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Legacy-Based Targets for Tropical Forest Restoration

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Abstract

Unparalleled levels of tropical forest restoration are required to counter decades of deforestation, minimise losses in biodiversity and aid in combating climate change. Restoration projects which disregard the temporal dimension (decades-centuries) risk restoring a degraded ecosystem, as our expectations of what is ‘normal’ diminish over generations. Actively incorporating ‘practical palaeo-reference ecosystems’ into restoration projects provide targets against which success can be measured.

The 2020's are the United Nations "Decade on Ecosystem Restoration" with the goal of "preventing, halting, and reversing the degradation of ecosystems worldwide"¹. In the Neotropics unparalleled levels of forest restoration have been called for to reverse decades of deforestation and aid in combating climate change²⁻⁴. The aim is to conserve biodiversity whilst enhancing carbon sequestration, mitigating soil erosion and improving water security^{5,6}. However, restoration projects that replace what was once diverse tropical forest with simplified communities risk undermining their very purpose and increase the vulnerability of these systems to collapse^{7,8}. Successful restoration depends on understanding past human impacts and identifying the rate and route (forest succession) in which tropical ecosystems regenerate through time (decades-centuries) and over landscape-scales⁹.

Current restoration methods that aim to restore ecosystems to a near-natural state, those indicative of minimal human impact, employ a 'reference ecosystem' approach. This is where evidence from the recent past, present and projected future is used to derive a model of the ecosystem had it not been degraded¹⁰. Successful restoration then rests on effectively working towards this target whilst maximising beneficial outcomes and engaging with stakeholders¹¹. Local mature ecosystems are favoured as reference targets if considered analogous to that of the pre-degraded past¹⁰. However, determining if they are indeed intact, and to what extent, is challenging. Cleared Neotropical forest takes more than c. 50 years to recover its species richness¹², c.130 years to recover its structure^{13,14}, and likely centuries if ever to recover its species composition^{12,15}. The reliance on recently (< 100 years) disturbed forests as reference ecosystems risks species characteristic of old growth forests being underrepresented in restoration plans. Forests close to settled human populations have almost certainly been burned, cleared, or selectively logged during the last century, as bearing relict ecosystems, such as those found in the most inaccessible parts of the Andes almost nowhere remains untouched by direct human impact¹⁶. Today at least two-thirds of the world's

tropical forests show some degree of human intervention ^{17,18}. Without establishing reference ecosystems with a greater temporal aspect there will always remain the risk of restoring a ‘shifted ecological baseline’ *sensu* Pauly ¹⁹, one that reflects long-term degradation as our expectations of what is ‘normal’ diminish over generations ²⁰.

Palaeoecology offers the ability to provide near-natural restoration targets rooted in empirical data. Using proxy data recovered from sedimentary archives, long-term ecosystem change and community response to environmental and anthropogenic drivers can be characterised over periods beyond that of observational studies. The advantages of incorporating evidence of past vegetation into conservation and restoration planning has long been recognised ^{21–27}. However, the laborious nature of an in-depth, multi-millennial palaeoecological analysis prior to restoration work means that the outcomes are seldom incorporated into restoration goals ²⁸. Here we suggest the use of a ‘practical palaeo-reference ecosystem’ for the Neotropics, and use the cloud forest of Ecuador, a biodiversity hotspot and global priority conservation area ^{29–31} as a case study (Box 1).

Prior to European arrival in the Americas (CE 1492), c.60 million people lived in social structures from small groups of hunter-gathers to vast civilisations ³². For thousands of years people domesticated crops, moulded landscapes to fit their needs and drove changes in ecosystems. However, within a century as much as 90% (54 million people) of the population was dead as the result of European conquest and imported diseases ³². This continental scale depopulation led to population centres, managed land and cultivated fields (c.56 million hectares ³²) undergoing secondary succession, as vegetation reoccupied what was previously cleared.

Across the Americas in the following century (CE 1500’s) this sequence of indigenous depopulation followed by the expansion of vegetation and an increase in carbon sequestration is repeated. However, its effects were felt globally. Ice cores from Antarctica

show that c. CE 1600 a rapid (~20-50 years) decline (7-10 ppm) in atmospheric CO₂ occurred³³. At the same time (c. CE 1600-1750) biomass burning in the southern hemisphere reached a new low, only increasing again during the industrialisation of the 1800's^{34,35}. Vegetation, previously held at bay by indigenous land management recolonised the land, sequestering some 5-10 Gt C (Gigatonnes of carbon)^{32,36,37} driving changes in global climate, contributing to the Little Ice Age which reached its peak c. CE 1610^{36,38}.

Throughout South America forest recovery driven by indigenous population decline is observable in palaeoecological proxy records³⁹. In Neotropical rainforests⁴⁰⁻⁴², savannahs^{43,44} and Andean montane forests^{13,45,46} pollen assemblages record vegetation rebounding following depopulation. Evidence of indigenous agriculture in the form of cultivar pollen and phytoliths e.g. *Zea mays*, disappear from sedimentary archives^{13,47}. While in areas regularly burned prior to European arrival, charcoal disappears^{37,41,48}, in contrast to areas naturally prone to fire such as dry forests, where burning increases as the previously cleared forest expands⁴⁹.

Abandonment of the pre-1500 agricultural land (Fig 1a) led to more than a century of vegetation succession through the 1600's (Fig 1b). The 1700's (Fig 1c) therefore provide the most recent phase of substantial mature vegetation that has undergone over a century of recovery and represents a practical palaeo-reference ecosystem. Exploration of more ancient pre-human arrival, records would provide more robust data when exploring issues such as species migration, adaption and extinction⁵⁰. While changes in climate through the Quaternary likely provide useful analogues of biotic responses to our current human driven climate²¹. However, the primary issue that limits the implementation of palaeoecology into restoration practice is 'practicality' and here ancient sediment becomes 'impractical'. Ancient palaeo-reference ecosystems i.e. those established prior to human arrival in the Americas and therefore during the last ice-age are 1) unlikely to best represent the vegetation composition

required in the Anthropocene; 2) would completely eliminate any human signal, representing millennia of indigenous selective cultivation and domestication⁵¹; 3) the paucity of ancient sediment within the tectonically dynamic Andes and fluvially dynamic Amazon, would lead to large regions being categorised on single records; and 4) ancient sediments, requiring large lakes would produce proxy signals (particularly pollen) from a wide region, leading to a homogenisation of the local landscape signal⁵².

The use of a recent target i.e. the 1700's, overcomes these issues as 1) only a short (< 1m) sediment cores are required, easily obtainable from frequently occurring bogs and small ponds; 2) cores can be quickly and easily recovered with confidence that the required sediments are present; 3) multiple short cores focused on a narrow time frame can be examined, overcoming the issue of relying on single sites; and 4) the indigenous human signal, containing taxa culturally favoured over the preceding millennia are retained.

Expanding the search for practical palaeo-reference ecosystems across the Americas will likely identify differing periods for individual regions dependant on historical changes in human impact on the landscape. However, the scale of continental forest regrowth following indigenous depopulation across the Americas, and occurring on a scale detectable in global climate records, provides a compelling continental scale marker.

There is little doubt that massive global reforestation efforts are required to help mitigate anthropogenic climate change and combat deforestation²⁻⁴. Despite this, active restoration of cleared tropical forests cannot continue to overlook the long-term impacts of humans if the target is to re-establish vast areas to a near-natural setting. The myth of the pristine American wilderness has been thoroughly debunked⁵³. However, the vegetation of the recent past can still help us establish practical and robust palaeo-reference ecosystems, that reduce the risk of recreating ecologically diminished ecosystems that today we may see as 'normal'.

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Data Availability: The data used in this study are archived at the Natural Environmental Research Council (NERC) Environmental Information Data Centre (EIDC) at <https://doi.org/10.5285/952e8ddb-b573-44ad-a930-2c8c5164a381>

Figure 1. Cloud forest succession driven by changes in land use. A) pre-CE 1588 Indigenous agriculture, B) CE 1588-1718 European arrival and Indigenous depopulation leading to secondary forest growth, C) CE 1718-1819 a diminished population and establishment of mature forest, and D) post-CE 1819 re-colonisation of the landscape and modern farming.

Box 1: A Case Study from Ecuador

Eastern Andean tropical cloud forest forms a distinctive vegetation corridor (1300-3,600 m asl) separating the lowland rainforests of Amazonia from the high-altitude grasslands (páramo) of the Andes ^{54,55}. In northern Ecuador, the Quijos Valley cuts perpendicular through the cloud forest forming a historically important trade route connecting past Andean civilizations such as the Inca to the peoples of Amazonia ⁵⁶. Today an increasing human population, deforestation and cattle farming has led to the formation of a secondary forest mosaic landscape driven by human activity and encroaching on the outskirts of the surrounding three national parks (SI Fig. 1). Restoration of this degraded landscape is underway, driven by international ⁵⁷ and local ⁵⁸ reforestation projects looking to plant native and culturally important species in areas previously cleared for farming. However, without an appreciation of the long-term vegetation history of the region, reforestation projects based solely on planting a few species risks working towards a simplified vegetation community.

To establish a palaeo-reference ecosystem in this setting pollen assemblages covering six time bins were characterised from sedimentary records corresponding to 1) pre-human arrival; 2) Indigenous cultivation, 3) European arrival / Indigenous depopulation, 4) diminished populace, 5) re-colonisation, and 6) industrial agriculture ¹³. Detrended correspondence analysis (DCA) was used to provide a method of visualising the relationship between the pollen signals within their respective time bins (SI Fig. 2). The ordination shows the signal from the pre-human landscape (c. 45-42,000 years ago), indicative of an intact vegetation assemblage, is most similar to that which occurred in the historical record between CE 1718-1819, a period following peak Indigenous depopulation and the abandonment of the region by Europeans (time bin 4 – diminished population). Whilst the period after re-colonisation (post-CE 1819 and industrial agriculture) was shown to be most like that of the early secondary forest succession which followed European arrival and early Indigenous

depopulation (c. CE 1588-1718). The open-agricultural landscape managed by the pre-European Indigenous population showed the greatest disparity and is characterised by evidence of intensive land management ¹³.

The vegetation history of the cloud forest viewed through this palaeoecological lens shows a direct response to changing human impact characteristic of the narrative of European arrival in the Americas ³². Within 30 years of the establishment of the first European settlement in the Quijos Valley (Baeza; CE 1559), the Indigenous cultivated landscape began a 250-year sequence of forest regrowth (c. CE 1588-1819). As the Indigenous peoples were exploited as forced labour by the occupying Europeans their numbers declined, culminating in CE 1578 with the Indigenous revolt led by the “great cacique Jumandi” ⁵⁹. As much of the surviving Indigenous population fled reprisals and disease, the region was gradually abandoned by the European colonizers ⁵⁶. For c. 130 years (CE 1588 -1718) secondary forest regrowth occurs, characterised by pioneer taxa such as grasses and the fast growing tree *Cecropia*. This was subsequently followed by a more mature and structurally developed cloud forest becoming established c. CE 1718-1819, in a region that was by then virtually uninhabited (Newson 1995). Not until c. CE 1819 does any evidence of renewed human impact on the palynological signal occur, and even then, the former population centre at nearby Baeza contained only three small huts ⁶⁰.

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Supplementary Information Figure 1. A) Republic of Ecuador with elevations corresponding to montane forest (1300-3,600 m asl) highlighted in green. B) The Quijos Valley and surrounding protected areas, Antisana Ecological Reserve (AER), Cayambe Coca National Park (CCNP), and Sumaco Napo-Galeras National Park (SNP). Black squares indicate present and past population centres. Black dots indicate location of study sites (Loughlin et al. 2018a; 2018b).

Supplementary Information Figure 2. DCA of pollen data grouped into time bins (re-plotted from Loughlin et al. 2018). 1) Ancient (pre-human arrival); 2) Pre-European (Indigenous cultivation), 3) Successional (European arrival / Indigenous depopulation), 4) Mature (diminished populace), 5) Deforestation (re-colonisation), and 6) Modern (industrial agriculture). Red arrow indicates an increasing signal of human impact.

Figures

Figure 1

Cloud forest succession driven by changes in land use. A) pre-CE 1588 Indigenous agriculture, B) CE 1588-1718 European arrival and Indigenous depopulation leading to secondary forest growth, C) CE

1718-1819 a diminished population and establishment of mature forest, and D) post-CE 1819 re-colonisation of the landscape and modern farming.