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Vegetation and climate of the Last Glacial Maximum in Sulawesi

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Abstract

Lake Towuti, a large lowland tectonic lake situated within the Indo-Pacific Warm Pool, is perfectly situated to evaluate how large-scale changes in climate have manifested themselves in the Asian tropics. High-resolution geochemical data serving as proxies of surface runoff and vegetation for the last 60,000 years suggest that the Last Glacial Maximum (LGM) was extremely dry, bracketed by the much wetter conditions of marine isotope stage 3 (MIS3) and the Holocene. Existing pollen-based records for Sulawesi also suggest that the LGM was drier than present; however, these records are short and discontinuous over this time period. A pollen record, still being refined for Lake Towuti, also shows a sudden and profound response in the vegetation over the LGM period; however, the expected increase in grassland, in line with the enriched $\delta^{13}C$ of terrestrial leaf wax in the geochemistry record, is not apparent. Instead, there is a loss of high-altitude taxa and the expansion of several lowland dicots that remain taxonomically unresolved. An expanded research program under the auspices of Towuti Drilling Program has begun to improve our insight and understanding of this globally important region, enabling a better assessment of the potential threats that projected climate change and human activities pose for one of the most diverse rainforest ecosystems on Earth. While numerous questions of fine detail remain concerning LGM climate and its impact on these tropical forests, in the context of this monograph, palaeoenvironmental research, and in particular the palaeovegetation record, provides an important environmental backdrop to trajectories of human occupation in Sulawesi and the subsequent cultural changes and interactions that took place across the region.

Keywords: Sulawesi, Lake Towuti, palaeovegetation record, pollen record, human environmental impacts

Introduction

The geographic position of Sulawesi, within the heart of the 'Maritime Continent' (Ramage 1968), is an important setting for exploring how the tropics have responded to global climate change. The Maritime Continent, also known as the Indo-Pacific Warm Pool, has the highest sea surface temperatures on earth and, as a consequence, is an area of deep atmospheric convection and a significant driver of the Earth's climate through its interactions with the El Niño-Southern Oscillation (ENSO), the Austral-Asian monsoons and the Intertropical Convergence Zone (ITCZ) (Cane 2005; Chiang 2009). Despite all this, we do not completely understand how the climate system in this region operates today, how it will respond to future change, nor what environmental conditions were like in the past (Meehl et al. 2007; Kumar et al. 2013). In addition, Sulawesi is recognised as a 'hotspot' of Southeast Asian biodiversity (Whitten et al. 1987; Cannon et al. 2009), yet we know very little about the modern vegetation of the island, how resilient it has been in the past and what threats future change may pose for its numerous species.

The region

The Last Glacial Maximum (LGM) is the most recent significant deviation from current climatic conditions. From around 27,000 to 21,000 years ago, global temperatures were significantly cooler and global sea level was lower by around 120 m due to the extensive growth of ice-sheets in the northern hemisphere and thickening of the Antarctic ice sheet (Lambeck and Chappell 2001). The dramatic impact the LGM had on plants, animals and dependent human populations in the northern hemisphere is well documented (Gamble et al. 2004); however, much less is known about its impact in the tropics. It is clear though that the tropical regions did not go unaffected, with the most unequivocal evidence for change in this region observed in records from the larger mountain ranges of New Guinea. Here, for example, tropical glaciers expanded and montane forest zones shifted to lower elevations (Hope and Peterson 1975; Hope 2005). Similarly, faunal evidence from archaeological sites at 350 metres above sea level (m asl) on the Bird's Head of Papua reveal montane forest mammals present during LGM times at an elevation that today supports lowland rainforest with its distinctive mammal species (Pasveer and Aplin 1998). Other lowland records, such as the fauna recovered from the caves of Liang Lemdubu and Nabulei Lisa, in the Aru Islands, point to increasingly drier conditions during the LGM with a peak in open grassland species and a corresponding decline in forest species between 20,000 and 16,000 years BP (O'Connor et al. 2005).

Palaeovegetation records based on the fossil content of lake and swamp sediments are some of the most powerful descriptors of terrestrial landscape change at our disposal. The available evidence from the broader region are locally variable, but overall demonstrate a similar timing and direction of change over crucial time periods from locations such as Sumatra (Stuijts et al. 1988; Flenley and Butler 2001), Java (van der Kaars and Dam 1995, 1997) and Papua (Hope and Tulip 1994; Haberle 1998), as well as two records from Sulawesi (Dam et al. 2001; Hope 2001) (Figure 3.1). While many of these records are low in resolution and sometimes poorly dated, generally they document responses to the glacial cycle; cool and wet conditions over much of Indonesia c. 30,000 years ago, universally cooler and dryer conditions during the LGM, replaced by warmer and wetter conditions during the Holocene (see reviews by De Deckker et al. 2003; Hope et al. 2004; Reeves et al. 2013).

The longest published palaeovegetation record from a terrestrial location in the region is the 135,000-year-old record from the Bandung Basin, in Java (van der Kaars and Dam 1995, 1997) (Figure 3.1). This lowland record indicates that the last inter-glacial (approximately 125,000 years ago) was warm and humid, and that drier conditions had their onset around 81,000 years ago, thought to be in response to lower sea levels and the consequent changes to monsoon flows. The period from 47,000 to 20,000 years BP is interpreted as the driest and coolest in the record, once again suggesting the strong influence of the glacial cycle on vegetation structure.

The records that underpin much of our understanding of long-term Quaternary vegetation change in the region, however, come from marine cores (van der Kaars 1991; van der Kaars and Dam 1995; van der Kaars et al. 2000, 2010) (Figure 3.1). The two longest marine records, spanning 300,000 and 180,000 years, also suggest significant reorganisation of vegetation in line with glacial–interglacial cycles and infer drier and cooler conditions during glacial periods and warmer and wetter conditions during interglacials. A drawback of marine pollen records, however, is their complexity, incorporating pollen from vast source areas that often represent several biogeographic zones and, as a consequence, they are not sensitive indicators of change at any one location (e.g. van der Kaars et al. 2000). They can also be influenced by changes in land–ocean distributions that 'mimic' orbitally forced precipitation.

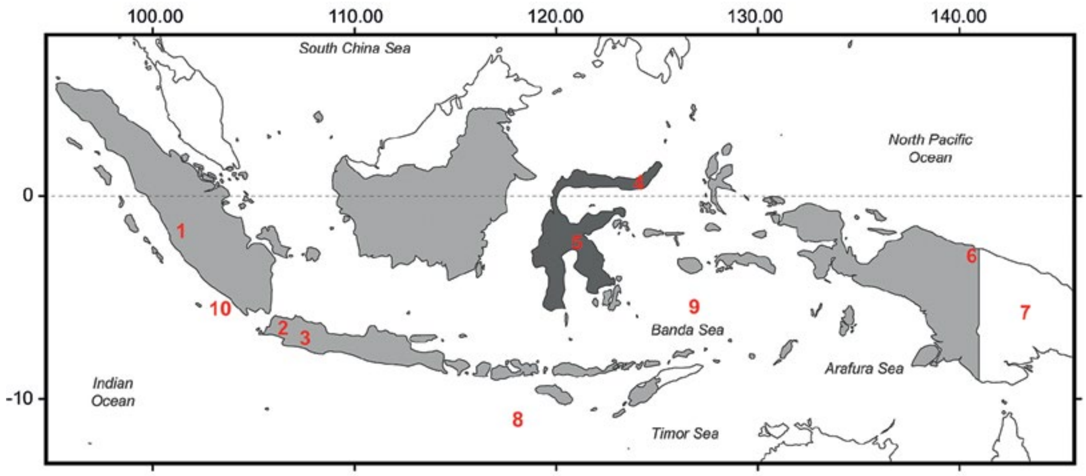

Figure 3.1: Sites mentioned in text.

Terrestrial Pollen Sites: 1. Danau di Atas, Sumatra (Newsome and Flenley 1988; Stuijts et al. 1988); 2. Rawa Danau, Java (van der Kaars et al. 2000); 3. Bandung Basin, Java (van der Kaars and Dam 1995, 1997); 4. Lake Tondano, Sulawesi (Dam et al. 2001); 5. Wanda mire, Sulawesi (Hope 2001); 6. Lake Hordorli, Irian Jaya (Hope and Tulip 1994); 7. Tari Basin, Papua New Guinea (Haberle 1998). Marine Cores: 8. Lombok Ridge (van der Kaars 1991); 9. Banda Sea (van der Kaars et al. 2000); 10. core BAR94-42, Sumatra (van der Kaars et al. 2010).

Source: CartoGIS, College of Asia and the Pacific, The Australian National University.

Sulawesi

The two published palaeovegetation records for Sulawesi that extend beyond the LGM are from Lake Tondano in the north of Sulawesi (Dam et al. 2001) and Wanda mire from South Sulawesi (Hope 2001) (Figure 3.2). Both are lowland/submontane records (i.e. below 800 m) and both are from near-shore shallow water settings, making them highly sensitive to shoreline fluctuations. Consequently, both are discontinuous from around 30,000 years ago through to the late glacial/early Holocene, with the absence of record interpreted as signifying lower lake levels and therefore a much drier LGM (Figures 3.3 and 3.4).

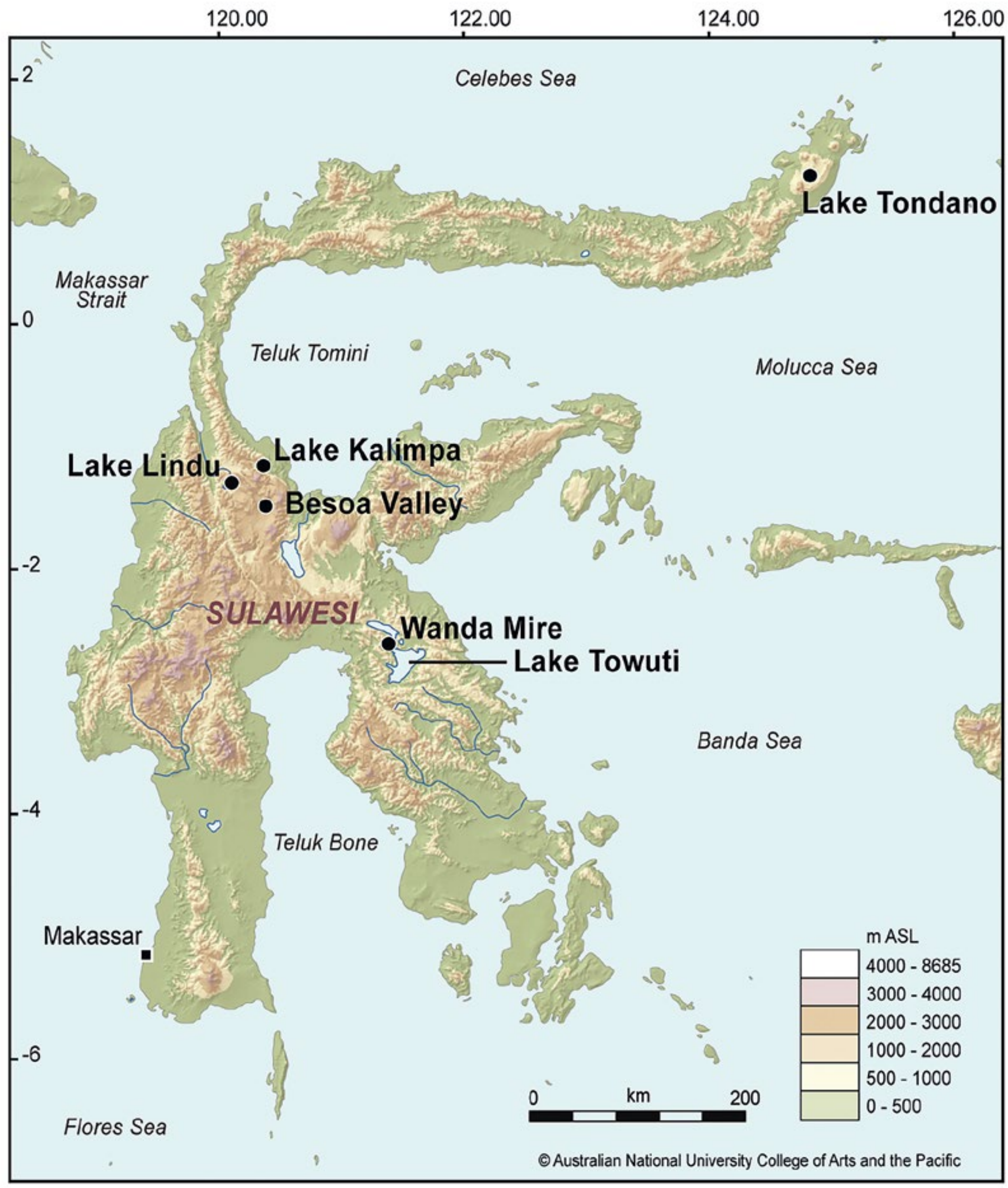

Figure 3.2: Location of pollen sites mentioned in text for Sulawesi.

Source: CartoGIS, College of Asia and the Pacific, The Australian National University.

Although discontinuous over the LGM time period, pollen assemblages of these two records have many similarities including the greater abundance of submontane taxa around 30,000 BP (Figures 3.3 and 3.4). In particular, both records have a greater representation of *Castanopsis–Lithocarpus* (Fagaceae) forest, today found at higher altitudes (i.e. above 850 m). This suggested, to all authors, cooler and wetter conditions during the late Pleistocene, becoming drier during the LGM; in other words, the movement downslope of temperature and moisture conditions only found above 800 m today. The degree of altitudinal lowering, however, remains uncertain. Also of note during the LGM is an expansion of grasses and an increase in fire frequency in the lowland environment (Figures 3.3 and 3.4). Hope (2001) interpreted the increase in grass as representing small forest openings or the growth of swamp vegetation on a drying swamp floor, with the charcoal record possibly suggesting onsite fires as a result of burnable vegetation. Dam et al. (2001) came to similar conclusions for the increase in burning during the late Pleistocene for the Lake Tondano record.

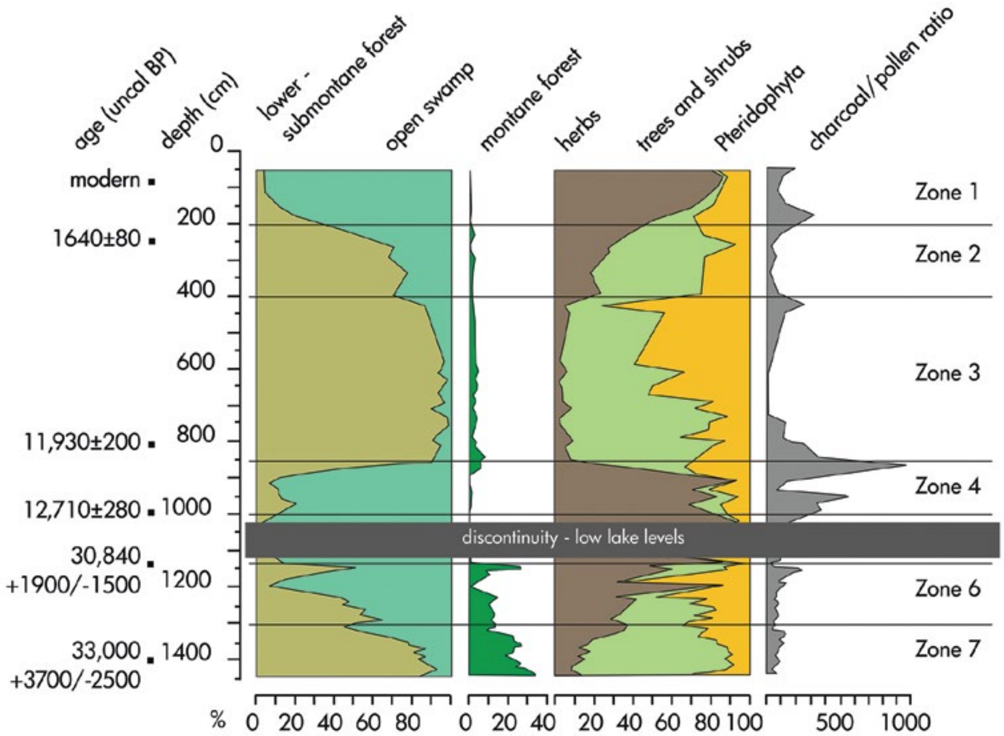

Figure 3.3: Lake Tondano pollen record.

Source: Adapted from Dam et al. (2001).

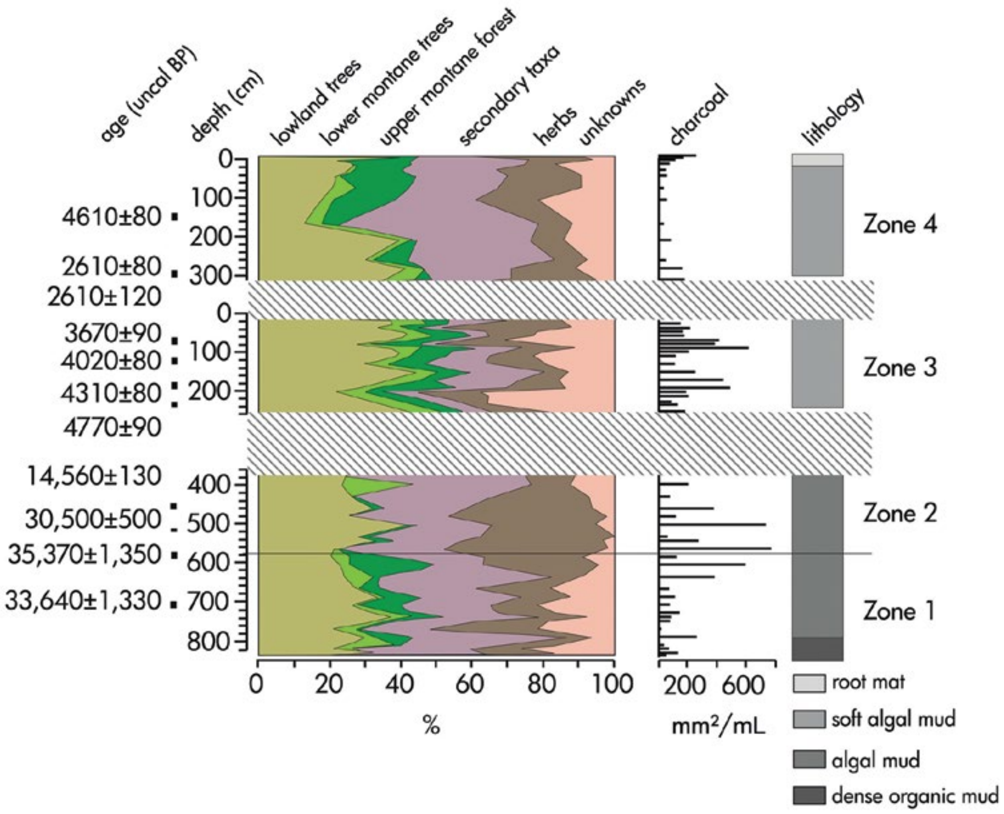

Figure 3.4: Wanda mire pollen record.

Source: Adapted from Hope (2001).

The Lake Tondano diatom record (Dam et al. 2001) also suggests that conditions were wet in the period immediately preceding the LGM, with the relative water level of the lake 4–6 m higher than present levels, then dropping significantly from 31,000 to 13,000 years ago, before rising above present levels until the mid-Holocene when they once again began to fall. Possibly not surprisingly, the combined pollen and diatom data from Lake Tondano attributes a greater magnitude of temperature and precipitation change for the region during the LGM than is commonly concluded from the marine records alone.

The composition of both records, Wanda and Tondano, during the Holocene is substantially different to the pre-LGM record, with Hope (2001) suggesting rapid turnover at the Wanda site associated with ongoing disturbance. However, the dating of the two Holocene sections at Wanda is wildly inconsistent, and it is hard to reconcile whether these segments are truly representative of the site for last 5,000 years.

In the far north of Sulawesi, at Lake Tondano, the landscape becomes more open from around the mid–late Holocene onward, in association with an increase in burning (Figure 3.3; Dam et al. 2001). The potential that these changes are associated with human activity need greater exploration, but they do overlap temporally with known archaeological record, such as the Mansiri site that contains dentate stamped pottery (Azis et al., this volume).

The only continuous palaeoenvironmental record stretching back beyond the LGM is from Lake Towuti, in South Sulawesi (Figure 3.2). Formed in the mid-Pleistocene (Brooks 1950), Lake Towuti is one of three lakes known as the Malili lake system. It is also Indonesia's largest tectonic lake with a surface area of around 560 km^2, a catchment area of around 1500 km^2 and a maximum water depth of just over 200 metres.

In 2010, Russell and Bijaksana (2012) collected nine piston cores across Lake Towuti, concentrating their palaeoenvironmental analyses on a 12 m core from the northern basin (Figure 3.2). The high-resolution geochemical records from the lake suggest reduced terrigenous runoff and strong drying from 33,000 to 16,000 years ago, in keeping with interpretations from the discontinuous records of Wanda mire and Lake Tondano (Russell et al. 2014) (Figures 3.4 and 3.5). The strong signal of drying is derived primarily from the stable isotope measurements of terrestrial leaf waxes ($\delta^{13}C_{wax}$), which exhibit an enrichment of 15‰ over the LGM from ~–40‰ to ~–25‰, suggesting to the authors a more open forest canopy, potentially with an expanded grass understorey (Russell et al. 2014) (Figure 3.5). The interpretation of grassland expansion is based on the premise that vegetation utilising the C_3 photosynthetic pathway (the bulk of herbaceous and woody plant life) has $\delta^{13}C$ values between –29‰ to –31‰, whereas plants utilising the C_4 pathway (primarily tropical and warm season grasses) have $\delta^{13}C$ values of –14‰ to –26‰ (Chikaraishi and Naraoka 2003; Bi et al. 2005). However, while the $\delta^{13}C_{wax}$ signal can vary with these two different photosynthetic pathways, it can also be influenced by water availability and temperature as well as vegetation structure (e.g. closed-canopy verses open-canopy forest), with closed-canopy forest often producing more depleted signals (i.e. more negative) due to microclimate cycling (Cowling 2007; Marshall et al. 2007; Vogts et al. 2009).

Shifts to more enriched values of $\delta^{13}C_{wax}$ over the LGM are also seen in a record from neighbouring Lake Matano (from –38‰ to –35‰) (Wicaksono et al. 2015) and again in a record from Mandar Bay off the southwest coast of Sulawesi (from –28‰ to –25‰) (Wicaksono et al. 2017). In each of these records, enrichments over the LGM is more muted than the Lake Towuti record, with the differences in magnitude of change attributed to catchment size and catchment morphology.

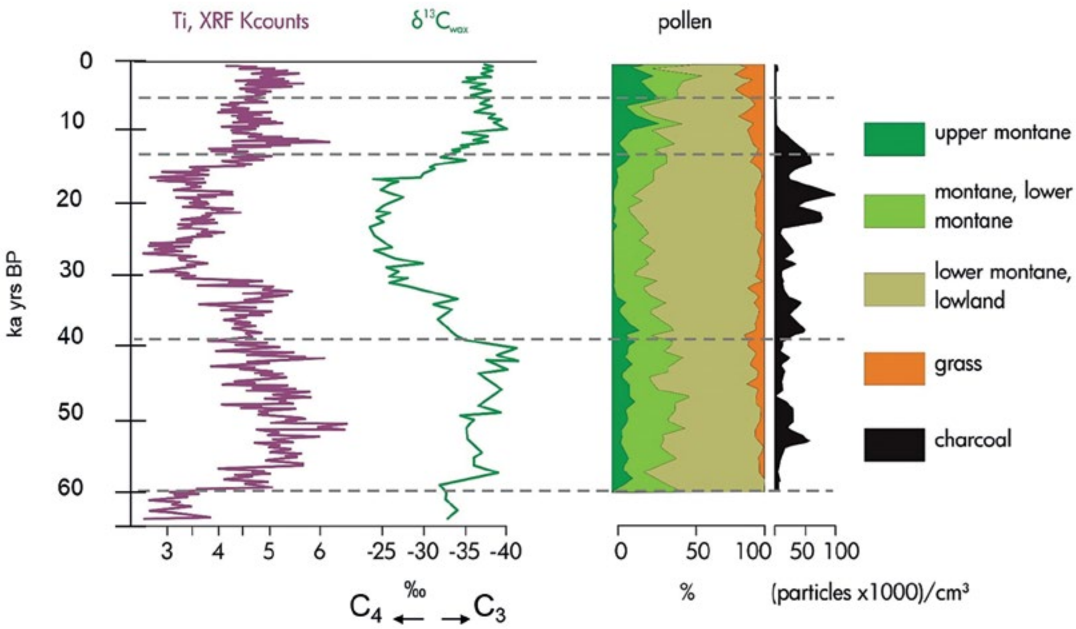

Figure 3.5: Geochemical and pollen data for Lake Towuti (TOW-10-9). Ti counts – proxy for terrestrial erosion. δ13Cwax – proxy for C_3/C_4 vegetation.

Source: Adapted from Russell et al. (2014).

Liu et al. (2005) have cautioned, however, that the interpretation of LGM C_4 grass expansion globally could be over-estimated, as drought-stressed C_3 grasses can give similar shifts in $\delta^{13}C$ values. In addition, a more open canopy alone will produce a quite different sub-canopy microclimate and a more enriched signal. All three records from Sulawesi, however, suggest some degree of forest canopy change during the LGM for the island.

While the pollen data from Lake Towuti exhibits similar large-scale changes in vegetation over the late Pleistocene, it does not immediately support a more open forest or the expansion of grassland. On the contrary, the amount of grass pollen changes little over this period (Figure 3.5) (Stevenson, unpublished data). Complicating this picture is the fact that grass pollen cannot usually be resolved beyond the family level, leaving the possibility open that while the coverage of grasses in the landscape may not have changed, the grasses growing around Lake Towuti during the LGM may have undergone a compositional shift with a greater dominance of C_4 species. Sedge pollen (Cyperaceae), another potential source of C_4 leaf waxes, also increase during this period, possibly expanding in extent on exposed shoreline sediments, suggesting that the $\delta^{13}C_{wax}$ signal could be reflecting quite local changes and not broader-scale landscape change.

Instead, the most profound changes in the Lake Towuti pollen record supporting drier than present conditions are the reduced quantities of montane gymnosperms (*Agathis, Dacrydium, Phyllocladus, Podocarpus*) from around 35,000 to 12,000 years BP, species that are sensitive to both temperature and moisture availability (Figure 3.5) (Stevenson, unpublished data). The Wanda and Lake Tondano pollen records both have an increase in Fagaceae forest prior to the LGM. What the Lake Towuti record reveals, however, is that this forest type declines over the LGM, a finding not in keeping with marine records of the region, and that these forest elements are instead replaced by other submontane taxa that tend to grow within a much broader climatic envelope such as the Cunoniaceae/Elaeocarpaceae and *Triadica* (Euphorbiaceae), a small deciduous lowland tree of primary and secondary forest.

The Wanda mire and Lake Tondano records hint at the likelihood that fire is more prevalent over the LGM. The Lake Towuti record bears this out, with the greatest fire activity occurring during the LGM and lowest during the Holocene (Figure 3.5). Overall this probably suggests that seasonality increased during the late Pleistocene, providing both sufficient rainfall for growth and fuel, and a season dry enough for ignition and fire.

What is known so far from the only long and continuous pollen record for Sulawesi is that higher altitude elements declined during the LGM, suggesting that lower temperatures were not the only aspect of the climate that changed, and that rainfall and seasonality in particular must also have changed significantly. While the composition of the lowland vegetation around Lake Towuti appears not to have altered significantly during the LGM, the structure of the vegetation—that is, how closed or open the canopy structure was—remains unknown at this point.

Holocene records and human impact

There are more records covering various periods within the Holocene for Sulawesi, with the biggest disturbance factors interpreted as a result of human activity, in particular the use of fire with the arrival of the metal age and later with European contact. The most profound impact on all ecosystems appears related to late 20th-century forest clearance associated with logging and other land use pressures (Kirleis et al. 2011, 2012; Biagioni et al. 2015, 2016).

The mountain regions of the Lore Lindu National Park in Central Sulawesi today have an ever-wet climate and little seasonality in precipitation. The Lake Kalimpa record at 1600 m asl reveals that Fagaceae forest has dominated this landscape for the last 1500 years, and although several episodes of increased fire activity are detected in the record (thought to be associated with increasing El Niño intensity), this forest type has overall been resilient to both drought and fire (Biagioni et al. 2015). A different trend is apparent starting from the second half of the 20th century, however, as a consequence of increasing human activities around the lake. In particular, *Agathis*, an emergent conifer in these montane forests, although able to respond to long-term rainfall variability and fire in the past, has not re-established after the years of intensive selective logging in the second half of the 20th century. Other records from this region but from lower elevations show similar responses to late Holocene climate variability, but overwhelmingly the changes correspond to human activity with, for example, the conversion of forest to grassland as early at 2000 years ago (Kirleis et al. 2011) and the effects of late 20th-century deforestation (Biagioni et al. 2016). While the impact of people in Wanda mire record is equivocal, the expansion of grassland and the increase of fire in the Lake Tondano record since the late Holocene is possibly related to human activity and has many similarities with the work from Lore Lindu region.

Possibly the most important development in palaeoenvironmental research for Sulawesi, however, has been the establishment of the Towuti Drilling Project (TDP) (Russell et al. 2016). The overarching goal of this project is to generate multi-proxy palaeoclimate and palaeoenvironmental data to better understand long-term environmental and climatic change in the tropical western Pacific over multiple glacial–interglacial cycles. Geophysical work associated with the project has established that the lake contains a well-stratified sequence up to 150 m thick (Russell and Bijaksana 2012), potentially representing the longest and most continuous terrestrial record in the tropical western Pacific. In 2015, with the assistance of the International Continental Scientific Drilling Program (ICDP), the TDP carried out a drilling program at Lake Towuti, resulting in the collection of approximately 1000 m of sediment from 11 boreholes centred on three drilling locations. The maximum core depth recovered was 175 m below the lake floor, capturing the entire sedimentary infill of the basin and estimated to cover the last 600,000 years (Russell et al. 2016). While the analysis of these cores has only just begun, initial data from core and borehole logging reveals the evolution of a highly dynamic system.

Summary

Numerous reviews have concluded that temperature is the major variable influencing vegetation change at high altitudes in this region during the LGM, and that moisture availability had the greatest effect on lowland vegetation (De Deckker et al. 2003; Hope et al. 2004; Kershaw et al. 2007; Reeves et al. 2013). In particular, they highlight the influence on rainfall and its seasonality by the alternate drowning and exposure of the extensive continental shelves as a result of sea level fluctuations over glacial cycles.

The pollen records from Sulawesi reveal a significant vegetation shift in response to glacial climate. If climatic conditions in central/southern Sulawesi during the LGM were not only cooler but also remained wet with reasonable cloud cover, then we could expect montane gymnosperm forest taxa and ferns to increase in abundance in the lowland records, as they do in the lower montane site of Lake Hordorli, Irian Jaya (Hope and Tulip 1994). The various pollen records, however, as well as the Lake Towuti geochemistry record, instead suggest that conditions were in fact drier or more seasonal during the LGM in Sulawesi (Dam et al. 2001; Hope 2001; Russell et al. 2014).

As Hope (2001) noted, the lowland Sulawesi landscape during the LGM seems to reflect conditions midway between those observed in Java to the west and those seen in Irian Jaya to the east. In the Bandung record from Java, van der Kaars and Dam (1995, 1997) saw only minor evidence of cooling in this lowland record but significant evidence for much drier conditions, keeping in mind that due to lowered sea level this site occupied a much more continental position during the LGM than it does today. By contrast, Hope and Tulip (1994) concluded that LGM climate at Lake Hordorli in Irian Jaya was cool enough and, importantly, cloudy enough to produce an altitudinal lowering of montane forest with an absence of fire. The combined Sulawesi records have some evidence for cooling leading up to the LGM, but overwhelmingly the data suggests a significantly drier or more seasonal climate over the LGM associated with greater natural fire activity than present.

Given the size and volume of Lake Towuti, the water body would have remained a viable water resource for humans throughout the LGM. What impact the significantly drier or more seasonal climate had on the other smaller river systems in the area, however, remains uncertain. The degree to which the forest opened up during the LGM at Lake Towuti is also still equivocal, but faunal evidence from archaeological excavations in the region may give some clues similar to those for the Aru Islands and Bird's Head Peninsula (Pasveer and Aplin 1998; O'Connor et al. 2005). Post LGM, the nutrient poor ultramafic soils of the Towuti catchment (Brooks 1987) are a factor limiting the attractiveness of this region for human activities. This contrasts with the more fertile regions of Lore Lindu and Lake Tondano, where pollen records appear to capture the impact of late Holocene forest clearance and the use of fire (Dam et al. 2001; Kirleis et al. 2011, 2012; Biagioni et al. 2015, 2016).

Throughout the region, but for Sulawesi in particular, numerous questions of fine detail remain. Through the expanded research program of the TDP, improved insight and understanding will be gained of climate and environmental change in this globally important region, with the findings contributing to a better assessment of the potential threats that projected climate change and human activities pose for one of the most diverse rainforest ecosystems on Earth.

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