Amazonian exploitation revisited: ecological asymmetry and the policy pendulum

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The first scientists to enter Amazonia encountered a wonderland of undescribed organisms living in what appeared to be unoccupied and untouched forest. Adjectives they used to describe the forest included “virgin”, “pristine”, and “timeless”, a vision which became incorporated into scientific thinking. Explanations of high Amazonian diversity invoked the stability and the museum-like quality of unchanging environments that accumulated species and minimized extinctions (Stebbins 1974). Coupled with this view was the romantic idyll of hunter–gatherers living in harmony with nature.

Such views have been altered by excavations of archaeological sites from the mouth of the Amazon to the High Andes, which reveal a long record of human occupation, ceramics manufacture, and agriculture (eg Roosevelt 1991; Roosevelt et al. 1991). For at least some groups, a trajectory of increasing populations and greater reliance on agriculture is evident for the past several thousand years. As anthropological and paleoecological knowledge of these systems has deepened, the view of Amazonia as untrammelled and changeless has disappeared (Clark 1996).

The realization that human populations throughout the Americas declined sharply following European contact altered expectations of the level of human disturbance and modification of systems prior to 1492. Indeed, a series of articles (eg Clark 1996; Erickson 2000; Heckenberger et al. 2003; Erickson 2006) and a recent book (Mann 2005) suggest that the pendulum of scientific opinion has swung from the extreme view of the Amazon as “virgin”, has passed a midpoint of “disturbance localized around main waterways”, and is now headed toward the other extreme of “widespread and pervasive human disturbance”. The title of Heckenberger et al.’s (2003) article, Amazonia 1492: pristine forest or cultural parkland?, was deliberately provocative, but if taken literally depicts a simple dichotomy. We suggest the possibility of a middle path. Here, we provide an alternative interpretation of the existing data, and caution that uncritical acceptance of Amazonia as a manufactured landscape may be misguided and could lead to unsound policy.

In Amazonia, there has been a commendable use of science by governments, particularly the Brazilian Government, to set conservation policy. Refuge theory was widely accepted in the mid-1980s and was used at the time, together with maps of diversity, to prioritize areas for conservation (Dinerstein et al. 1995). Although this theory is now largely discredited (Colinvaux et al. 2001), the basic biogeographic patterns of high local endemism and diversity used to identify “refugia” also formed effec-

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In a nutshell:

- Pre-Columbian human influence on Amazonia was spatially heterogeneous, with some sites intensively altered
- The large majority of Amazonia was probably barely influenced by human activity
- Fossil pollen and charcoal data point to localized influence around widely scattered occupation sites rather than a uniform influence
- Arguments that the Amazon forest is a manufactured landscape, and hence resilient to human activity, are often locally true and should not be used to set regional management policy
Estimates of human population in Amazonia at the time of European arrival range from one to 11 million, with a tendency toward higher values in more recent estimates (for overviews see Denevan [1996] and Mann [2005]). The population collapse that occurred between ca 1520 and 1600 AD may have reduced Amazonian populations by an astounding, yet plausible 95% (Denevan 1976).

Diseases brought to Central America by the first Europeans spread into South America via trade among native peoples. It is probable that the Incan emperor Huayna Capac died when a deadly epidemic (probably smallpox) swept through the Andes in 1524–1525 (Figure 1), 6 years before the arrival of Pizarro, the first conquistador to enter Peru (Hemming 1970). Smallpox, measles, diphtheria, and influenza ravaged the Andean populations over the next 50 years (Denevan 2003). While Spanish accounts describe scenes of bodies piled up and abandoned in Andean villages, nothing is known about epidemic diseases in the lowlands. However, the same genetic susceptibility to European diseases (Black 1992), known trade contact with Andean communities (Hemming 1970), and densely packed populations along major rivers (Smith 1990), make it likely that Amazonian populations were similarly devastated.

At the heart of the discussion over pre-Columbian influence in Amazonia are contradictory estimates of human population size, cultural development, and the geographic extent of their influence. The initial European descriptions of Amazonian populations, their size, wealth, and societal sophistication, are at best incomplete and at worst misleading. Friar Gaspar de Carvajal, who accompanied Francisco de Orellana on the first European voyage down the Amazon River in 1541, was writing to impress the King of Spain. While he describes extensive settlements stretching for tens of kilometers along the river, and encounters with thousands of warriors, his credibility is undermined by fanciful descriptions of such curiosities as single-breasted, warrior women. Although the river was named for these “Amazons”, they were never encountered in subsequent exploration. In stark contrast to Carvajal’s account, Charles Marie de la Condamine, who traveled the Amazon in 1743, described a very different setting, in which isolated bands of people struggled for existence in the most basic circumstances (Smith 1990). Many subsequent visitors validated this portrayal of physical and cultural poverty, so different from the agrarian idyll described by Carvajal. However, in a similar debate over indigenous influence on the vegetation of New England, Foster and Motzkin (2003) caution against accepting eyewitness accounts that post-dated European arrival by > 100 years as proper reflections of conditions immediately prior to first contact. For many years, Carvajal’s account was seen to be essentially unreliable (Smith 1990). However, there was renewed interest in the possibility of disease decimating this society, prompting Mann (2005) and others to suggest that both accounts were essentially true. Carvajal did witness dense populations, whereas Condamine was viewing the shattered remnants of a society in which 90–99% of the population had succumbed to smallpox and other European diseases (Smith 1990). If there had been large, settled populations in Amazonia for a thousand or more years prior to contact, this raises the question: “To what extent did human activities prior to the population collapse influence Amazonian ecosystems?”

Drawing from the archeological literature, Mann (2005) elaborates a vision of Amazonia in which the area supported upwards of 10 million people, with great urban centers (eg Marajó Island, Santarém), and many other, smaller cities with well-developed infrastructure (eg those adjacent to the Xingu River and Lake Manacapuru). The banks of the main Amazon channel and tributaries such as the Rio Negro, Madeira, Xingu, and Tapajós, teemed with villages (Denevan 1996). Great transforming public works, such as the raised villages, causeways, and fish weirs of the Beni region of southern Amazonia, are attributed to large workforces.

**Figure 1.** Annotated schematic diagram of human population in Amazonia. Low, medium, and high estimates are shown.
and complex societal hierarchies (Balée 1989; Erickson 2000).

A further legacy of human endeavor is the distinctive soil layering, up to 2 m deep, of black or brown soils with elevated nutrient availability, known as terra preta del Indio (Figure 2). These nutrient-rich black soils often contain broken ceramics and appear to have been altered by the addition of ash, green manure, or, in some cases, fish meal (Lehmann et al. 2003). Such soil modification by humans may have held the key to sustainable exploitation of the land.

Some Amazonian locations were occupied for several thousand years. Shellfish and fish were undoubtedly important dietary components, but so too were maize and manioc. On most Amazonian soils, five harvests of maize in a span of 2–3 years exhausts the soil of essential nutrients. A fallow period of about 20–30 years is needed before the land can again support crops of maize (Kellman and Tackberry 1997). A prevailing view is that land can again support crops of maize about 20–30 years is needed before the exploitation in the future (Glaser et al. 2001).

Based on a wide array of evidence, Balée (1989) estimated that 11% of Amazonian vegetation in pre-Columbian Amazonia was extensively used and altered by human activity. That use ranged from slash-and-burn agriculture to enrichment with fruit-bearing trees (eg Bactris gasipaes [peach palm], Bertholettia excelsa [Brazil nut], Annona spp [includes guanabana or sweet soursop], and Mauritia flexuosa [aguaje, moriche, or nontoca; a palm whose fruit is used to make a drink]).

Infering past human disturbance

Fire is the oldest human tool for both small- and large-scale manipulation of the landscape, and one of the major sources of evidence for past human disturbance of tropical forest systems comes from fire histories. Charcoal is produced by forest fires and is gradually buried within a soil profile. Charcoal layers from soil pits can be radiocarbon dated, yielding an age estimate for fire events (generally ± 50–100 years). If old wood is burned, the resulting 14C dating of charcoal overestimates the time since the fire (Gavin 2001). Sources of such old wood could be the heartwood of an old tree killed by the fire, or dating long-dead but undecomposed wood lying on the soil surface. As most tropical forest fires char bark but not heartwood (sensu Cochrane 2003), it is unlikely that heartwood from this source is represented in the charcoal. Also, because rapid rates of decay in the tropics lessen the fuel load of undecomposed heartwood lying on the forest floor compared to temperate or boreal settings, the probability of charcoal being composed of heartwood is similarly low. The charcoal ages in tropical forest soils are therefore likely to be reasonably representative of the actual fire date (taking into account the errors of 14C dating). When 304 ages for Amazonian soil charcoal are plotted against time (Figure 3 a,b), the data strongly suggest an expansion of agricultural activity at ca 250 AD, then a series of peaks of fire activity between ca 700 and 1550 AD, followed by a sudden collapse at ca 1600 AD. One of the more surprising results of this analysis is that the highest peak of apparent fire activity is not at ca 1550 AD, but at ca 700–800 AD. Nevertheless, the trajectory of implied disturbance fits well with archaeological estimates of village expansion (eg Roosevelt 1980; Heckenberger et al. 1999).

Hammond et al. (2006) conducted the first systematic survey for soil charcoal in a 60 000-ha area of Guyana. Their analysis of > 280 soil profiles revealed charcoal in all of them. The authors considered it unlikely that these were natural fires – although this section of Guyana is subject to El Niño-related droughts – and concluded that there had been extensive human influence in upland eastern Amazonian forests within the past millennia.

Pollen, charcoal, and phytolith data from Amazonian lakes also provide evidence for widespread human occupation prior to European contact (Figure 4), and there is vir-
the data underlying the assertions of widespread alteration of Amazonia?

The hypothesis of widespread Amazonian landscape management is based on analyses of archaeological sites and the assumption that there was a large pre-contact Amazonian population (>10 million people). A caveat must be applied to these data, and indeed all of the data that we have to date about human disturbance in the Amazon, which is that they are derived from just a few locations, and do not represent either a systematic or a randomized sampling design. There is no ecological component predicting which forest was most likely to be occupied. Was disturbance spread evenly across all of Amazonia or concentrated near human habitation? Is it safe to extrapolate results from sites where we know human habitation occurred to the rest of Amazonia?

Ecologists are familiar with problems of scale. Indeed, “the problem of relating phenomena across scales is the central problem in biology and in all of science” (Levin 1992). Some general observations from ecology raise at least three concerns regarding how we may extrapolate data from the kind of dot map shown in Figures 3 and 4. First, landscapes are heterogeneous, and the resulting variability in environmental factors produces characteristic patterns of distribution and habitat use in nearly all species. Second, although species distributions can be widespread, their occurrence may be very local. For example, a dot map of the painted turtle (Chrysemys picta) would show that it is distributed across much of the continental US, but its actual occurrence is highly localized within a landscape. Third, a species can be widespread and also have a very substantial impact on the system where it is found, but this is not the same as saying that a species has a widespread, intense impact, or makes wholesale changes to the habitat in which it lives. Thus, extrapolating observations from dot maps can be dangerous, especially when the dots represent discrete activities of limited spatial extent (e.g. terra preta formation).

A first step in making the conjectures that are so critical to ecosystem management in Amazonia is recognizing the potential sources of bias that affect what we infer from data. The data in Figure 4 have two major potential sources of bias. First, lakes used to study paleoecology may not accurately represent the landscape as a whole, because they are attractive places for human settlement – humans like to live by water now and, apparently, always have (e.g., Bush et al. 2007b). Also, while maps of terra preta sites are available, we have no data on the distribution of soil pits that did not show modified soils. It is a statistical certainty that when extrapolations about land use are made from known archaeological centers and exclude other samples, the analyses will exaggerate human impacts. So how do we go about painting a more accurate picture of past human impacts?

### Investigating occupation: the scale of impact

Fossil pollen and charcoal records (Figure 5 a,b) derived from the analysis of lake sediments can provide detailed
insights into Amazonian history. Pollen and spores released from plants and blown or washed into lakes become incorporated into the sediment. Year after year, the sediment accumulates, burying and preserving these plant microfossils in anoxic mud. Lake sediments are retrieved using coring rigs supported by inflatable boats. The vertical columns of mud and the buried layers of microfossils they contain record the composition of vegetation that grew around the lake. Neotropical pollen and spores can often be identified to genus, and sometimes even to species. The radius of land represented in the microfossil record – the vegetation directly represented in the record – depends on lake size. In the moderate-sized lakes we discuss here, the great majority of the pollen would have been derived within a few kilometers of the lake.

During a forest fire, charcoal particles are created in both the smoke and the charred plant remains. This charcoal falls or is washed into nearby lakes. The finest fraction of charcoal reflects regional fire histories, whereas relatively large particles (i.e., those > 160 μm in length) indicate past fire in the adjacent watershed (Clark 1988). Today, fire is rare in most natural Amazon systems, and many sediments from undisturbed settings contain no charcoal. Finding evidence of regular burns may therefore indicate past hunting activity, where fire is used to drive game or improve its habitat, as a mechanism to clear forest for semi-permanent dwellings, or to increase populations of those light-demanding plants preferred by hunter-gatherers. Finding both charcoal and pollen from crops such as corn (Zea mays) or manioc (Manihot esculenta) is a clear indicator of past agriculture. Zea mays is not native to Amazonia, and its pollen is distinctive, due to its surface pattern and large size (commonly 80–110 μm). Maize pollen is particularly poorly dispersed, making it a good marker of local crop use.

Given these two proxies for human activity – microfossils and charcoal – we can start to look at regional comparisons of where humans have altered the landscape (Figure 4). Of the 22 pollen and charcoal records from lakes shown as yellow squares, 13 contained evidence of pre-Columbian occupation. A minority of these sites lay within the area predicted by Mann (2005) to be heavily occupied, but this pattern may reflect the relative abundance of lakes suitable for paleoecological study as much as it does human distribution. Most of these lakes were chosen for the purpose of looking at the vegetation history of the particular area, not as a random or even representative sample of Amazonia. At the scale of Figure 4, it is not always possible to show individual lakes, and so if one or more lakes in a cluster show human activity, then the district is circled. At the broadest scale – whether a region shows human impacts or not – it appears that Amazonia was broadly, and possibly universally, influenced by people.

Looking at the lake data on a finer scale, however, shows the dangers of extrapolation. Three lake districts in which multiple lakes have been analyzed provide similar spatial extents of human activity in widely separated Amazonian landscapes (Athens and Ward 1999; Weng et al. 2002; Bush et al. 2007). In two settings, Prainha and Maldonado (Figure 6a,b), one lake has an unambiguous record of occupation and agricultural use from about 4000 years ago until ca 1600 AD. The third location, a swamp named Maxus 5, near Yasuni in Ecuador (Figure 6c), lies in wet forest that has very little seasonality. This site has a long record of charcoal in its sediment, while two neighboring wetlands have none. Human occupation in this landscape is more tentative than in the other settings, as no crop pollen or artifacts are associated with Maxus 5. Nevertheless, the discovery of charcoal at just one of three settings is a likely indicator of human activity. The forest at Yasuni receives ~2800 mm of precipitation each year, with no distinct dry season, making natural fires exceptionally rare, if not totally absent. That only one of the three sites contains charcoal, and that the charcoal was found in multiple samples, adds strength to the suggestion by Athens and Ward (1999) that the charcoal was produced by local human activity.

In the Maldonado lake district, the paleoecological record of human activity at Lake Gentry is supported by
the presence of stone tools and a midden adjacent to the lake. The paleoecological markers of human occupation at this lake, corn and manioc pollen and charcoal, indicate that agricultural activity in the region began around 4400 years ago, with as much as 3000 years of burning prior to that time. Similarly, at Lake Geral in the Prainha group, corn pollen was found regularly between 4000 and 400 years ago (Bush et al. 2000, 2007c), and regularly occurring charcoal appeared between 8000 and 400 years ago. However, in both the Maldonado and Prainha groups, other lakes showed either a small increase in charcoal abundance or no charcoal whatsoever, and none contained pollen from corn or manioc. These records suggest that human occupation and land conversion were local in nature. Sites within 3–5 km of an occupation center appeared to be quite heavily used but, beyond this, human influence declined markedly, so that at distances of 50 km there was no evidence of human activity. This pattern is very similar to that described by modern anthropologists, where hunting and land management is concentrated in a 1–3 km radius around the center of habitation (Glanz 1991; Apaza et al. 2002).

The absence of humans in these records is also striking in another way. In both the Prainha and Maldonado lake districts, human population collapses followed European contact, as both crops and charcoal disappear from the records in the past 400 years. Notably, the apparent collapse is evident even at sites that were never visited by Europeans, providing unambiguous support for the anthropological and historical hypotheses of widespread epidemics.

An overall picture is clear: the paleoecological data confirm that Amazonia was exploited by indigenous peoples who practiced agriculture and developed urban centers (Roosevelt 1980, 1991; Roosevelt et al. 1991; Heckenberger et al. 2007), and the populations collapsed shortly after European contact. However, the data do not support the extrapolation of observations from occupied sites to infer uniformly widespread impacts and landscape transformation. There is no doubt that humans are important transformers of Amazonian landscapes and have been so throughout much of the Holocene. Determining how widespread those effects were is in the vast area of the Amazon basin, particularly those far from water, requires further study. Specifically, it requires a research program that integrates existing data with new samples taken in ways that allow inferences to be made about broader Amazonia.

Two other observations emerge from analysis of the charcoal data from Amazonian soils. The peak of fire frequency was observed not when human populations were presumably at their largest (i.e. immediately prior to European contact), but at ca 700–800 AD (Figure 3b). This period was thought to be one of peak El Niño activity (Thompson 2000), when droughts beset Amazonia and forests were more highly flammable. It is highly probable that the great majority of these fires were human-induced, but that during periods of intense drought, large areas were burned (making them more likely to be detected today) when small-scale fires escaped to become wildfire. In this way, the spatial scale of human disturbance in Amazonia as a whole does not necessarily track the intensifying history of local land use in the most populous areas. The capacity of humans to disturb the system appears to have been strongly influenced by climatic conditions, not simply a growing human presence. In addition, the time for post-disturbance forest recovery in these settings is not the 500 years implied by the disease model, but > 1000 years.

One model of human settlement in Amazonia does incorporate known and inferred densities at the landscape level, albeit through observations of the preferences of modern indigenous populations. Denevan (1996) proposed a bluff model of human occupation, in which indigenous peoples preferentially settled sandy bluffs alongside rivers and where there were views over wetlands. Denevan estimates that as many as 10 million people lived in these densely populated riverbank settings. With just 400,000 scattered through all the rest of Amazonia, the impact of people outside the high-density locations may have been very limited. The paleoecological data are entirely consistent with the long-term aggregation of people around key landscape features implied by Denevan’s settlement model, and the inference that the rest of Amazonia was lightly settled.

Seasonality and location

Although our knowledge of past human occupation in Amazonia is still in its infancy, the case for extensive occupation and use of the landscape by pre-Columbian human activity in Mesoamerica is clear. We need to develop hypotheses that predict where humans would have existed in Amazonia at densities sufficient to alter landscapes. For example, one initial prediction might be based on seasonality. Civilizations such as the Olmec, Maya, and Aztec
flourished in the highly seasonal settings of the Yucatan and central Mexico. In landscapes with stronger gradients between ever-wet and seasonal forests, such as in Panama and Costa Rica, the dense populations may have deforested the seasonal areas (Piperno et al. 1991), whereas impacts on the dense, wet forests of the Caribbean slope were never as great (Dickau et al. in press).

A similar pattern may also have prevailed in Amazonia, with highly favorable areas supporting large populations. Figure 7 shows the major archaeological sites that have been described. The main Amazon channel is clearly important as a trade route, and also as an excellent source of fish, shellfish, and game. Within this setting, the confluences of rivers became centers of settlement and population hubs, as did the mouth of the Amazon. Away from this ribbon of occupation, signs of human habitation can be found scattered across Amazonia. Of the areas further away from the major rivers, the most complex cultural development appears to have occurred in the seasonal (defined as having the greatest intra-annual monthly variability in rainfall) locations of southern Amazonia (eg Heckenberger et al. 2007). This incorporation of seasonality as a factor paralleling geographic location may form a powerful predictive model for where major occupation sites are likely to be found.

Our contention that pre-Columbian transformation of Amazonian landscapes was essentially local and spatially predictable does not contradict the development of complex societies (Heckenberger et al. 2003; Heckenberger et al. 2007) or that substantial areas were influenced by human activity (Balée 1989), but it is at odds with assertions regarding the generality of disturbance in Amazonia, particularly broad-scale, intensive disturbances. More importantly, our admittedly preliminary analysis provides a set of predictions and a means for testing them, so that we can update our model of past human disturbance in the Amazon, and of the effects of the different kinds and intensities of disturbances on Amazonian forests.

### Asymmetry of policy

Some years ago, Bush and Colinvaux (1994) showed that two lake records from the Darien region of Panama demonstrated surprisingly long histories of human disturbance and abandonment. Since then, logging companies have attempted to use that paper to justify timbering some of these remote forests, arguing that, if the region supported cornfields 500 years ago, the forest ecosystems must be young and resilient, and that, therefore, logging now would not lead to loss of biodiversity. The problem with this argument is that the real scale of disturbance is ignored. The extended-family, slash-and-burn farming style of pre-Columbian times would have had a very limited impact on these systems. Certainly, there may have been much larger impacts around major population centers, but the case has yet to be made that the halo of human influence was anything other than local for the great majority of settlement sites.

There is no question that more effort needs to be invested in obtaining a clearer picture of the extent of pre-Columbian settlement and alteration of Amazonian habitats. In the meantime, it would be prudent for ecologists to dig a soil pit on their research site and analyze the soil for charcoal (in tropical soils, manganese and titanium also form black accretions that are strikingly similar...
cal interactions may greatly increase the amount of forest (Peres 2005). Trophic cascades and other strong ecological disturbances may also be disrupted by such disturbance to the maintenance of diversity, and regeneration after disturbance, than just trees, and the plant–animal interactions crucial to the structure of tropical forests (Silman et al. 2003). In appearance to charcoal) to determine the probability that they are working on an impacted site. However, it would be sensible for policy makers to assume minimal past impacts at sites away from major rivers and known archaeological centers.

If policy makers err on the side of underestimating past human impacts and the forests are truly more resilient than we believe, the forest may be overprotected. At worst, this policy conserves a resource for later exploitation and buffers against disruptions of ecological interactions, such as trophic cascades, which may be vitally important to the structure of tropical forests (Silman et al. 2003; Terborgh et al. 2006). If, on the other hand, the error is in overestimating past exploitation and assumed forest resilience, then forests are likely to be used unsustainably, and in ways that may have broad repercussions in the face of climate change. A particular worry is that increasing fragmentation will lead to more frequent fires in the future (Nepstad et al. 2001), and will also impede plant migration in the face of climate change (Ibáñez et al. 2006). Worse still, Amazonian forests are much more than just trees, and the plant–animal interactions crucial to the maintenance of diversity, and regeneration after disturbance, may also be disrupted by such disturbance (Peres 2005). Trophic cascades and other strong ecological interactions may greatly increase the amount of forest resilience, then forests are likely to be used unsustainably, and in ways that may have broad repercussions in the face of climate change. A particular worry is that increasing fragmentation will lead to more frequent fires in the future (Nepstad et al. 2001), and will also impede plant migration in the face of climate change (Ibáñez et al. 2006). Worse still, Amazonian forests are much more than just trees, and the plant–animal interactions crucial to the maintenance of diversity, and regeneration after disturbance, may also be disrupted by such disturbance (Peres 2005). 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Dickau R, Ranere J, and Cooke RG. Starch grain evidence for the preceramic dispersal of maize and root crops into tropical dry and humid forests of Panama. Proc Natl Acad Sci USA. In press.


