3 Climate and Environment in Prehistoric Yunnan

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3.1 Modern Yunnan Landforms, Vegetation and Climate

Yunnan is the furthest southwestern Chinese province within mainland China (N 21.9-29.15; E 97.39-106.12) **[fig. 11]**. It has an area of over 394,000 km^2, which equates to only 4.1% of modern Chinese territory, however, Yunnan has the highest natural biodiversity compared to all other provinces in the country. It is estimated that 49% of all native seed plant species present in China come from Yunnan (14,822 out of 30,270, of which many are endemic to Yunnan; Tang 2015, 30).[1] Yunnan is also considered one of the most diverse places globally (it is included in the 25 biodiversity hotspots outlined in Myers et al. 2000; see also Walkers 1986). The reason for this richness and diversity is closely related to its peculiarly rugged topography **[fig. 12]**. Sitting at the eastern end of the Himalayas and the southeastern corner of the Tibetan Plateau, Yunnan Province is enclosed by the Hengduan Mt. range (*Hengduan shanmai* 横断山脉) on the northwest (N 22-32.05; E 97-103),[2] which highest peak, Gonggashan 贡嘎山 (situated in Sichuan), reaches 7,556 m asl. The highest Yunnan peak of the Hengduan

1 Cf. Wu 1977-2006; Zhongguo 1998; López-Pujol, Zhang, Ge 2006.

2 The Hengduan Mt. are a series of ranges that go parallelly north-south across the border where Tibet, Sichuan and Yunnan provinces meet (extending into Qinghai). They represent the eastern-southernmost section of the Himalayas. The Chinese name means ‘traverse cutting mountains’, perfectly describing the crossed intersected direction of the Hengduan Mt. ranges against the usual east-west direction of mountain ranges in Eastern Asia.

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belongs to the Meili Snow Mt. range (*Meili xueshan* 梅里雪山) and is known as Kawagebo/Kawagarbo Mt. (also spelled Khawa Karpo, *Kawagebo shan* 卡瓦格博山) with 6,740 m asl. The Hengduan end on the Jade Dragon Snow Mt. massif (*Yulong xueshan* 玉龙雪山), which highest peak is at 5,596 m asl.[3] In eastern Yunnan, the Yungui Plateau sits east of the Ailao Mt. range (*Ailao shan* 哀牢山; N 23.49, E 101.33); the Yungui Plateau itself has an average altitude comprised between 1,500-3,000 m asl, but its highest peak is Jiaozi Snow Mt. (*Jiaozi xueshan* 轿子雪山) at 4,344 m asl, situated within the Gongwang Mt. range (*Gongwang shan* 拱王山) of the Plateau. The highest peak of the Ailao Mt. range is Damoyan Mt. (*Damoyan shan* 大磨岩山) with 3,166 m asl. Mountains and highlands constitute the majority of Yunnan territory (94%), with average altitudes decreasing progressively as one descend north to south, from over 6,000 m asl at the Meili Mt. in the Hengduan, to only 76.4 m asl at the intersection of the Nanxi River (*Nanxihe* 南溪河) with the Red River (*Honghe* 红河), in Hekou County (*Hekou yaozu zizhixian* 河口瑶族自治县) at the border with Vietnam (Zhou 1985) **[fig. 12]**.

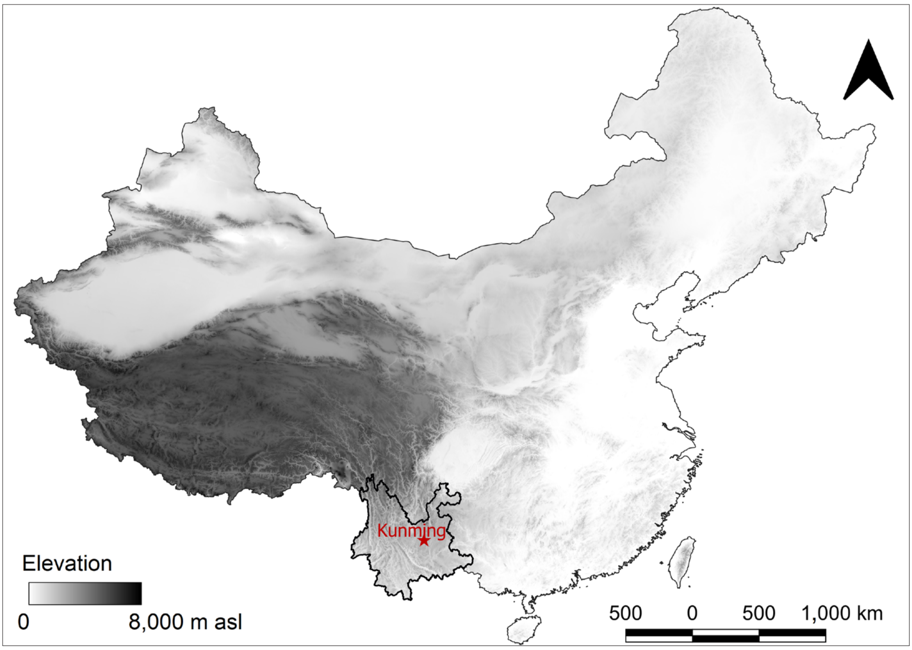

Figure 11 Location of Yunnan in relation to modern mainland China. Made by the Author with QGIS 3.28.5-Firenze, Natural Earth and EROS Center Digital Elevation basemap, U.S. Geological Survey

3 The highest peak of the Jade Dragon Massif is Shanzidou 扇子陡.

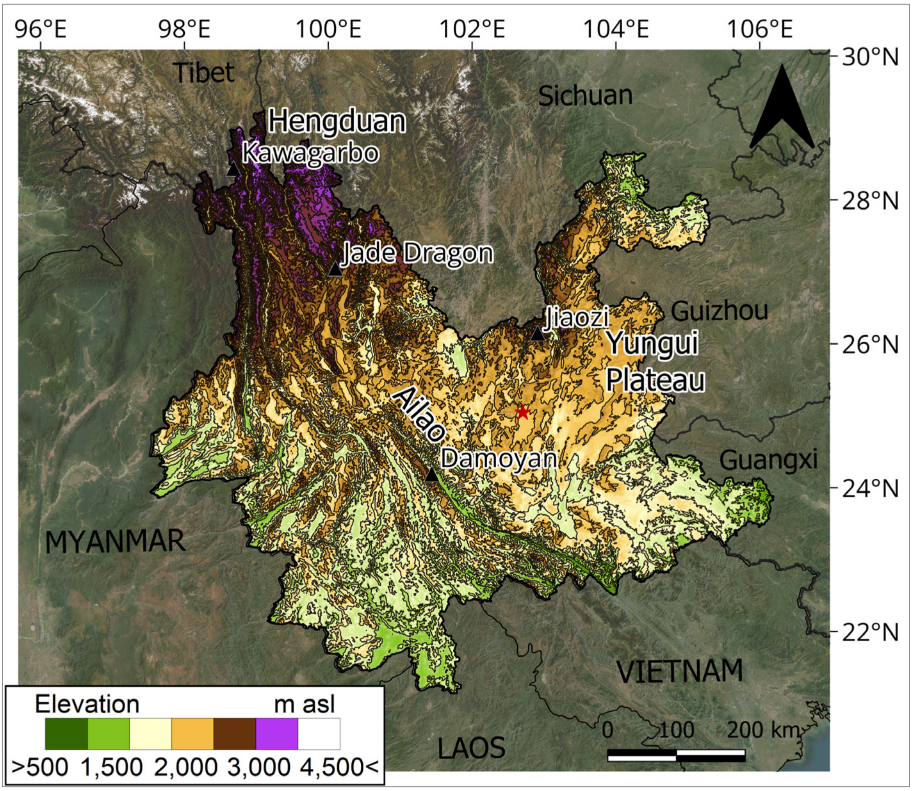

Figure 12 A topographic map of Yunnan showing altitudes lines at every 500 m. Peaks mentioned in text: Kawagarbo (6,740 m), Jade Dragon Snow Mt. (5,596 m), Jiaozi Snow Mt. (4,344 m), Damoyan (3,166 m). The red star indicates Kunming. Made by the Author with QGIS 3.28.5-Firenze, Natural Earth, ESRI and EROS Digital Elevation basemap, U.S. Geological Survey

Yunnan mountains are crisscrossed by a complex river network, which creates deep river valleys within the mountain ranges. Three major Asian rivers originate on the Tibetan Plateau and then run through the province; the Salween (*Nujiang* 怒江), Mekong (*Lancangjiang* 澜沧江), and the upper branch of the Yangzi (*Changjiang* 长江) known as *Jinshajiang* 金沙江 in Chinese. These run parallel at less than 100 km of distance to each other in northwest Yunnan, and for this reason this area is known as the Three Rivers area, or the three parallel rivers area from the Chinese *Sanjiang* 三江 (three rivers; see also § 2.2.1.1). The Red and Pearl (*Zhujiang* 珠江) Rivers originate in Yunnan and from there flow into Vietnam and Guangxi, respectively. In addition to rivers, numerous lakes (more than 40 recorded) provide plenty of water resources to the province, the largest one include the Dian Lake (*Dianchi* 滇池; 312 km^2), near Kunming and the Erhai 洱海 Lake (250 km^2), near Dali 大理 **[fig. 13]**.

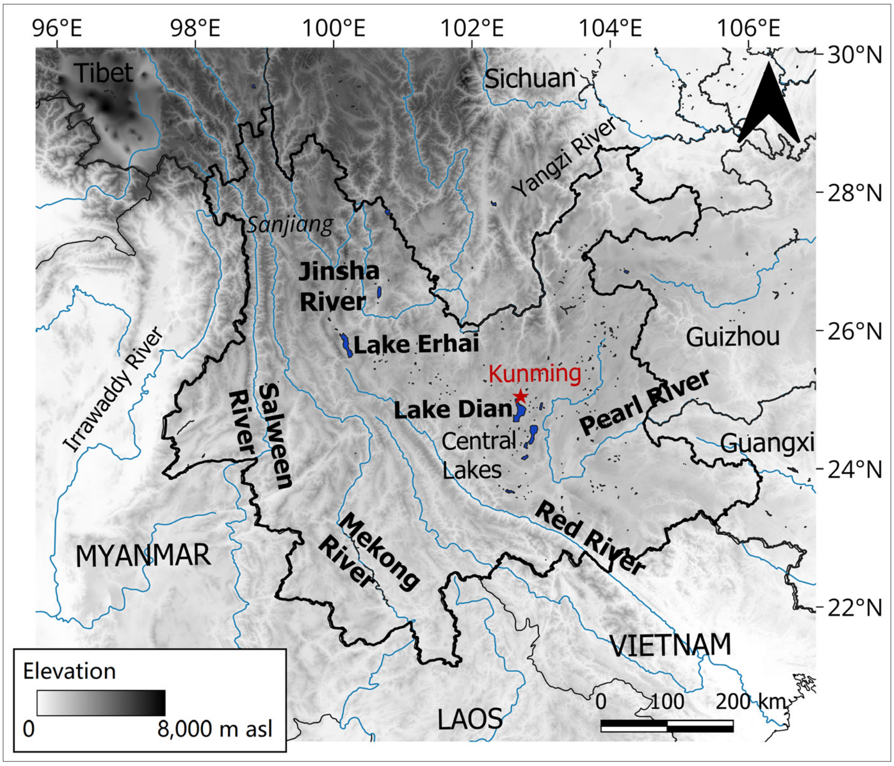

Figure 13 Main rivers and lakes in Yunnan. Made by author with QGIS 3.28.5 Firenze, Natural Earth Basemap

Ecologically, Yunnan sits between temperate East Asia and tropical Southeast Asia, acting *de facto* as a transitional belt between the two regions (Tang 2015). Modern Yunnan climate is humid, subtropical and tropical in the very far south (such as Xishuangbanna 西双版纳) **[figs 14-15]**. Today Yunnan is characterised by short, dry winters and long, warm and humid summers (Kottek et al. 2006). The Indian (or Southwest) Summer monsoon, the East Asian (of Pacific) Summer Monsoon, and the East Asian winter monsoon all reach into Yunnan and altogether create clearly demarcated wet and dry seasons and allow for a longer rainy season than that attested in the northern area of the East Asian continent. In Yunnan this is from May to October, when up to 90% of the annual precipitation occurs (Zhao 1994). However, the effects of the monsoons are also mitigated by the numerous mountain ranges in the province. In the northwest, the Hengduan Mt. range stops the cold Siberian winds during winter, allowing for milder temperatures year-round; the Ailao lessens the Indian Monsoon and creates a northwestern wet-southeastern dry divide in the province; this benefits interior areas by creating suitable conditions for truly subtropical climate and vegetation (Tang 2015). Annual precipitation varies greatly across the province, averaging 1,500 mm in the southern lowlands and around 600-800 in the northern highlands (see Tang 2015; Zhao 1986) **[fig. 14]**. Of note, river valleys today present a savanna-like vegetation and are generally drier than the rest of the province. Precipitation in the valleys varies between 600-900 mm annually, being higher in the south-central Yunnan, valleys here are hot-dry, and decreasing as we go north, where valleys are warm-dry, and temperate-dry at the limit with Tibet and Sichuan (Tang 2015, 166 fig. 6.1). Temperatures follow the altitudinal gradient, with around 10°C degrees difference in mean annual temperature north to south, but being generally mild year-round.[4] For example, in southern Yunnan the mean temperature in January is 12-16°C, and in July it is 22-26°C. **[fig. 15]**. Since Southwest China was never covered by unified ice sheets, many relict species have found refuge in this region, including presumed extinct in the wild *Ginkgo biloba* trees (Tang 2015).

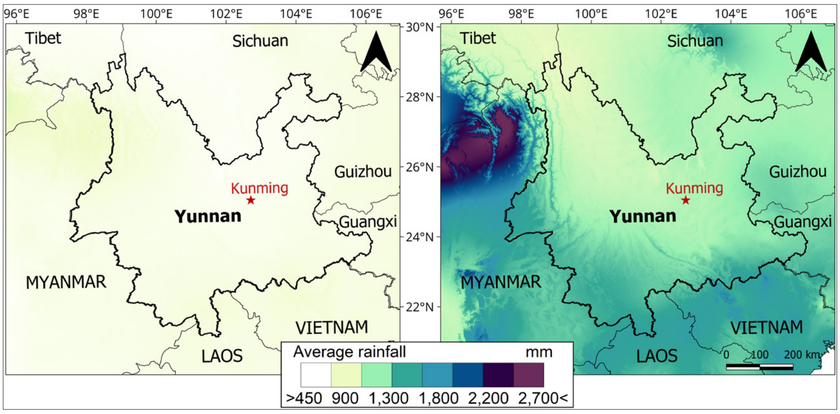

Figure 14 Modern (1970-2000) average precipitation in Yunnan, shown in cumulative value from November to April (dry season, left) and May to October (rainy season, right). Made by the Author with QGIS 3.28.5-Firenze, Natural Earth basemap; precipitation data from WorldClim v2 (Fick, Hijmans 2017)

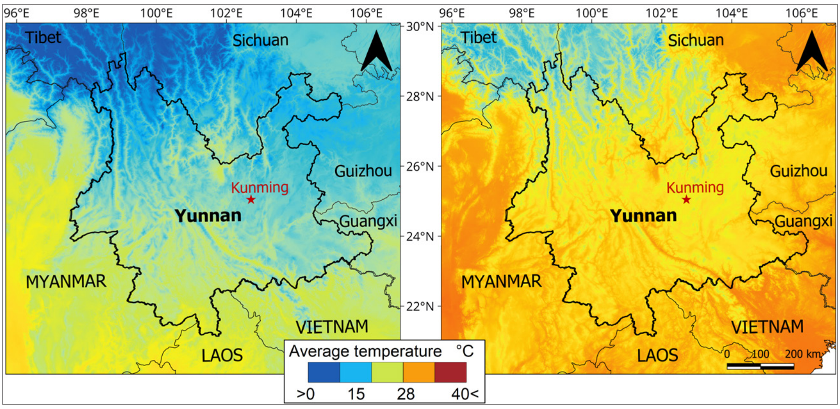

Figure 15 Modern (1970-2000) average temperatures in Yunnan in January (left) and July (right). Made by the Author with QGIS 3.28.5-Firenze, Natural Earth basemap; temperature data from WorldClim v2 (Fick, Hijmans 2017)

The Yunnan landscape is defined by a strong 'biogeographical vertical zonation' (Zhao 1986; Guo, Long 1998), indicating that climate and floristic vegetation patterns are strictly correlated to the elevation. Broadly speaking this means that Yunnan's vegetation can be divided into sequential belts

4 Kunming, the capital city of Yunnan, is in fact also known as the 'city of eternal spring' (*chuncheng* 春城). Here, January average temperature is 8-10°C, and in July it is 19-22°C.

according to the specific elevation, transitioning from alpine, subalpine, temperate, subtropical, and tropical belts. Above 4,500 m asl there is perennial snow, and alpine scrub meadows characterise elevations between 3,800-4,500 m asl. Below that, several forest regions are present according to elevation and area **[tab. 10]**.

Table 10 Original evergreen broad-leaved forest regions in Yunnan (after Tang 2015; Shen et al. 2006)

Forest Type	Dominant species	Altitudes	Annual rainfall	Distribution
Fir forest	*Abies forrestii* *Larix potaninii* *Pseudotsuga forestii* *Cephalotaxus fortune* *Taxus chinensis* *Taxus wallichiana* *Taiwania cryptomeriodoides* *Taiwania flousiana* *Pinus excelsa* *Tsuga yunnanensis* *Tsuga dumosa*	3,100-3,800 m asl	-	Northwest Yunnan
Mid-montane moist and mossy evergreen broad-leaved forest	*Cyclobalanopsis lamellosa* *Cyclobalanopsis oxyodon* *Cyclobalanopsis myrsinifolia* *Lithocarpus variolosus* *Lithocarpus hancei* *Lithocarpus pachyphyllus* *Lithocarpus xylocarpus* *Lithocarpus echinotholus* *Castanopsis echidnocarpa* *Castanopsis wattii* *Castanopsis remotidenticulata* Further species: *Machilus longipedicellata* *Machilus viridis* *Cinnamomum iners* *Phoebe faberi* *Schima khasiana* *Schima argentea* *Schima villosa* *Manglietia gongshanensis* *Manglietia insignis* *Alcimandra cathcartii*	(1,600) 1,800-2,500 (2,800) m asl	1,700-3,700 mm	All of the provinces apart from central Yunnan
Subtropical semi-humid evergreen broad-leaved forest	*Castanopsis orthacantha* *Cyclobalanopsis glaucoides* *Cyclobalanopsis delavayi* *Lithocarpus dealbatus*	(1,500) 1,900-2,400 m asl	1,100-1,700 mm	Central, south-central, eastern Yunnan

Forest Type	Dominant species	Altitudes	Annual rainfall	Distribution
Monsoon evergreen broad-leaved forest	*Castanopsis hystrix* *Castanopsis fleuryi* *Castanopsis calathiformis* *Lithocarpus truncatus* *Lithocarpus polystachyus* *Lithocarpus fenestratus* *Trigonobalanus doichangensis* *Cyclobalanopsis augustinii* *Cyclobalanopsis kerrii* *Cryptocarya calcicole* *Cryptocarya densiflora* *Beilschmiedia yunnanensis* *Schima wallichii* *Anneslea fragrans*	(800)1,000-1,800 m asl	>1,600 mm	Northwest, southern Yunnan
Montane mossy dwarf evergreen broad-leaved forest	Ericaceae Dwarf Fagaceae Vacciniaceae Rosaceae Aceraceae	Summits	-	Southern Yunnan
Tropical monsoon evergreen broad-leaved forest	*Hopea haimonensis* *Hopea mollissima* *Dypterocarpus tokinensis* *Dypterocarpus pilosus* *Myristica cagayanensis* *Myristica sinnarum*	800-1,000 m asl	900-1,200 mm	-

In addition to the species listed in the table, further species recorded include several dry-climate adapted sclerophyllous (hard-leaves) evergreen *Quercus* found at high altitudes[5] and in hot-dry valleys.

The whole province is generally described as originally having been covered by subtropical evergreen broad-leaved forest. Original[6] forests have decreased drastically in the last 90 years, due to the continuous expansion of cropland and pastures into Yunnan, and original species are now relegated in remote montane (alpine and subalpine) areas, natural reserves, temples, or generally inaccessible places. It is estimated that only 10% of modern Yunnan presents its original vegetation cover (Lin, Qiao, Walker 1986). Today there is a high documented presence of warm, temperate coniferous trees, including *Pinus* and *Ketelleria* species, which have substituted the original forests and are indicative of human disturbance of the landscape. At lower altitudes (>1,800 m asl), trees such as *Cunninghamia lanceolata, Cryptomeria japonica* var. *sinensis, Pinus yunnanensis, Pinus armandii, Alnus nepalensis* and *Eucalyptus smithii* are a strong indication of human disturbance to the original vegetation. Mixed conifer woodlands are also reported between 2,800-3,200 m asl, where *P. yunnanensis* is the most

5 For example, *Q. aquifolioides, Q. fimbriata, Q. guyavifolia* and *Q. monimotricha* are endemic to the Hengduan region (Tang 2015).

6 Here, 'original' vegetation refers to forest cover that stabilised at the beginning of the Holocene and created the basis of modern vegetation composition before any human intervention. For an overview of the development of Yunnan vegetation before the Pleistocene era, see Zhu, Tan 2022; Ding et al. 2020.

common species documented today. Strands of *Tsuga* are instead present in areas little impacted by human activity **[fig. 16]**.

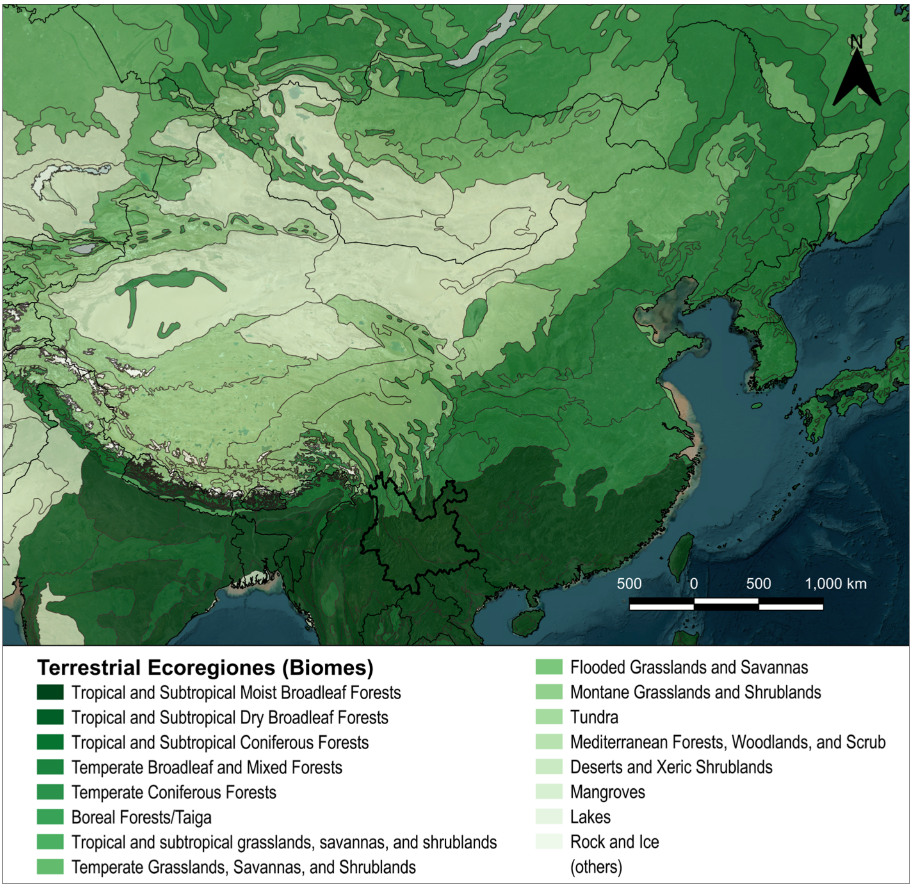

Figure 16 Modern biome regions in Yunnan seen in Asian context. Yunnan Province is highlighted in black. Ecoregions[7] as defined by the Terrestrial Ecoregions of the World (TEOW) map by the World Wildlife Fund (WWF; Olson et al. 2001). Made by the Author with QGIS 3.28.5-Firenze, ESRI and TEOW basemaps

7 According to TEOW categories, the subalpine conifer forests of the Hengduan Mt. and the alpine conifer and mixed forests of the Nujiang-Langcang Gorge belong to Biome 5 (temperate coniferous forests); the subtropical evergreen forests of Yunnan belong to Biome 1 (tropical and subtropical moist broadleaf forests). Full definitions are available at `https://www.worldwildlife.org/publications/terrestrial-ecoregions-of-the-world`.

3.2 Palaeoenvironmental Reconstruction of Ancient Yunnan Climate and Flora

Studies on pollen data retrieved from lake sediment cores in Yunnan have provided an almost uninterrupted record for the palaeoclimate of the province;[8] these, in conjunction with data from cave speleothems,[9] have allowed the reconstruction of climatic phases, including monsoon intensity, and vegetation cover during different earth geologic eras in Yunnan.

During the late Pleistocene (ca. 15000 to 10500 BCE), the Yunnan climate was generally colder than today, and the winter monsoon intensity was much stronger than that of the summer monsoon. Throughout the province, the dominant forest cover was composed of conifers, and many species that are now confined at higher altitudes were present at least 500 m below their current altitudinal limit. Climate and vegetation changes at the transition from the Pleistocene to the end of the Holocene climatic optimum transformed Yunnan from a subtropical dry/semi-dry forested region characterised by warm-rainy winter and hot-dry summer to a subtropical evergreen broad-leaved forested region with dry winters and rainy summer.

From about ten thousand years ago, after the transition to the Holocene, climate fluctuated and underwent almost five millennia of warm and wet climate, a period known as the climatic optimum, or Holocene thermal maximum. During this period, temperatures were higher by at least 2-3°C degrees, and it is estimated that precipitation was 20-40% higher than present-day. This caused an inversion of rain period seasonality compared to the previous period, winters became dry and summers rainy. The summer monsoon intensity reached its peak during this period. The increased precipitation is attested, for example, by increased water level at the Erhai Lake (Shen et al. 2006; Sun et al. 1986), and rainfall estimate reconstruction from lake sediment core pollen records from Xingyun and Qilu Lakes (Chen F.H. et al. 2014; Chen X.M. et al. 2014; Hillman et al. 2017), and Yilong Lake (Yuan et al. 2021). The warmer and wetter climate caused a retreat of the conifer forests to above 2,800 m asl, and an expansion of the evergreen broad-leaved forests, especially of *Cyclobalanopsis*, *Lithocarpus*, and *Castanopsis* species, including to the area north of present-day Dian Lake, near Kunming. Altitudinal differentiation and current vegetation belts and altitudinal limits for species became gradually defined. For example, between ca. 6000-4000 BCE, subtropical evergreen forests became dominant in the lowlands, and montane humid evergreen forests became prevalent in the highlands. Subtropical and tropical vegetation during the sixth to the third millennia BCE extended to north of the Yangzi Basin (Yu et al. 1998, 2000; Fuller, Qin 2010) **[fig. 17]**.

8 Walker 1986; Sun et al. 1986; Yu et al. 1990; Fang 1991; Brenner et al. 1991; Long et al. 1991; Hodell et al. 1999; Yu et al. 2000; Zheng et al. 2002; Yang. et al. 2005; Shen et al. 2005; 2006; Dearing et al. 2008; Jones et al. 2012; Chen X.M. et al. 2014; 2022; Chen F.H. et al. 2014; Hillman et al. 2017; 2021; Xiao et al. 2017; 2020; Zhang E. et al. 2017; Yuan et al. 2021; Zhao et al. 2021b; Wu D. et al. 2023.

9 For example, speleothems from Dongge cave, located ca. 750 km from Erhai Lake in northwestern Yunnan are particularly useful as proxy for Yunnan paleoclimate reconstruction (Dykoski et al. 2005). For a review of cave speleothem records from broader China see Zhang et al. 2011. More recently, leaf wax isotope studies have started to be undertaken and contribute to palaeoclimate reconstruction (e.g., Zhang et al. 2021a).

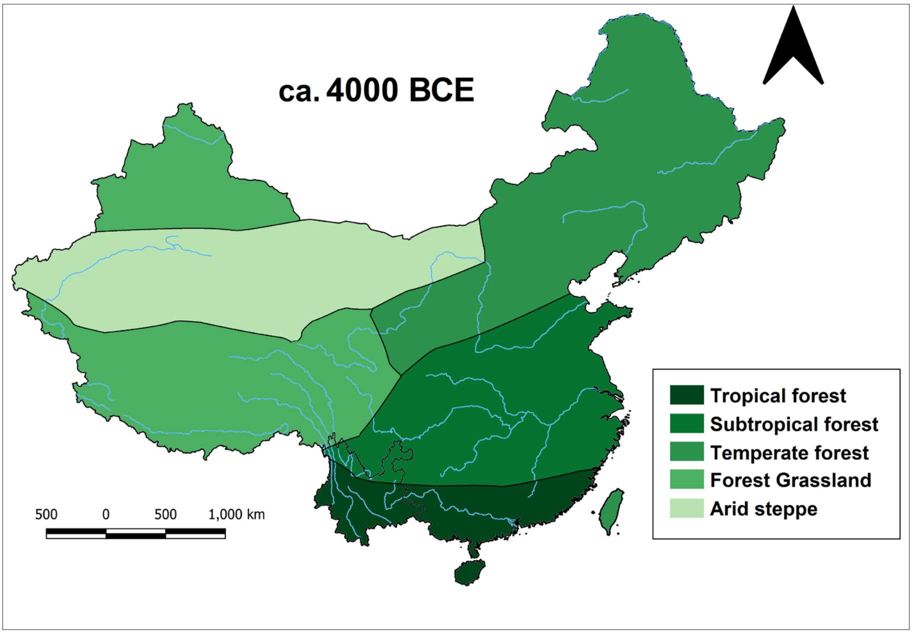

Figure 17 Map showing a schematic reconstruction of Chinese vegetation, dating to ca. 4000 BCE, with illustration of main rivers and modern Yunnan borders (redrawn from Li, Chen 2012, 31, fig. 2.4). Made by the Author with QGIS 3.28.5-Firenze, Natural Earth basemap

It has been suggested that this warmer and wetter climate greatly contributed to the expansion of Neolithic Cultures and especially provided suitable environmental conditions for the domestication of rice and millet during the sixth and fifth millennia BCE (Fuller, Qin 2010; see § 2.3). The similar tropical vegetation and environmental conditions present both where rice was domesticated and in Yunnan, would have not created a barrier for the crop spread to Southwest China at this time.

In Yunnan, the Holocene thermal maximum ended around the fourth millennium BCE. Since then until about the end of the first millennium BCE, the monsoon density decreased, and temperatures cooled; a possible sharp drop event is documented around 1500 BCE (Dykoski et al. 2005). This caused a decline of *Cyclobalanopsis*, *Castanopsis*, and *Tsuga* species and a retreat of the tropical forest to its modern limits (Shen et al. 2005). More generally it is in these millennia that current vegetation belts definitively stabilised (Wrinkler, Wang 1993). *Pinus*, Poaceae, Chenopodiaceae and *Artemisia* taxa show a drastic increase during these millennia, indicating a more open landscape. This could have been linked to an expansion of wetlands, shallow lake phases, or even clearing of the forest through fire (Shen et al. 2005; 2006; Cao et al. 2024). These species are also considered 'disturbance taxa', meaning they are indication of human activities and their impact on the vegetation. An increase in *Pinus* is usually interpreted as the result of forest clearance through fire and therefore possibly linked with removing the vegetation cover to bring in new land for agriculture (Dearing et al. 2008). This has led some authors to push back anthropogenic driven environmental change in northwest Yunnan to as early as ca. 5500 BCE, possibly even ca. 7000 BCE (Dearing et al. 2008). However, no archaeological evidence in support of this hypothesis has been uncovered yet.

Compositional analyses of lake sediments from Dian Lake have also shown that between the third millennium BCE and the first millennium CE lake levels fluctuated and were characterised by a series of frequent flood-shallow lake phases. This allowed human settlement of the lake shores and a more extensive exploitation of lacustrine resources during the Dian Kingdom (Yan, Wünnemann, Jiang 2020). Lake Fuxian, south from Dian Lake shows a thinning of the vegetation density after the third millennium BCE, with a big deforestation event in the mid-first millennium BCE, when forests were replaced by grasslands, wetlands and cultivated vegetation (Wang M. et al. 2024). In the same area, charcoal and pollen records indicate significant human impact on the natural vegetation only starting from the mid-first millennium BCE (Xiao et al. 2020; Hillman et al. 2021). Historical documents attest the development of intensive water irrigation systems in the Dian Basin from at least 16 CE (Yao et al. 2015). Some scholars have suggested that whereas temperature fluctuations in Yunnan during the early and mid-Holocene would have created unsuitable conditions for agriculture, the decreased humidity and retreat of the forest cover from fourth to first millennia BCE would have instead provided suitable conditions for the development of agricultural systems (Wu D. et al. 2023).