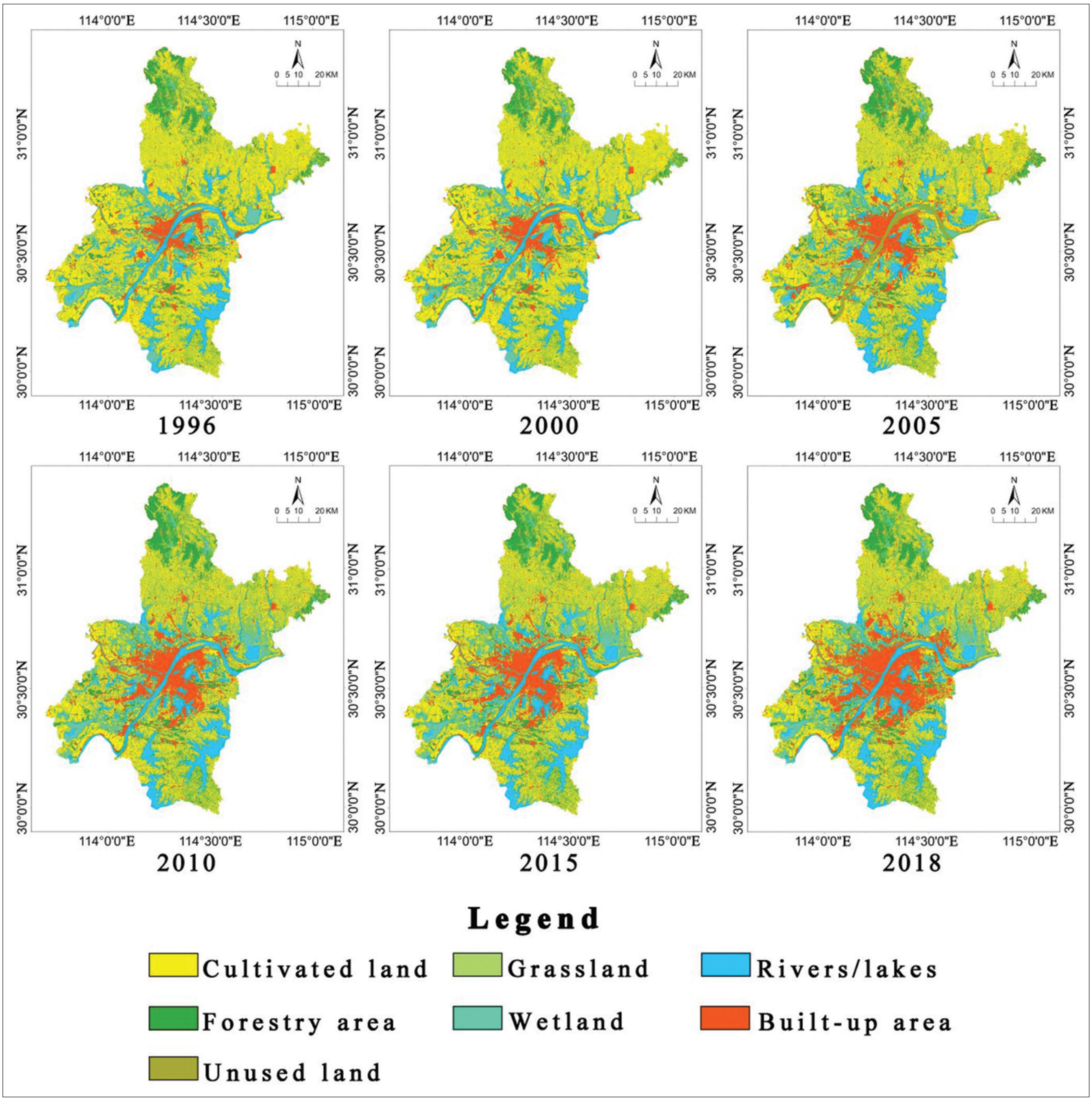


**Figure 2.** Land use change in Wuhan during the period of 1996 – 2018. Source: Diagram by the authors

### 3.2. Changes of ESV

*3.2.1. Changes in total ESV*

Table 4 lists the ESV and changes in total ESV in Wuhan from 1996 to 2018. The total ESV were about 119.32 billion yuan, 125.50 billion yuan, 151.66 billion yuan, 180.01 billion yuan, 208.41 billion yuan, and 220.30 billion yuan in 1996, 2000, 2005, 2010, 2015, and 2018, respectively. Therefore, the total ESV increased 100.98 billion yuan, accounting for 84.62% of the total ESV in 1996. These figures indicate that an increasing trend can be seen throughout the study period.

During the period of 1996 – 2018, although the ESV had been showing an increasing trend, the growth ranges and rates varied in different periods. An obvious increase in the change of ESV can be seen during the first (1996 – 2000), second (2000 – 2005), third (2005 – 2010), fourth (2010 – 2015), fifth (2015 – 2018), and the entire

**Table 4. Total ESV for each land use type in Wuhan from 1996 to 2018**

| Land use types | Cultivated land | Forestry area | Grassland | Water area | Rivers/ lakes | Wetland | Built–up area | Unused land | Total |
|---|---|---|---|---|---|---|---|---|---|
| 1996 | | | | | | | | | |
| ESV | 666.74 | 115.57 | 9.19 | 386.41 | 250.87 | 135.55 | 11.45 | 3.85 | 1193.21 |
| P (%) | 55.88 | 9.69 | 0.77 | 32.38 | 21.02 | 11.36 | 0.96 | 0.32 | 100.00 |
| 2000 | | | | | | | | | |
| ESV | 677.05 | 115.21 | 9.07 | 437.31 | 291.32 | 145.99 | 12.02 | 4.38 | 1255.03 |
| P (%) | 53.95 | 9.18 | 0.72 | 34.84 | 23.21 | 11.63 | 0.96 | 0.35 | 100.00 |
| 2005 | | | | | | | | | |
| ESV | 730.00 | 178.82 | 0.44 | 588.39 | 401.74 | 186.66 | 14.79 | 4.19 | 1516.63 |
| P (%) | 48.13 | 11.79 | 0.03 | 38.80 | 26.49 | 12.31 | 0.98 | 0.28 | 100.00 |
| 2010 | | | | | | | | | |
| ESV | 860.48 | 236.49 | 0.00 | 681.81 | 445.69 | 236.12 | 19.10 | 2.24 | 1800.13 |
| P (%) | 47.80 | 13.14 | 0.00 | 37.88 | 24.76 | 13.12 | 1.06 | 0.12 | 100.00 |
| 2015 | | | | | | | | | |
| ESV | 1036.09 | 248.84 | 0.00 | 771.54 | 521.87 | 249.67 | 25.58 | 2.08 | 2084.13 |
| P (%) | 49.71 | 11.94 | 0.00 | 37.02 | 25.04 | 11.98 | 1.23 | 0.10 | 100.00 |
| 2018 | | | | | | | | | |
| ESV | 1086.87 | 267.64 | 0.00 | 818.17 | 549.50 | 268.67 | 28.27 | 2.01 | 2202.96 |
| P (%) | 49.34 | 12.15 | 0.00 | 37.14 | 24.94 | 12.20 | 1.28 | 0.09 | 100.00 |
| 1996 – 2000 | | | | | | | | | |
| C | 10.31 | –0.35 | –0.12 | 50.89 | 40.45 | 10.44 | 0.57 | 0.52 | 61.82 |
| CR (%) | 1.55 | –0.31 | –1.35 | 13.17 | 16.13 | 7.70 | 4.96 | 13.57 | 5.18 |
| AAGR | 0.38% | –0.08% | –0.34% | 3.14% | 3.81% | 1.87% | 1.22% | 3.23% | 1.27% |
| 2000 – 2005 | | | | | | | | | |
| C | 52.95 | 63.60 | –8.63 | 151.09 | 110.42 | 40.67 | 2.77 | –0.19 | 261.59 |
| CR (%) | 7.82 | 55.20 | –95.16 | 34.55 | 37.90 | 27.86 | 23.06 | –4.34 | 20.84 |
| AAGR | 1.52% | 9.19% | –45.42% | 6.11% | 6.64% | 5.04% | 4.24% | –0.88% | 3.86% |
| 2005 – 2010 | | | | | | | | | |
| C | 130.48 | 57.67 | –0.43 | 93.42 | 43.95 | 49.46 | 4.31 | –1.95 | 283.50 |
| CR (%) | 17.87 | 32.25 | –99.04 | 15.88 | 10.94 | 26.50 | 29.12 | –46.50 | 18.69 |
| AAGR | 3.34% | 5.75% | –60.52% | 2.99% | 2.10% | 4.81% | 5.24% | –11.76% | 3.49% |
| 2010 – 2015 | | | | | | | | | |
| C | 175.60 | 12.35 | 0.00 | 89.73 | 76.18 | 13.55 | 6.49 | –0.16 | 284.00 |
| CR (%) | 26.68 | 5.22 | –0.57 | 13.16 | 17.09 | 5.74 | 33.97 | –7.10 | 15.78 |
| AAGR | 3.78% | 1.02% | –0.11% | 2.50% | 3.21% | 1.12% | 6.02% | –1.46% | 2.97% |
| 2015 – 2018 | | | | | | | | | |
| C | 50.78 | 18.80 | 0.00 | 46.63 | 27.63 | 19.01 | 2.69 | –0.07 | 118.83 |
| CR (%) | 4.90 | 7.55 | 0.99 | 6.04 | 5.29 | 7.61 | 10.50 | –3.31 | 5.70 |
| AAGR | 1.61% | 2.46% | 0.33% | 1.98% | 1.73% | 2.48% | 3.38% | –1.12% | 1.87% |
| 1996 – 2018 | | | | | | | | | |
| C | 420.13 | 152.07 | –9.19 | 431.76 | 298.63 | 133.13 | 16.82 | –1.84 | 1009.75 |
| CR (%) | 63.01 | 131.58 | –99.95 | 111.74 | 119.04 | 98.22 | 146.88 | –47.79 | 84.62 |
| AAGR | 2.25% | 3.89% | –29.48% | 3.47% | 3.63% | 3.16% | 4.19% | –2.91% | 2.83% |

Abbreviations: ESV: Ecosystem services value (×108 yuan); P: Percentage (%); C: Change (×108 yuan); CR: Change ratio (%); AAGR: Average annual growth rate (%/a).

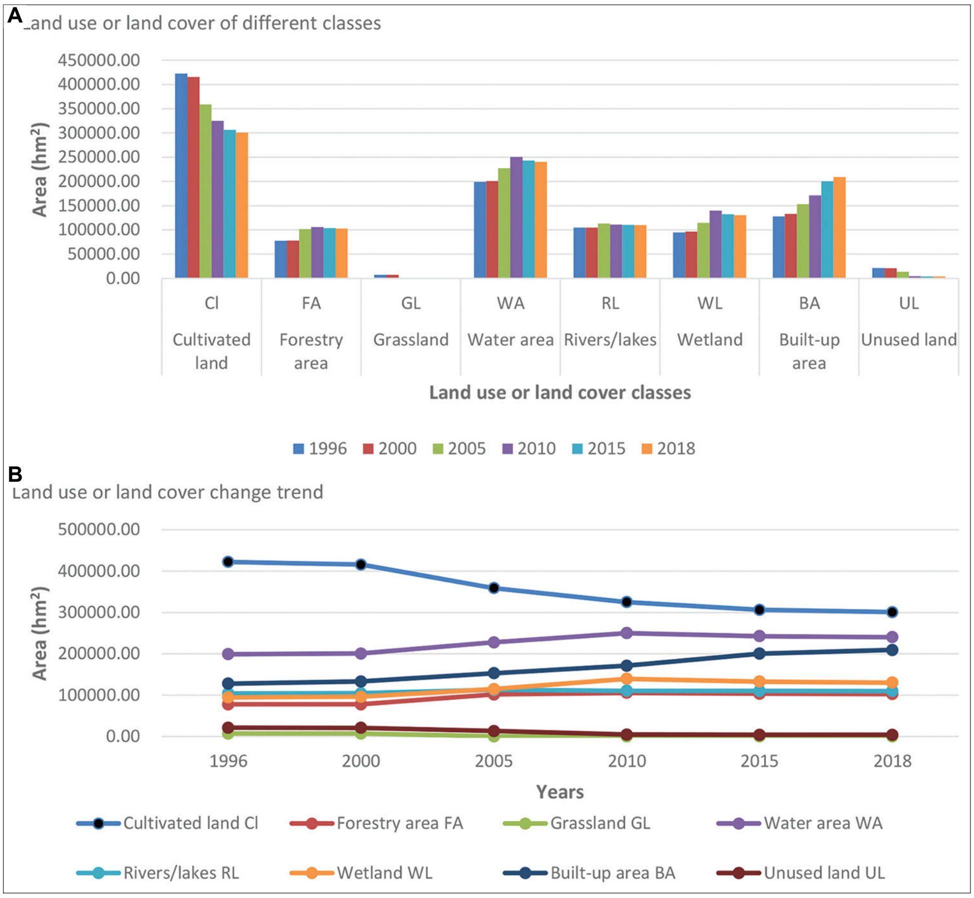


**Figure 3.** Land use or land cover area of different classes (A) and change trend (B). Source: Bar chart and line graph by the authors

(1996 – 2018) periods. The increase of total ESV in the first period was about 6.18 billion yuan with an average annual growth rate of 1.27%. The total ESV increased further, amounting to 26.16 billion yuan, 28.35 billion yuan, 28.40 billion yuan in 2005, 2010, and 2015 over the second, third, and fourth periods, respectively, with average annual growth rates of 3.86%, 3.49%, and 2.97%. Then, although the total ESV continued to increase, the number of growths amounted to 11.88 billion yuan with a relatively low average annual growth rate of 1.87%. There was a slight increase during 1996 – 2000 period and then a sharp increase during 2000 – 2015 period, but the growth rate finally slowed down during 2015 – 2018 period. Thus, the process can be divided into three phases: first increasing slowly, then accelerating, and finally slowing down again (Figure 4).

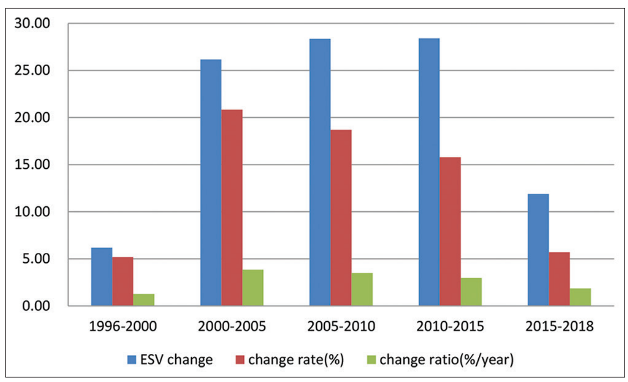


**Figure 4.** The change in total ecosystem service values in different periods. Source: Bar chart by the authors

### *3.2.2. Changes in ESV of different ecosystem services*

In 1996, the ESV for Wuhan was 119.32 billion yuan (Table 4), with about half of the value (55.88%) comprised by cultivated land. Water bodies contributed 32.38% to the total ESV, among which rivers/lakes and wetland contributed 21.02% and 11.36% of the total ESV, respectively. Forestry area accounted for 9.69%. Built-up area, grassland, and unused land accounted for less than 1%, just 0.96%, 0.77%, and 0.32% of the total ESV, respectively (Figure 5).

From 1996 to 2018, cultivated land was the major contributor to ecosystem services with about half (55.88%

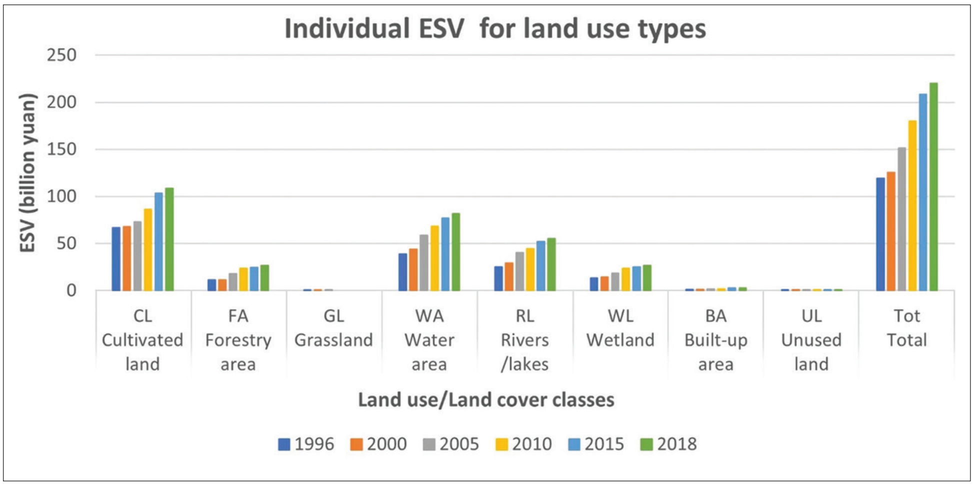


**Figure 5.** The change of ESV in different land use types. Source: Bar chart by the authors.
Abbreviation: ESV: Ecosystem services value

in 1996 to 49.34% in 2018) over the entire period among the seven land use types in Wuhan, as it covered the largest area. Next, the most valuable land use was water area (32.38% in 1996 to 37.14% in 2018), including rivers/lakes (21.02% in 1996 to 24.94% in 2018) and wetlands (11.36% in 1996 to 12.20% in 2018). The forestry area contributed about 10%. Cultivated land, water area, and forestry area accounted for the bulk of the ESV from 97.97% in 1996 to 98.67% in 2018. Other three land use types accounted for 2.05% in 1996 to 1.33% in 2018. The changes indicated that these three land use types (cultivated land, water area, and forestry area) played a key role in ecosystem services, especially cultivated land, and water area.

Grassland and unused land showed the lowest proportion because of their small area comparison and improved land utilization rate. The ESV of grassland and unused land showed the lowest proportion and had almost been in decline since 1996 due to the small area proportion and the decrease of the two land use types, with especially the ESV of grassland declining to near zero. Although the ESV of built-up land is also small, it rose slightly because the total area of built-up land increased and green space rate improved. Though the ESV of grassland and unused land had decreased, such a decrease was too small to counterbalance the increase of other land use types. The ESV of cultivated land, water area (rivers/lakes and wetland) continued increasing during the corresponding period, rising from 66.74 billion yuan to 1086.87 billion yuan, 250.87 billion yuan to 549.50 billion yuan, and 135.55 billion yuan to 268.67 billion yuan, respectively, despite that forestry area covered small area but water area occupied the second largest proportion with the highest value coefficients. Cultivated land also produced high service value due to its large area coverage.

#### *3.2.3. Changes in ESV of ecosystem function*

Table 5, Figures 6 and 7 show the ESV and the changes in ecosystem functions from 1996 to 2018. In general, regulation service contributed most to the ESV, accounting for more than half of the ESV (from 61.93% in 1996 to 55.49% in 2018). The value of cultural service was the lowest, accounting for less than 8% of the total in 1996, while the ESV of cultural service increased more rapidly than any other ecosystem service with average annual growth rate of 29.14% during the study period, followed by provision (6.53%) and regulation service (2.31%), but only supporting service decreased by 1.23%.

In sub-functions, all ESV of provision and cultural services increased rapidly, especially aesthetic landscape and agricultural production, 17.04 billion and 39.15 billion, with the maximum average annual growth rate of 29.14% and the second largest average annual growth rate of 6.94%, respectively. In contrast, almost all regulation and supporting services decreased, except for hydrological regulation and gas regulation (15.29 billion and 46.56 billion), with average annual growth rate of 4.31% and 1.75%, respectively.

Hydrological regulation always accounts for the largest proportion of ESV (from 25.92% in 1996 to 35.50% in 2018), indicating the importance of hydrology to the ecosystem in Wuhan. It is followed by agricultural production (from 9.71% in 1996 to 23.03% in 2018) and gas regulation (from 14.55% in 1996 to 11.55% in 2018).

## 4. Discussion

### 4.1. Comparison with ESV changes in other studies

According to Costanza *et al.* (1997; 2014), global terrestrial ESV declined by 28.82% due to land use change from 1997

**Table 5. Total ESV of different functions in Wuhan from 1996 to 2018**

| Ecosystem service functions | Provision | | | Regulation | | | | | Supporting | | | | Culture | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | AP | WS | $S_{total}$ | GR | CR | EP | HR | $S_{total}$ | SR | NC | BC | $S_{total}$ | AL | |
| ESV | | | | | | | | | | | | | | |
| 1996 | 115.85 | 26.33 | 142.18 | 173.64 | 251.21 | 4.81 | 309.28 | 738.94 | 233.01 | 1.23 | 77.24 | 311.48 | 0.62 | 1193.21 |
| 2000 | 146.76 | 34.77 | 181.53 | 174.62 | 248.37 | 4.76 | 364.47 | 792.23 | 202.90 | 0.88 | 76.50 | 280.29 | 0.98 | 1255.03 |
| 2005 | 187.63 | 53.70 | 241.33 | 186.53 | 237.93 | 5.57 | 545.68 | 975.71 | 210.02 | 1.02 | 77.14 | 288.19 | 11.40 | 1516.63 |
| 2010 | 249.83 | 52.18 | 302.01 | 217.37 | 232.29 | 4.96 | 724.99 | 1179.61 | 223.41 | 0.93 | 68.51 | 292.86 | 25.66 | 1800.13 |
| 2015 | 487.69 | 69.38 | 557.07 | 242.68 | 194.88 | 4.21 | 783.00 | 1224.77 | 173.04 | 0.72 | 58.05 | 231.81 | 70.48 | 2084.13 |
| 2018 | 507.40 | 64.67 | 572.07 | 254.48 | 181.91 | 3.94 | 782.16 | 1222.48 | 182.30 | 0.72 | 54.34 | 237.36 | 171.05 | 2202.96 |
| P | | | | | | | | | | | | | | |
| 1996 | 9.71 | 2.21 | 11.92 | 14.55 | 21.05 | 0.40 | 25.92 | 61.93 | 19.53 | 0.10 | 6.47 | 26.10 | 0.05 | 100.00 |
| 2000 | 11.69 | 2.77 | 14.46 | 13.91 | 19.79 | 0.38 | 29.04 | 63.12 | 16.17 | 0.07 | 6.10 | 22.33 | 0.08 | 100.00 |
| 2005 | 12.37 | 3.54 | 15.91 | 12.30 | 15.69 | 0.37 | 35.98 | 64.33 | 13.85 | 0.07 | 5.09 | 19.00 | 0.75 | 100.00 |
| 2010 | 13.88 | 2.90 | 16.78 | 12.08 | 12.90 | 0.28 | 40.27 | 65.53 | 12.41 | 0.05 | 3.81 | 16.27 | 1.43 | 100.00 |
| 2015 | 23.40 | 3.33 | 26.73 | 11.64 | 9.35 | 0.20 | 37.57 | 58.77 | 8.30 | 0.03 | 2.79 | 11.12 | 3.38 | 100.00 |
| 2018 | 23.03 | 2.94 | 25.97 | 11.55 | 8.26 | 0.18 | 35.50 | 55.49 | 8.28 | 0.03 | 2.47 | 10.77 | 7.76 | 100.00 |
| VC | | | | | | | | | | | | | | |
| 1996 – 2000 | 30.91 | 8.44 | 39.35 | 0.98 | −2.84 | −0.05 | 55.19 | 53.28 | −30.10 | −0.35 | −0.74 | −31.19 | 0.37 | 61.82 |
| 2000 – 2005 | 40.87 | 18.92 | 59.79 | 11.91 | −10.43 | 0.80 | 181.20 | 183.49 | 7.12 | 0.14 | 0.64 | 7.90 | 10.42 | 261.59 |
| 2005 – 2010 | 62.20 | −1.52 | 60.68 | 30.84 | −5.64 | −0.61 | 179.31 | 203.90 | 13.39 | −0.10 | −8.63 | 4.67 | 14.26 | 283.50 |
| 2010 – 2015 | 237.86 | 17.20 | 255.06 | 25.31 | −37.41 | −0.75 | 58.01 | 45.16 | −50.37 | −0.21 | −10.46 | −61.04 | 44.82 | 284.00 |
| 2015 – 2018 | 19.71 | −4.71 | 15.00 | 11.79 | −12.96 | −0.27 | −0.85 | −2.29 | 9.26 | 0.00 | −3.71 | 5.54 | 100.57 | 118.83 |
| 1996 – 2008 | 391.55 | 38.34 | 429.89 | 80.84 | −69.29 | −0.88 | 472.88 | 483.54 | −50.70 | −0.51 | −22.90 | −74.12 | 170.43 | 1009.75 |
| CR | | | | | | | | | | | | | | |
| 1996 – 2000 | 26.68 | 32.07 | 27.68 | 0.57 | −1.13 | −1.04 | 17.85 | 7.21 | −12.92 | −28.08 | −0.96 | −10.01 | 59.78 | 5.18 |
| 2000 – 2005 | 27.85 | 54.42 | 32.94 | 6.82 | −4.20 | 16.89 | 49.72 | 23.16 | 3.51 | 15.85 | 0.84 | 2.82 | 1057.79 | 20.84 |
| 2005 – 2010 | 33.15 | −2.83 | 25.14 | 16.53 | −2.37 | −10.94 | 32.86 | 20.90 | 6.38 | −9.30 | −11.18 | 1.62 | 125.01 | 18.69 |
| 2010 – 2015 | 95.21 | 32.97 | 84.46 | 11.64 | −16.11 | −15.07 | 8.00 | 3.83 | −22.55 | −22.31 | −15.27 | −20.84 | 174.68 | 15.78 |
| 2015 – 2018 | 4.04 | −6.78 | 2.69 | 4.86 | −6.65 | −6.51 | −0.11 | −0.19 | 5.35 | −0.56 | −6.39 | 2.39 | 142.70 | 5.70 |
| 1996 – 2008 | 337.98 | 145.62 | 302.36 | 46.56 | −27.58 | −18.20 | 152.90 | 65.44 | −21.76 | −41.62 | −29.65 | −23.80 | 27649.9 | 84.62 |
| AAGR | | | | | | | | | | | | | | |
| 1996 – 2000 | 6.09 | 7.20 | 6.30 | 0.14 | −0.28 | −0.26 | 4.19 | 1.76 | −3.40 | −7.91 | −0.24 | −2.60 | 12.43 | 1.27 |
| 2000 – 2005 | 5.04 | 9.08 | 5.86 | 1.33 | −0.85 | 3.17 | 8.41 | 4.25 | 0.69 | 2.99 | 0.17 | 0.56 | 63.20 | 3.86 |
| 2005 – 2010 | 5.89 | −0.57 | 4.59 | 3.11 | −0.48 | −2.29 | 5.85 | 3.87 | 1.24 | −1.93 | −2.34 | 0.32 | 17.61 | 3.49 |
| 2010 – 2015 | 14.31 | 5.86 | 13.03 | 2.23 | −3.45 | −3.21 | 1.55 | 0.75 | −4.98 | −4.92 | −3.26 | −4.57 | 22.40 | 2.97 |
| 2015 – 2018 | 1.33 | −2.31 | 0.89 | 1.59 | −2.27 | −2.22 | −0.04 | −0.06 | 1.75 | −0.19 | −2.18 | 0.79 | 34.39 | 1.87 |
| 1996 – 2008 | 6.94 | 4.17 | 6.53 | 1.75 | −1.46 | −0.91 | 4.31 | 2.31 | −1.11 | −2.42 | −1.59 | −1.23 | 29.14 | 2.83 |

Abbreviations: AP: Agricultural production; WS: Water supply; GR: Gas regulation; CR: Climate regulation; EP: Environmental purification; HR: Hydrological regulation; SR: Soil retention; NC: Nutrient cycling; BC: Biodiversity conservation; AL: Aesthetic landscape; $S_{total}$: Subtotal; ESV: ESV ($\times 10^8$ yuan); VC: Value change ($\times 10^8$ yuan); P: Proportion (%); CR: Change ratio (%); AAGR: Average annual growth rate (%/a).

to 2011 (−2.06%/year). There are two different views about the ESV in China. According to Wei & Deng (2017), the terrestrial ESV in China decreased 0.55% by $0.42 billion from 1988 to 2008 (−0.028%/year) even if Wei & Deng (2017) adopted the same unit values as Costanza *et al.* Thus, Wei & Deng (2017) thought that the ESV change in China was more modest than those globally. While Ouyang *et al.* (2016) analyzed the China Ecosystem Assessment (CEA) launched by China's Ministry of Environmental Protection and Chinese Academy of Sciences in 2012 and

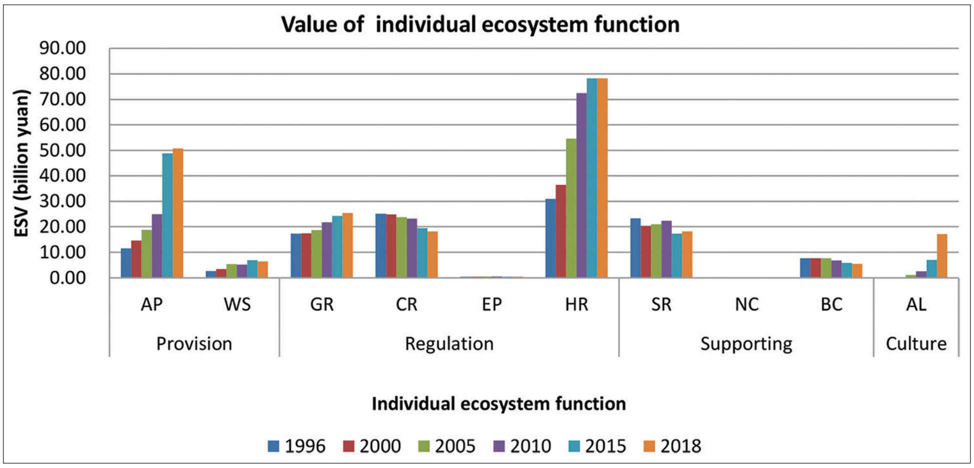


**Figure 6.** The ESV of different ecosystem function. Source: Bar chart by the authors
Abbreviations: ESV: Ecosystem service value; AP: Agricultural production; WS: Water supply; GR: Gas regulation; CR: Climate regulation; EP: Environmental purification; HR: Hydrological regulation; SR: Soil retention; NC: Nutrient cycling; BC: Biodiversity conservation; AL: Aesthetic landscape.

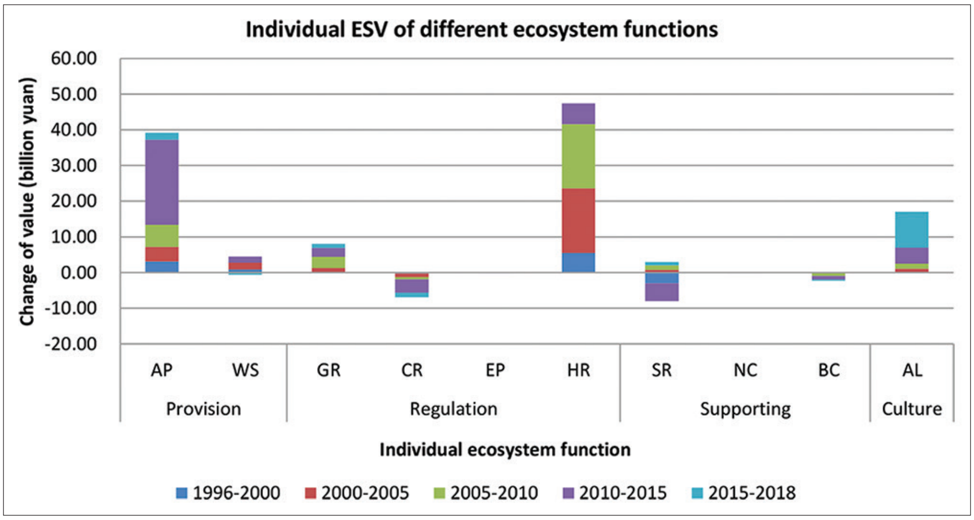


**Figure 7.** The change of ESV in different ecosystem functions. Source: Bar chart by the authors
Abbreviations: ESV: Ecosystem service value; AP: Agricultural production; WS: Water supply; GR: Gas regulation; CR: Climate regulation; EP: Environmental purification; HR: Hydrological regulation; SR: Soil retention; NC: Nutrient cycling; BC: Biodiversity conservation; AL: Esthetic landscape.

concluded in accordance to InVEST and other biophysical models that the ESV in China increased between 2000 and 2010 (Ouyang *et al.*, 2016). Therefore, on the national scale, although there were increases and decreases in the ESV in China according to the research by different scholars, the degree of change was relatively small. Many studies on the impact of land use change on ESV, which had been carried out in different areas and cities in China, produced many research results. Some studies point out that land use change caused by the natural environment and human activities would lead to the loss of ESV, while others indicated an increase (Ye *et al.*, 2018). This finding indicated the existence of large spatial heterogeneity in ESV.

Our study revealed that the ESV of Wuhan increased from 119.32 billion yuan in 1996 to 220.30 billion yuan in 2018, showing an overall upward trend. For the trend of change, the results in this study are consistent with some related research results, such as those by Liu & Yang (2021) and Zhang *et al.* (2018). However, there are also a few studies that are inconsistent with the results of the present study (Chen *et al.*, 2021), showing a decreasing trend in the value of ecosystem services. The reasons for this difference are that the data used were different, and the research methods were also different. Most studies have shown that with the increase of forestry area and water area, the ESV in Wuhan had increased to varying degrees.

### 4.2. Impact on ecosystem services of land use change

Globally, the slump in ESV can be mainly attributed to the declines in areas of high ESV per unit area of land, such as forestry area and wetlands. With the fast economic development and speedy urbanization in China, the decline in areas of forest, farmland, and grassland due to human activity, such as overgrazing and deforestation, has led to the loss of ESV in some areas of China (Sun *et al.*, 2016). Due to the geographical characteristics of the city of Wuhan, the influences of change in land use had been different. Although the ESV of built-up land increased and that of cultivated land declined, the total ESV in Wuhan increased.

The first reason is that many areas have been converted to forestry and wetland, and the per unit area values of these two land types are the highest, much higher than that of cultivated land. Thus, the forestry area and water area increased by 32.21% and 20.72% from 1996 to 2018; in turn, the ESV of these two land use types increased by 131.58% and 111.74%, respectively. These land transformations are mainly attributed to the project of ecological protection (the "Returning Farmland to Lake" in the middle reaches of the Yangtze River since 1998 and the "Grain for Green" since 1999).

The increase of ESV in Wuhan reflected the effects of ecological protection to some extent in China. Ecological protection has been practiced in China since the turn of the 21st century (Wang & Yang, 2021; Sun *et al.*, 2016). The Yangtze River Basin had been hit in 1998 by the worst flooding in half a century due to deforestation and erosion, causing enormous life and economic losses, especially in Wuhan, the central city in the middle reaches of the Yangtze River. This disaster stimulated the emergence of the largest government-sponsored ecosystem services programs in the world in 1999: the Grain for Green (GFG) and the Returning Farmland to Lake (RFL). By 2018, the GFG had been implemented nationwide and the RFL had been practiced in the middle reaches of the Yangtze River. Being the largest city in the region, Wuhan was regarded as a key pilot city of RFL. Thus, the wetland increased substantially by 37.71%, contributing to a big increase in ESV with the highest per unit area value.

The second reason is the increase in output value per unit area from the adjustment of the agricultural industrial structure. Although cultivated land loss caused by urbanization usually led to a total ESV (Deng *et al.*, 2016; Jin *et al.*, 2015; Collard & Zammit, 2015; Kong, 2014), agricultural technological advances and agricultural industrialization structure change had become the main force to promote the growth of agriculture and agricultural production (Cao & Nie, 2021; Xiang & Mao, 2016). Thus, although the area of cultivated land decreased by 28.73%, the ESV of which increased by 63.01%. The growing population and the improvement of living standards created higher demands for agricultural production. The decreasing cultivated land posed a huge threat to agricultural production. Under these pressures, the municipal government of Wuhan turned their attention to adjusting the agricultural structure (Zhang, 2012). The urban agriculture theory and practice were put forward. Agriculture in Wuhan had transformed from traditional suburban agriculture to modern urban agriculture, including facility agriculture, processing agriculture, leisure agriculture, and rural tourism, and gradually formed pillar industries that encompass vegetables, aquatic products, trees, and flowers. With the increase in income, people's demand for spiritual culture became higher and higher. During the study, agricultural values and rural tourism income increased significantly, leading to the increase of the ESV of provision and culture.

### 4.3. Limitations

There are different methods to estimate the ESV, but they basically involve the multiplication of the land use area of the corresponding biome by the unit values directly and indirectly. So, the accuracy and reliability of the results of ESV depend on two aspects: the accuracy of the land use area, and the accuracy of the value of unit area. Land use is regarded as one of the most important factors of ecosystem services and has been used as a proxy through matching land use patterns with the ecosystem. The accuracy of historical land use data provides an important base for the evaluation of ESV. Most studies in China adopted the land use data collected from the Chinese Academy of Sciences, which were obtained with a man-machine interactive interpretation technique based on remote sensing images of lands. However, field surveys were rarely conducted to such data because of time and budget constraints. In this study, land use data were collected from government departments in charge of land resources, which combined several years of field survey and remote sensing image recognition, so they were the most authoritative and accurate land use data in China.

Although the accuracy of land use area was improved, the accuracy of unit area value was still a problem to be solved. In the market valuation method, the material parameters and the material are important, which directly affect the accuracy of ESV. The value of provision and cultural services can be measured using market value, which can be obtained from the local statistical yearbook. However, regulation and supporting services are not marketed goods and services, but public goods or common pool resources, thus direct market valuation methods are often not the best assessment method, and substitutable market method must be used. Although the price information at different stages were collected and corrected with the Consumer Price Index (CPI) to improve the comparability of prices, the historical material parameters were hardly accurate due to the large number of evaluation indicators, especially its historical dynamic change indicators; therefore, constant average condition of material parameters were adopted. Such constant average material parameters would affect the accuracy and precision of ESV over time. Compared with the benefit transfer method criticized due to the validity and accuracy (Plummer, 2009), market valuation method assesses ESV in each area directly, but further accurate analysis is necessary, and the use of various technologies and resources will be required.

## 5. Conclusions

In this study, we adopted a detailed estimation of ESV in the response of land use change in Wuhan, a big city in central China. Based on the land use data, socioeconomic data, and natural resources data, the ESVs during the 22 years from 1996 to 2018 were evaluated from the perspectives of urban ecology. The main conclusions are as follows:

(i). The land use changed substantially from 1996 to 2018. Although the built-up area expanded significantly (63.52% in 1996 – 2018), and the cultivated land continued to decrease significantly (28.73% in the period 1996 – 2018) due to economic development and rapid urbanization, forestry area, and water area increased by 32.21% and 20.72%, respectively, at the same time.

(ii). The ESV maintained an increasing trend throughout the study period, with average annual growth rate of 1.27% (from 1996 to 2000), 3.86% (from 2000 to 2005), 3.49% (from 2005 to 2010), 2.97% (from 2010 to 2015), and 1.87% (from 2015 to 2018).

(iii). Although the total ESV continued to rise during the study, the development direction of the internal structure had undergone further changes. Direct use value, which directly generates economic value including provision and cultural services, increased significantly, up by 21.77% (from 11.97% in 1996 to 33.73% in 2018), with an average annual growth rate of 6.53% and 29.14%, respectively. Meanwhile, indirect use value, which had no direct economic value including regulation and supporting services, continued to decline (from 88.03% in 1996 to 66.27% in 2018) with an average annual change rate of −1.45% and −1.23%, respectively, except for hydrological regulation and gas regulation.

In this study, we evaluated the ESV based on the national land survey data whose resolution ratio is better than 2.5 m, which is conducive to the accuracy of land use classification and valuation. The unit value-based approach was often used in previous works that evaluated the ESV of Wuhan, whereas the primary data-based approach was applied and many dense new parameters were adopted in the present study, which provide reference for subsequent research.

Although urbanization had caused the increase of built-up area and the massive loss of cultivated land, the total ESV in Wuhan showed an increasing trend due to the combined effects of rapid economic development and ecological protection policies implementation. Thus, it is necessary to implement ecological protection policies for sustainable development. However, the different stages of urbanization and the potential of ecological protection measures have different influences on the ESV, which should be further studied in future research, especially in highly dispersed, heterogeneous, and complex urban areas.

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## Conflict of interest

The authors declare they have no competing interests.

## Author contributions

*Conceptualization:* Yunhua Lin, Donghoon Lee
*Investigation:* Yunhua Lin
*Visualization:* Yunhua Lin
*Writing – original draft:* Yunhua Lin
*Writing – review & editing:* Yunhua Lin, Donghoon Lee

## Ethics approval and consent to participate

Not applicable.

## Consent for publication

Not applicable.

## Availability of data

Not applicable.

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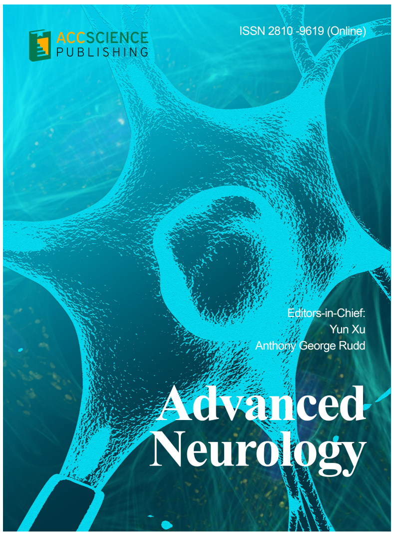


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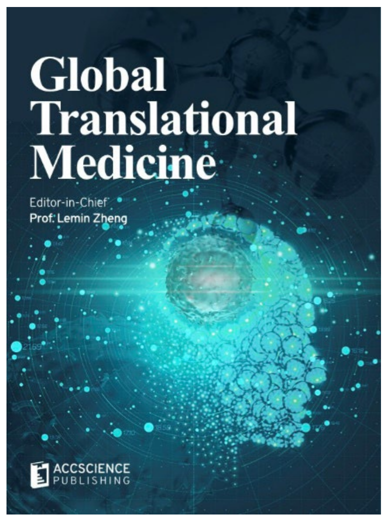


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