A Big History of Land Clearance and Deforestation

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Abstract: The gathering and hunting humans who evolved from earlier manifestations of *Homo* changed the distribution of forests on the planet through their use of fire to direct biological productivity to their sustenance, and through their contribution to the elimination of much of the global terrestrial megafauna. Land clearance at any scale awaited the development of agriculture, the several independent origins of which may indicate that it is an emergent outcome from the combination of a social animal who can transmit knowledge through generations and who lives in environments that support high numbers of food plants. The transition from uncleared forest and treeless land to land cleared for agriculture was slow, often reversed, and limited by the necessity to produce more energy in food production than in the inputs that created comestibles. Increases in cleared land until the nineteenth century were largely a product of the displacement of gathering and hunting people by disease-ridden European agriculturalists and world trade imposed on non-Europeans by colonialists. The explosion in fossil fuel usage from the nineteenth century onwards enabled exponential growth in human populations and cleared land, with the consequence of a crash in forest cover. Ironically, attempts to mitigate global warming caused by increased fossil fuel use, deforestation and land clearance have resulted in more land clearance for biofuels. While settlements, roads, logging, plantation establishment and dam construction have all contributed to the decrease in the native terrestrial cover of the planet, their contribution has been minor compared to the massive impact of agricultural development.

1. Purpose and Definitions

During most of the long history of the physical and cultural evolution of the human animal, our interactions with the rest of nature were not without effect on the vegetation that directly or ultimately supports us, but the effect was probably no more than that of many other vertebrate species, such as penguins, or even invertebrates such as termites. Our development of fire technologies and commensal relationships with other mammal species resulted in vegetation changes over much of the planet but did not totally replace indigenous biotas. Our invention of agriculture marked a transition from modification to transmogrification. In the early 2020s, the transmogrification is extreme, with most of the terrestrial areas of the planet not having vegetation that resembles that of the early Holocene, only ten thousand years ago. The processes of clearance and deforestation are not slowing, despite their effects in exacerbating climate and biodiversity crises.

In this paper I address the history of land clearance and deforestation. I am concerned with both pattern and process: the spatiotemporal patterns of change; and the ecological and cultural drivers and accidents of change. I adopt an ecological perspective in placing human activity in the context of energy and material flows in ecosystems. My thesis is that clearance and deforestation are symptoms of the increasing capture of energy and material resources by one species, ourselves.

I define clearance as the replacement of native ecosystems with bare ground, artefacts or largely exotic ecosystems, where exotic refers to taxa that were not native to a locality before agricultural societies covered most of the world, and 'largely' refers to biomass, or the dry weight of the living things in the ecosystem, rather than the proportion of species, which is always biased towards native because of the profusion of fungi, microbes and other cryptic species found everywhere on the planet where conditions suit. In using accounts of land use change, such as that of Goldewijk et al. (2017) 'I do not count 'rangeland' as land clearance, because rangeland is typically largely composed of native species. Deforestation is defined as the elimination or reduction of trees to less than 10% projective foliage cover (Specht 1972). Trees are in turn defined for my purposes as woody plants more than 5 m tall, also following Specht (1972).

2. Our Precarious Planet

The limited set of conditions in which we know life occurs may be widespread in the universe. Alternatively, a series of random accidents, still ongoing, may have allowed life to develop on our planet in a nonentity solar system on the rim of a nonentity galaxy. Some of us appear to be desperate to find other life, elsewhere, to refute our suspicion of chaos and allay our fear of singularity. Yet, the history of life on planet Earth seems more consistent with the hypothesis of randomness, rather than inevitability. Our geological timescale is defined by extinctions caused by random meteorite strikes, random volcanic eruptions, random driftings and collidings of continents and the side effects of particular forms of life getting out of hand. Our planet, a non-renewable resource, wobbles around a sun that we believe is doomed to life-destroying bloating and eventual extinction.

During the last 2.8 million years, the planet transitioned from forest from the poles to the equator to a series of oscillations between icy extremes and slightly more balmy interludes, in which deserts were as characteristic of the terrestrial environment as forests. We are moderately confident that our species had nothing to do with this new state apart from labelling it as the Tertiary-Pleistocene transition, as we have no fossils closely resembling us from that long ago.

3. Life in Ecosystems

One way that our species thinks about the living components of the ecosystem in the 21st century is through the lens of Linnaean classification. The process of evolution can be gradual, as with the stooped ape to upright financial executive series we are so fond of depicting, or sudden, as with polyploidy, the doubling of chromosomes which prevents interbreeding. Both of these processes tend mostly to result in sets of populations of organisms that are relatively uniform genetically within and separated from other sets of organisms by genetically-based morphological or physiological discontinuities. Linnaeus labelled these plateaus in variation as species and formalised their nomenclature. Most were recognised in the vernacular before Linnaeus was born, First Nation taxonomies having been shown to closely resemble scientific taxonomies, with sometimes greater division of useful entities and lesser division of the superficially useless (Berlin 1992).

Species interact, most often in minor ways, but sometimes catastrophically. For example, the fox (*Vulpes vulpes*} is believed to be largely responsible for the extinction and endangerment of much of the marsupial fauna of Australia since its introduction in the 19th century (Woinarski et al. 2015). The principle of competitive exclusion states that no two species have the same position within the ecosystem, because if they did, one would competitively displace the other. So, the introduction of a new species will change ecosystem processes, as would the local extinction of a species, or even decreases or increases of populations of existing species.

A penguin trudges from the sea along a well trod path cut into the slope. An occasional predatory skua swoops. The path debouches into a wide bare space occupied by many other penguins, chicks at feet, an adult peck apart (Fig. 1). An occasional flurry marks a dive bombing from above. Subantarctic Macquarie Island saw no humans until the 19th century, land clearance being the province of penguins and

Fig. 1. A penguin breeding colony on Macquarie Island (Source: Collection of author). Note the complete vegetation cover in the absence of penguins and the pathway leading to the sea.

seals in their breeding colonies. Ecosystem interactions can result in the baring of ground of visible native vegetation we call land clearance or the mass death of trees that we call deforestation. Mammal and bird breeding colonies bare the ground, while outbreaks of herbivorous invertebrates can result in mass death of trees. These phenomena are likely to have occurred well before our ancestors ceased stooping.

More spectacular prehuman examples of land clearance and deforestation occurred through the agency of extreme climatic and geologic events. Volcanic eruptions, landslides, floods and fire are just a few examples of clearance and deforestation causal phenomena that are well documented in the geologic record.

Given that land clearance and deforestation are not just outcomes of the activities of the human animal, there is some interest in the degree to which we have been responsible, because responsibility implies a possibility of restitution.

4. Importance of Clearance and Deforestation

History cannot help but be written from perspectives that might have seemed bewildering to those who are its subjects. In 2022, the prospects for humans and other beings are clouded by linked crises: exponential climate change fuelled by human activities; accelerated extinctions of species; a high probability of conflict with nuclear weapons. In this context, it is not surprising that some of the themes that weave through the present paper are the energetics of agricultural systems, their effects on the rest of nature and the interaction of clearance and deforestation with conflict between human groups. Until fossil fuels dominated economies, the need to produce more energy than was spent producing food was so obvious that it did not need mention. Until the European conquest of most of the globe, it could be assumed that the elimination of species from a home region was unlikely to mean its total demise, in a context in which wild species and wilderness were seen as dangers to humanity, best eliminated, albeit with great difficulty. There would be no bewilderment in relation to warfare.

Land clearance and deforestation bear a large proportion of the responsibility for the steep part of the climate hockey stick, shown here for daily maximum temperatures in the city in which I live (Fig. 2). Food systems alone are estimated to account for one third of greenhouse gas inputs to the atmosphere (Crippa et al. 2021). Agricultural crops, sown pastures, deforested land under heath or grassland and even tree plantations hold and catch less carbon dioxide than the vegetation they replace. They have less biomass (weight of living things) than the original vegetation which in turn means that the carbon stored in the soil has a lower equilibrium level. These soil carbon stores can take centuries to reach equilibrium after a change in biomass, meaning that the great clearance and deforestation surge of the last few centuries still contributes new carbon to the atmosphere (Dean et al. 2017).

Given that clearance and deforestation are mechanisms to divert resources from other ends to human beings, other sentient and non-sentient beings suffer collateral damage. Not only are many individuals of species killed to protect crops and stock, the sustenance that innumerable species gained from the cleared and deforested areas is no longer available. The rarer of these species, and those concentrated in the habitats most valued by humans for clearing have been, and will be, pushed into extinction. That is an outcome that is generally seen as undesirable among contemporary humans, who have been known to reintroduce wolves to places in which they had been laboriously extirpated (Smith and Peterson 2021).

In the context of preventing extinction of other species, warfare can be a plus, if it devastates agricultural civilisations to the extent that their cleared land is reinvaded by native species, as was likely in the apparently symbolic salting of the fields of Carthage by the Romans when the whole population was enslaved and the city destroyed (Ridley

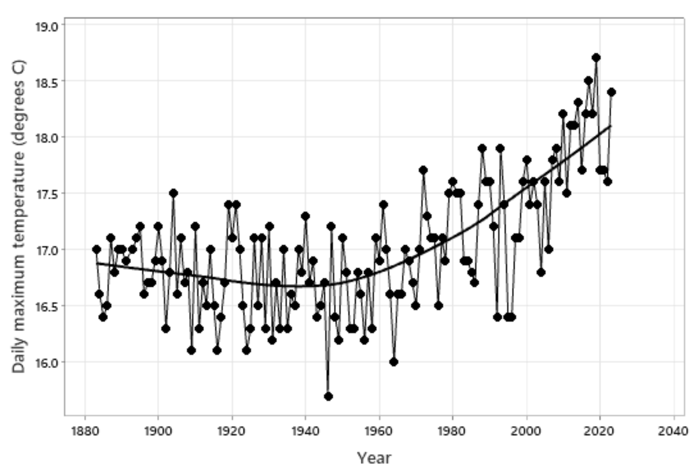

Fig. 2. Mean daily maximum temperatures by year for Hobart, Tasmania, Australia. Created by author from data from Bureau of Meteorology, Australia. Lowess line fitted.

1986). Nuclear warfare could not only cause global cooling, but also make much of the farmland humans currently occupy too dangerous to crop. The native plant and animal species have persisted after the Chernobyl power plant explosion (Deryabina et al. 2015), albeit not always in the peak of individual health (Mousseau 2021). The human population crash that would result from nuclear war may save a few other species. The abandonment of cleared land would result in a rapid uptake of carbon dioxide, mitigating or even reversing the hockey stick problem.

5. The Hair-Challenged Ape

There are probably no attributes of the morphology and behaviours of human beings in the species *Homo sapiens* that are totally peculiar to us. We have witnessed, or perhaps caused, the extinction of several other human species, some of whose genes survive within us. Excluding them from consideration, we can see non-human species, such as monkeys, using tools. Other species, such as whales, use language, predatory birds use fire, termites build complex cities, ants farm, bower birds create art, and wolves construct complex networks of social relationships. We have to be satisfied with degree, and emergent attributes from combinations of characters for our behavioural distinctiveness, rather than being distinct in kind. A lack of hirsuteness and the spectacularly large buttocks that keep us upright make us physically distinct from non-human mammals, but we are essentially the third chimpanzee of Diamond (1992), genetically almost identical to other mammals and not so genetically different from plants.

Our obvious animality would not have embarrassed our gathering and hunting ancestors but sits uncomfortably with the notion of human exceptionalism adopted by most of us today. If exceptionality exists, it is in the scale of our social relationships, and our ability to propagate and accept myths, ideologies and technologies among our global population as a whole (Harari 2011). As a small group social animal we have evolved to accept small group social and cultural understandings without critical thought, but also to use our verbal interactions with the rest of the social group to argue our path to better ways when they appear to be necessary. People have rejected old wisdom very rapidly once they subject it to discourse in changing objective circumstances. We have been a highly opportunistic species, capable of adapting to the ever-changing climates of the Pleistocene and Holocene by developing new technologies and fantasies.

6. Deforestation and Land Clearance by Gathering and Hunting Humans

The great attraction of prehistory to scholars is that the scant evidence can be incorporated into many different tales. Evidence is particularly sparse in relation to the time when humans evolved from their ancestral hominids. The multiregional origin hypothesis has been taken to suggest we began to evolve 1.8 million years ago, while, in an alternative more accepted hypothesis, our split from *Homo neanderthalensis* is suggested to have occurred between 550 and 765 thousand years ago (Stringer 2016; Galway-Witham and Stringer 2018).

The evolution from the predecessor taxon to *Homo sapiens* is likely to have been so gradual as to be imperceptible at the time, making the temporal boundary between the two taxa somewhat arbitrary. The sparse fossil evidence has been interpreted to mean that, for many millenia, we were one amongst several hominids. Breeding barriers between hominid species appear to have been weak, as were behavioural differences. For example, the people who left fossils since labelled as Neanderthal made tools and created artwork in caves. Their genes survive in the *Homo sapiens* genome. If one were a lumping taxonomist, there might be just one, not many, species of *Homo*.

Gatherering and hunting societies dominated the planet for most of human history and prehistory. Archaeological and anthropological observation have given us some insights to their functioning (Ingold et al. 2010, 2021; Sutton and Walshe 2021). Like chimpanzees, human beings formed social groups of about 20-30 animals who co-operated in gaining food, creating artefacts to collect the food and creating culture to stimulate their brains during the large amount of time not used for maintaining life. Based on observations of such societies by anthropologists, less than 15% of waking hours were devoted to activities that would be labelled as work in contemporary western societies. Human beings formed larger aggregations than the group which came together at places and times where and when food was profuse to talk, party and exchange genes. The groups that formed these predecessors of nations spoke the same languages, had the same customs and world views and sometimes fought with adjacent groups, although many were too peaceful for their own good when facing off expansionary agricultural or industrial people.

We know that gatherers and hunters who were observed by literate peoples were highly diverse in all aspects of life from who slept with whom to diet, which varied from almost entirely plant-based, as in some Californian peoples, to almost entirely animal-based, as in Inuit societies. Once established, they persisted indefinitely unless displaced by invaders, like the British in Australia, or environmental change, such as the sea level rise following the Last Glacial. Knowledge was effectively passed on through thousands of years through song, dance and story, as with the stories of the inundation of Port Philip Bay in Victoria, Australia 6500 years ago (Nunn and Reid 2016). Customs and culture appear to have reinforced the sustainability of resource use. People regarded themselves as part of the ecosystem, and often believed that their spiritual ceremonies, rather than their land use customs, bought food to their mouths (Sutton and Walshe 2021). People were a part of 'country'. That is not to say that gathering and hunting societies were totally static. There is evidence of rapid take up of new technologies. For example, dogs, *Canis familiaris*, were almost immediately adopted by the indigenous people when the British brought them to Tasmania (Boyce 2010). Archaeologists have documented many changes in technology, art and diet over many thousands of years, indicating our high adaptability to contingent circumstances.

Terrestrial megafauna are in short supply everywhere at present, but survived longest where human beings appear to have been the longest, in Africa. The suggestion that megafauna survived in Africa because they co-evolved with proto-humans and humans is attractive given the extinctions in large animal and bird species that followed soon after the human diaspora to places like the Americas, Australia, Malagasay and New Zealand (Burney and Flannery 2005). The hypothesis that invading humans hunted the young of big animals, thereby causing their extinction (Johnson 2006) does not imply that people wiped out species with intent, for the consequences of feasting on a young *Diprodonton* may not have been apparent until their parents died. However, if they knew, they may not have cared, many of the megafauna being notoriously bad neighbours. The species that became extinct after the first wave of humans tended to be those with a long period between birth and reproduction (Johnson 2006). Some scientists have questioned the responsibility of people for the extinctions of large animals in Australia and the Americas, preferring not to exclude climatic variation as a cause (e.g. Choquenot and Bowman 1998; Mann et al. 2019) in a context in which the climatic variation in some earlier glacial-interglacial cycles was much greater than in the last cycle when the large animals became extinct. The climate cannot reasonably be blamed for the extinction of Moas in New Zealand only a few hundred years ago.

As interesting are the debates about our degree of responsibility for the demise of big things, we are more concerned herein about the possible consequences of extinctions caused by humans on forest cover and bared ground. Mammoths may have enjoyed a decent wallow in mud, like elephants. Some of the extinct herbivorous species may have prevented trees from invading into grasslands or may have aided the spread of trees through endozoically dispersing and fertilising their disseminules, as is thought to be the case with *Macrozamia* in Australia (Burbidge and Whelan 1982; Hall and Walter 2013). These types of subtle consequences of likely human-caused extinction cannot be readily picked up in pollen, macrofossil, stratigraphic and archaeological records, mainly because the invading humans used the tool of fire to manage landscapes, a usage that almost certainly reduced forest cover and obscured more subtle impacts.

The amount of charcoal and the variety of pollen and macrofossils in sediments and organic deposits have allowed us to be confident that, in most parts of the world, the fire regimes that preceded humans were very different to those that followed our invasions into new lands, and that the change in fire regimes had a net effect of causing forest to retreat in favour of grassy ecosystems and treeless heath and scrub (e.g. Kershaw, Bretherton and van der Kaars 2007, Kershaw, McKenzie et al. 2007). This evidence is in the form of different vegetation and charcoal responses to glacial-interglacial climate change before and after humans invaded.

In Australia, the overwhelming of gatherers and hunters by agricultural people occurred only two centuries ago. The impact of gathering and hunting people on forests is much more easily deduced than elsewhere. There is no doubt that gathering and hunting people in Australia deliberately burned woody vegetation to produce herbaceous vegetation rich in food plants and game. Some of the strongest evidence is from the rapid reinvasion of trees after gathering and hunting societies were dispossessed (Fletcher et al. 2021) and from eyewitness accounts of burning by Indigenous people on the cusp of their dispossession (Gott 2005; Foreman 2020). These eyewitness accounts document the process of burning, down to the protective clothing worn by those engaged in ignition (Foreman 2020), as well as the process of protection of some vegetation from fire to provide shelter for hunted animals (Plomley 2008). Anthropogenic fires were usually small and patchy, burning to the footprints of each other, and only of sufficient intensity to set back invading shrubs and trees. Fire was also used in warfare between gatherers and hunters. Fires also occurred accidentally and from natural causes such as lightning and volcanic activity. In most places, fires resulting from natural ignition result in different vegetation structures to the fires resulting from ignitions by humans. For example, a five year interval between fires, adopted by gathering and hunting people in forests and woodlands in southeastern Australia (Gott 2005) maximises understorey grass cover (Kirkpatrick and Jenkinson 2022), whereas the more occasional large natural fires tend to result in dense woody understoreys.

Humans were not only grassland and savannah animals. Gatherers and hunters lived in and off forests in all parts of the world where forests could grow. Burning by humans did not prevent the reinvasion of forests into grasslands, tundra and treeless high country during the transition from the height of the Last Glacial to balmy and moist interglacial conditions of the Holocene. Burning by gatherers and hunters moved the forest boundary to a moister position than it would otherwise have been and tended to result in forest with open understories and fire-resistant trees, but the effects were marginal, rather than transformative, with climate change the main influence (Kershaw et al. 2002).

Behaviour with some of the characteristics of agriculture and animal husbandry has been well-documented for gathering and hunting people (Sutton and Walshe 2021), to the degree to which Pascoe (2014) argued that the gatherers and hunters of Australia were engaged in agriculture and aquaculture. Hynes and Chase (1982) coined the term domiculture to describe activities such as the replacement of myrniong (*Microseris lanceolata*) tops described by Gott (1982) and the placement of discarded parts of food plants on middens (Sutton and Walshe 2021). The distinction made between domiculture and agriculture is that the latter involves the intent to produce a new crop by planting seeds or tubers, whereas the former was simply food plants being reproduced by the discarding of their waste. Some of the examples given by Sutton and Walshe (2021) seem to involve intent, but certainly did not involve clearance or deforestation with the intent of producing food from agriculture.

Gathering of vegetable foodstuffs could be intensive enough to largely bare the land, as with the case of the myrniong. Gatherers and hunters also bared the land by building temporary or permanent villages and religious monuments, such as Gobekli Tepe in Turkey, where Harari (2011) suggests the urge to co-operate in constructing a religious monument could have motivated the domestication of wheat.

7. Commensalism Clears Forests

If one perceives that the whole landscape, living or dead, is sentient, as many gatherers and hunters appear to have done, even if in jest (Willerslev 2013), co-operation with other species might come easier than to a Cartesian dualist. If wild animals feel unthreatened they can be fed by hand and become attached to their feeder. If the feeding persists their young may be raised with the young of the other species, with the young most friendly to their providers being favoured in provision. Possibly in this manner, wolves evolved to become the dogs that love us, protect us and co-operate with us in hunting and herding our commensal grazing animals. The date for the domestication of the dog has steadily trailed backwards and will probably continue to do so. Mutation rates established through genomic analyses indicate a divergence of dogs from wolves 20,000 to 40,000 years ago. The oldest undisputed archaeological remains of dogs with humans is dated approximately 15,000 years ago (Irving-Pease et al. 2018).

The herders of Eurasia, Africa and the Americas replaced wild grazing animals with commensal grazing animals. Humans manage the landscape to maximise the flow of energy to our herds and thus us. We want savannahs and steppes, not dense, dank forests, so turned forest into lawn by burning and grazing. Sheep are particularly effective in suppressing woody regeneration after burning (e.g. Willems 1983). Goats preferentially consume woody vegetation with or without burning (e.g. Warren et al. 1984).

8. The Fall

The transition from gathering and hunting to agriculture and animal husbandry is likely to have been almost as gradual as the transition from proto-human to human. Agriculture may be an emergent outcome from the evolution of a social animal who can transmit knowledge through generations and environments that support high numbers of food plants, as it happened independently in several places. Gatherers and hunters controlled their populations in a variety of ways, ranging from extended breast-feeding to infanticide, all having the effect of living within the means provided by their territories. Why would they want to laboriously produce more food, when food was plentiful and took little and enjoyable time to obtain? The answer is usually 'by unfortunate accident'. This is the story of The Fall.

The story of The Fall involves the unconscious selection of food plants suited to fertile places disturbed by humans, the consequent establishment of permanent settlements, the growing of more food by breaking up the land and sowing seeds or burying vegetative material, and somewhere in this sequence, and most importantly, the easing or abandonment of social mechanisms for restricting population size.

Warfare was rife between many groups of gatherers and hunters, but not all, with deaths through violence judged from one set of skeletal remains in Sudan equalling 40% of all deaths, while other sets of remains elsewhere show next to no evidence of violence (Keeley 1996). Whether warlike or not, an agricultural band with a large population can easily displace gathering and hunting people from potentially cultivable areas, so agriculture and animal husbandry spread like a slow cancer from several independent nodes. The products of metastasis did not always persist, there being places where people abandoned agriculture to return to gathering and hunting, often because their agricultural activities were not sustainable (Diamond 2005).

Neolithic agriculturalists were the first of our species to clear extensive areas of land of native vascular plants. In the space created by clearance, they grew plants and animals that they domesticated into forms, physiologies and behaviours that suited their needs. As agriculturalist and pastoralists, we directed the energy of the sun and the nutrition of the soil to our own sustenance in places that formerly supported a rich variety and large biomass of non-commensal life.

Just because it is possible to grow crops does not mean that crops can be grown indefinitely. Early agriculturalists often cleared land then found it produced but one or two crops. Crops depleted nutrients, there was accelerated erosion and the loss of the cycling of nutrients between forest and soil prevented any replacement. The cleared land was thus rendered incapable of producing further crops in the short term.

The romantic wild heaths of western Europe are largely human-induced degradation states of forests that grew on low nutrient soils. Evidence of both cultivation and trees is found below the deep organic soils that now support a species-poor heathland (e.g. Prosch-Danieisen and Simonsen 2000). The removal of the trees by humans reduced evapotranspiration. Waterlogged soils and low nutrient levels slowed the breakdown of organic material, causing runaway paludification (the process of peat-forming). The peats drain more slowly than the sandy soils beneath, accelerating the process.

Agriculture on slopes often resulted in soils too shallow and rocky to cultivate as soil exposure results in accelerated erosion. The redistribution of sediment from slopes to valleys seldom improves the agricultural worth of either.

The deep red lateritic soils of the wet tropics (ferrosols) can become bricklike with the exposure to the elements that follows clearance. The nutrients in tropical forest systems circulate between ferrosol and forest in an almost closed loop, so the liberation of those in the trees by human burning is soon followed by a liberation to groundwater and out of the place. People eventually realised that if their agricultural occupation was brief, the forest would rapidly return, as would the fertility of the soil, fed by the cyclic salts in rainwater. People shifted their cultivation between years to preserve the positive balance between return in energy from crops and expenditure of energy in preparing and nurturing gardens (Rappaport 1971). Starvation was the reward for misjudgement of the time needed for resting beneath the regenerating forests, so shifting cultivation required ecological perception and cultural reinforcement of norms.

More fertile soils than ferrosols are found in the tropics, such as those that develop on basic volcanic deposits and alluvium derived from them in Indonesia and Niugini (New Guinea). Here the frequency of fallowing can be reduced, sometimes to zero. We are fortunate to have a record on film and in prose of the lives of a Neolithic (Stone Age) agricultural society in the highlands of Niugini (Gardner and Heider 1969). In the early 1960s, the Dugum Dani were untouched by the lives and customs of the post-Neolithic world. Warfare between adjacent groups was ritualised into a sacred part of the functioning of the society. The alluvial valley floor was decorated with a complex pattern of drainage channels and mounds on which a variety of tuberous plants were continuously grown. On the lower slopes of the high mountain valley shifting gardens were established by ringbarking large trees and grubbing out small ones, all with stone tools. The dried dead vegetation was then burned to fertilise the crops. The environment fixed the limit of human population, which was regulated into constancy by warfare and other less drastic cultural means (Gardner and Heider 1969). Like gatherers and hunters, Neolithic agriculturalists avoided the tragedy of starvation where possible by living within their environmental means, which the inhabitants of the nearby Baliem Valley did for 7,000 years (Haberle et al. 1991). Such avoidance was not always possible for those who lived on the flood plains of major rivers or close to active volcanoes.

Neolithic agricultural societies not only cleared vast areas of land by deforestation and/or drainage, as with the Dani, but also acted as geomorphological and edaphic agents. The construction of elaborate water distribution and diversion systems on flats and terraces on slopes was achieved with stone tools. Neolithic people also worked out how to turn poor soils, suited only for shifting cultivation, into soils suited to semi-permanent agriculture. The lazy beds of western Ireland mixed infertile peat with shells and marine algae (Bell 1984). The addition of charcoal to soils was worked out by many groups to help enable protracted cultivation. The legacy of this type of work is still seen in the terra preta soils of the Amazon Basin (Petersen et al. 2001). In the Niugini highlands, Neolithic agriculturalists of 1200 years ago worked out that a fallow cover of *Casuarina* trees would restore nitrogen to their soils (Diamond 2005). These discoveries enlarged the area potentially clearable and maintainable as cleared.

One major problem with agriculture is that it is easily disrupted by marauding pastoral hordes and other invaders; Assyrians descending on the fold. Once a crop cannot be sown or stock and stored food is destroyed or stolen, starvation awaits most of the victims, whereas in gathering and hunting societies their food persists until the invaders transform the landscape.

Agriculturalists who aggregate themselves can achieve population totals and densities well beyond the gathering and hunting band. They can afford the protection of armies. Such protection can be a twin-edged sword as the empires that develop are parasitic on agriculture, consuming its surplus. Those who rule and fool and kill in such empires are the last to starve if things go wrong, although emperors and kings had a high rate of violent demise even when things went more or less right (Saleh 2019). These empires may have enabled the expansion of clearing for agriculture to places previously recalcitrant, an expansion that was often associated with the development of the hydraulic civilisations of Geertz (1970). Hydraulic civilisations required an enormous degree of co-operation to maintain highly complex irrigation systems. This co-operation was helped by the development of religions that reinforced desirable complex social behaviours.

Hydraulic agriculture did not always result in a permanent transition from natural to cultural vegetation, witness the now largely infertile Fertile Crescent where agriculture may have first evolved. Hydraulic agriculture in arid and semi-arid regions outside perennial exotic rivers like the Nile is precarious, often being abandoned to desert more saline than when first cleared. Flooding by big rivers both replenishes fertility and flushes the soil of salt, enabling agriculture to continue indefinitely unless the sediments are trapped upstream by dams, as has happened in the twentieth century on both the Nile and the Yellow rivers.

Other major reversals of natural vegetation loss occurred in forested landscapes subject to cultivation but not irrigation. There are many examples, the most famous being the collapse of the Mayan and Angkor Wat civilisations, with other less well publicised examples in temperate North America and Zimbabwe (Diamond 2005). In all cases there is some evidence, often disputed (e.g. Pikirayi (2013) for Zimbabwe), that an incapacity to produce sufficient agricultural surpluses led to the demise of once-thriving nations, population crashes and a consequent reinvasion of forests. The agricultural systems were not sustainable at the level of intensity that became required to maintain empire. At some point the overworking or inappropriate working of the land caused negative feedback. Such collapses are argued by Diamond (2005) to be not inevitabilities in most cases, but rather failures of governance and the elite decision-makers, with agricultural systems in similar environments persisting at high levels of productivity.

In some cases, the collapse of agricultural and pastoral societies was a clear result of environmental changes that cannot be certainly attributed to human activity. Up to 5000 years ago, the present Sahara Desert was green, supporting many beneficiaries of the Neolithic Revolution. Changes in the global circulation system induced extreme aridity and the consequent retreat of most humans to oases and desert edges (Williams 2000, 2021). Similarly, the collapse of Norse communities in Greenland appears to have been at least partly associated with the climatic deterioration of the Little Ice Age (Diamond 2005).

The big success in hydraulic agricultural systems was wet paddy rice agriculture, the net effect of which was to conserve or improve the soil, the soil being kept in place on the terrace banks by human transport upslope and algae in the wet paddies producing vital nutrients. This form of agriculture has persisted on steep terraced slopes for thousands of years. The maintenance of dry land terraces, such as those widespread in the Mediterranean countries have also perpetuated land clearance on steep slopes.

Other big successes in persistence in dry land agriculture have been in places where it is almost impossible to destroy the soils, or where the soils are so deep that we have yet to run through them completely. Non-Mediterranean western Europe has deep soils that have been rejuvenated by the last episode of glaciation, when most of its area lay under a giant ice cap. During the few millenia in which agriculture has been present on the planet, the climate in this region has been mild and drizzly. Drizzle is far less likely to cause accelerated erosion of soils than more intense rain. The combination of rejuvenated soils and a gentle climate has allowed agriculture to persist for many thousands of years.

The transition from the Neolithic Age to the Iron Age in Eurasia and Africa was associated with the development of more efficient farming implements than were previously available, and much more effective tools to fell trees than were previously available. The invention of the wheel helped cement the empires by improving the transport of food and providing a new mobile means of warfare, the chariot. These technological developments seem likely to have caused increased clearing and deforestation, at least in the short term. However, in land clearance and deforestation, as in other areas of human endeavour, technological determinism does not stand up to close examination. Agriculture was developed independently in the Americas. So was metallurgy and the wheel. Yet, metals were used only for ornament and the wheel for toys (Mann 2011). Empires and irrigation nevertheless abounded (Mann 2011).

9. The European Hegemony

The explosion of Europeans over the surface of the earth in the sixteenth, seventeenth and eighteenth centuries was powered by the renewable energy of wind for transport and the renewable energies of wind and water for industry. It was facilitated by the susceptibility of populations in many other places to the cornucopia of diseases that infected the Spanish, Portuguese, French, British and Dutch, but were novel and often lethal in differently diseased populations (Diamond 1997). Steel weapons may have helped a little (Diamond 1997).

The Americas were depopulated by diseases introduced by Europeans. There is debate on the estimate of 95% of a population of 90-112 million people killed by introduced diseases (Dobyns 1966), but there is no doubt that there was mortality massive enough to facilitate the Iberian, French and British conquests of the Americas. The natural revegetation of previously cultivated areas in the Americas in response to this human population crash has been suggested to be a possible cause of the Little Ice Age. (Lewis and Maslin 2015). The expansion westwards of the ‘frontier’ in the United States felled forests that had invaded previously cultivated land and occupied prairies created by extinct civilisations. There seems little doubt that much of the Amazon Basin was cultivated, including large areas of food forest along the river itself (Mann 2011).

The British invasion of Australia in 1789 introduced land clearance and logging to the continent (Kirkpatrick 1999). It also introduced stock, some of which were grazed with such intensity in native vegetation that they prevented tree regeneration, compacted soil, promoted shrub invasion and converted streams that meandered moistly through flats to flash-flooding incised gullies. The native eucalypts are difficult to clear, resprouting readily from underground organs called lignotubers after fire or felling (Kirkpatrick 1999). In more temperate parts of the continent, persistence was widely rewarded with cropland and sown pastures reminiscent of East Anglia or the Cotswolds down to the hawthorn (*Crataegus monogyna*) hedges.

Sailing ship technology enabled the transport of the produce of far distant colonies to Europe, which fueled its population growth by clearing far flung lands, the native inhabitants of which either would not have cleared, as in the case of Australia, or had no reason to produce more than they consumed. Taxes in a money economy fueled by debt and enforced by armed men provided motivation either for the native people that survived the shock of colonisation or the colonisers with their African slaves. The Little Ice Age gave way to the handle of the hockey stick.

10. The Great Release

The frontier mentality and the capitalist mindset had taken hold of many populations by the early nineteenth century, but most frontiers had met sea or inland desert and capitalist economies constantly required new resources to avoid crashing. The world without fossil fuels was limited in its scope for expansion of populations and wealth. It was caught in the Malthusian trap – population cannot grow beyond the capacity to feed it, while tending to grow to this limit. Our species temporarily broke out of this trap by using the energy trapped in organic detritus in dinosaur-ridden Jurassic swamps. Coal, then oil and gas, freed agriculturalists and other food producers from the age old necessity of producing more energy than they put in, until, in the early 2020s there is hardly a food product on the market that provides more energy than it costs to produce (Carlsson-Kanyama et al. 2003).

Fossil-fueled industrial agriculture has resulted in a massive increase in the area of cleared land on Earth (Goldewijk et al. 2017, Fig. 3). Although estimates of increases in cleared land vary, there is no doubt that there was an order of magnitude increase from less than 10 million hectares in 5000 BC to over 2000 million hectares in the second decade of the twenty-first century and that most of the increase took place after 1850 CE (Fig. 3). In 1850, each person was supported on average by 0.65 ha of cleared land, while in 2015 there were 0.29 ha per person (calculated from data in Table 6 in Goldewijk et al. 2017). The population growth from 1271 million to 7301 million between 1850 and 2015 (Fig. 4) was reflected in a damped way in massive increases in the area of cleared land, from 831 million hectares to 2103 million ha (Fig. 5). Even in Great Britain, where there was no primaeval forest left in the early nineteenth century, native vegetation has suffered a precipitous decline. For example, hedgerows have been dramatically depleted to facilitate the cultivation of machine-managed crops (McCollin 2000).

The economic cost of converting natural vegetation to agricultural or pastoral land has declined dramatically as energy has become cheaper and machinery more effective. It was a life work for a family to clear a farm in the nineteenth century, but it is now a matter of mere days for an operator of a massive yellow machine.

The history of land clearance since the early nineteenth century consists of a series of rapid expansions enabled by technological advances, less than balanced by an occasional retreat. Australia is an exemplar of this process (Kirkpatrick 1999). In 19th century Australia, ringbarking, felling with

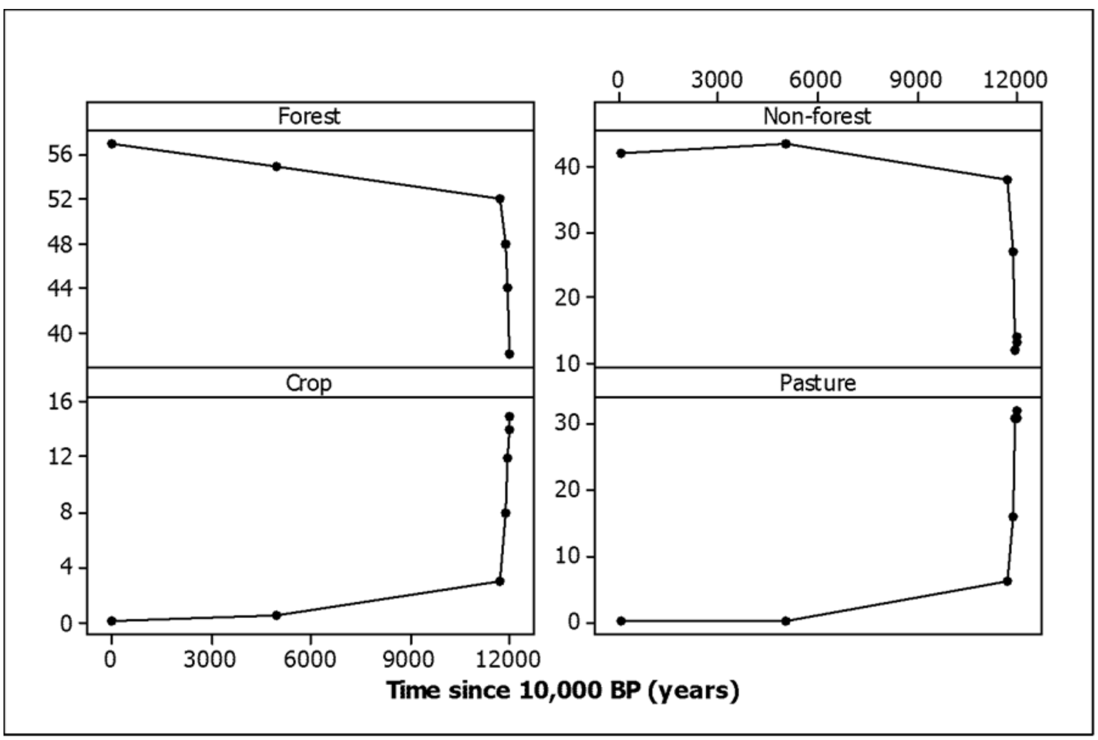

Fig. 3. Temporal change in forest vegetation, non-forest vegetation, crops and pasture as percentages of total planetary land area (https://ourworldindata.org)

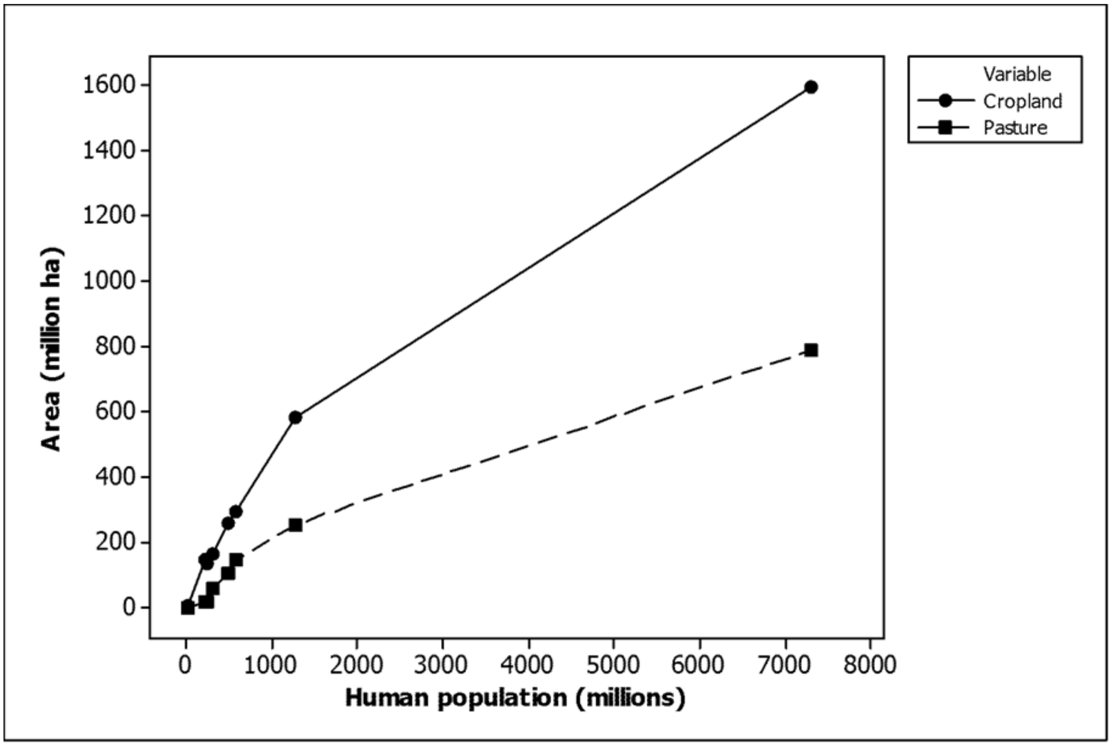

Fig. 5. Area under crops and pasture related to human population (data from Goldewijk et al. (2017))

axes and burning was used to clear forests on fertile, well-watered land, while woodlands and grasslands on fertile land were ploughed and enclosed or just grazed. Much of the cleared hill country was too steep and broken for later agricultural systems, so was allowed to return to forests that largely consisted of native species but were distinct in their composition from the original old growth. A massive expansion of cleared land took place in Australia in the mid twentieth century after the discovery that the addition of phosphorus, nitrogen, potassium and trace elements could make the soils under native heathy ecosystems productive for crops and introduced pasture. The development of cheap industrial fertilizers also resulted in native pastures being converted into exotic pastures. The latter were more productive in wet years, although poorer than the native pastures in dry years. Field agriculture had almost become hydroponic. The effective limits to clearing were imposed by topography, the availability of water and protected areas.

Some of the massive areas cleared in the wheat-sheep belt of Australia were lost to salinisation, but most continue to be cropped by virtue of the nitrogen drawn from the air using fossil fuels and the mining of phosphate and trace elements such as copper. Clearance and fertilisation technologies almost completely took out one ecosystem after another. The brigalow (*Acacia harpophylla*) forests that covered much of northern New South Wales and southern Queensland almost disappeared in a couple of postwar decades. A similar fate has befallen the Brazilian cerrado and, much earlier, the prairie grasslands of North America.

11. Logging and Deforestation

While most of the dramatic loss of forest (Fig. 3) has resulted from clearance for crops and pasture (Hughes and Thirgood 1982; Deacon 1999; Kaplan et al. 2009), other uses have had both direct and indirect effects.

Wood from trees has been used for heating and cooking since humans and their predecessors used fire as an everyday tool, many hundreds of thousands of years ago. The bark, small branches and fallen branches of trees were used by gatherers and hunters to make shelters. Bark was also used to make canoes and fish traps. Trees may have been killed by land management fires, but few were felled for their timber. The Neolithic revolution involved the construction of permanent dwellings and communal buildings, activities that often required the felling of trees for structural timber. Since the Stone Age the logging of forests has been a major human activity, the felled trees being used to produce commodities as different as paper and wooden warships.

Logging does not necessarily result in deforestation. Trees are tenacious in their grip on previously possessed land. The regenerating forest might have a different structure and even a slightly different species composition than the primaeval forest but is still forest. However, logging often requires access to previously remote areas. Access can facilitate clearing for agricultural development, as in Niugini and Brazil in the late twentieth and early twenty-first centuries. Roads, subsidised by the lucrative free good of logs from natural forests, enable access for the clearers and a way to get their produce to market. Roads are also associated with human-ignited fires, which can penetrate the logged forest at times when burning unlogged forest is not possible. These fires can eliminate the forest if repeated. Repeats are almost guaranteed, as each fire makes the former forest site more flammable. The removal of vegetation by repeated flames facilitates the clearance process.

Forests can be felled for plantation silviculture as well as agriculture (Barua et al. 2014). The growth of forest plantations globally has been rapid over the last two centuries, conforming to the hockey stick meme.

A contorted small rare coastal tree from California, Monterey pine (*Pinus radiata*) has been turned by selection into a rapid growing erect, self-pruning tree that was grown in large plantations in the southern hemisphere in the twentieth century. In New Zealand, the extensive plantations of Monterey pine were so much more productive in wood than the native forests that the remaining native forests on public land were devoted to conservation. In Australia, logging of the native forests continued as more plantations were established. The native Australian timber trees, mainly eucalypts, grow as rapidly as radiata pine. One of these eucalypts, the Tasmanian blue gum (*Eucalyptus globulus* ssp. *globulus*), is widely grown in plantations in places as diverse as Western Australia, Ethiopia, Chile and California. However, in the natural range of Tasmanian blue gum, southeastern Australia, a related species from Victoria, shining gum (*Eucalyptus nitens*), has been grown in extensive plantations since the 1970s. A high proportion of these plantations were established by clearing native forest.

As with agricultural crops, when a new profitable timber tree is developed there is an explosion of planting, often on sites that ultimately prove unsuitable for its growth. Plantings of shining gum displaced native forest and grasslands on basalt at Surrey Hills in the montane zone of Tasmania only to fail or grow extremely slowly. Plantations of eucalypts in California persist in the landscape but proved of little use for their intended purposes (Kirkpatrick 1977).

12. Mining and Land Clearance

From the ochre pits of gathering and hunting people to the massive open cuts of today, mining involves baring land to extract minerals from the surface of the earth. Mining activity is usually brief, soon abandoned because of economic exhaustion. Revegetation is usually rapid, except if the surface is poisoned by heavy metals, in which case revegetation may take many decades (Fig. 6).

13. Urbanisation, Transport and Land clearance

Human settlements and terrestrial transport routes have occupied an exponentially increasing proportion of the planet to the point at which approximately 1 in 100 hectares of land lie under tarmac and towns (Liu et al. 2020). A few native trees may survive the transition from native vegetation to settlement only to become too large or dangerous to keep among our houses, factories and shops. Some of the clearance for urban areas is for constructed parkland in which our species can hit or chase balls, run around in circles or ellipses or eat and sleep outdoors. However, some substantial tracts of uncleared vegetation are characteristic of cities in the more wealthy parts of the world. For example, London has fourteen percent of its area under tree cover, a large part in extensive parks like Hampstead Heath. Many of the larger tracts of native vegetation in European cities survived because they were pleasure parks for the ruling class. They were later to become democratised. In the nineteenth and twentieth centuries, planned cities were often provided with extensive natural parklands, such as those that surround the central business district of Adelaide, South Australia, and Kings Park in Perth, Western Australia.

Like agricultural land and mines, settlements and roads rapidly naturally revegetate once abandoned. The vegetation usually does not closely resemble that cleared for the roads

Fig. 6. Revegetation of the copper refinery induced Queenstown Desert between 1972 (top) and 2020 (below) (Collection of author). Zinc and copper deposition were responsible for total vegetation loss. Smelting of the ore ceased in 1922.

and settlements, as it occupies land that has very different environmental characteristics to the preclearing ecosystem.

14. Nature Conservation and Land Clearance

While living off the surplus of those no more able to gather and hunt, the rulers of complex agricultural societies spent much of their time in the atavistic behaviour of hunting. Gathering was not one of their major activities, reflecting the sexist nature of these societies. Good hunting requires good land, so lords, kings and emperors conserved nature on lands that would otherwise have supported more peasants. The fantasies that enabled kingdoms and empires were occasionally the only protection against extinction.

'The many species in the later hunting grounds of the rich benefited from a particularly pernicious political fantasy of god-given social stratification. In the nineteenth century a national park movement arose in the United States of America, to prevent the destruction by agriculture and logging of outstanding natural landscapes; to enable them to persist for the benefit of all people. The designation of these wild areas as 'natural' ignored the fact that they had been co-created by First Nations and were still adjusting to their absence. These wild areas were, in fact, original human habitat without the original humans, who had been killed and displaced by the ancestors of those promoting the parks.

National parks and other areas devoted to nature conservation provided some limits to land clearance and deforestation. These limits did not restrict clearance and deforestation to any great degree, because the type of land placed in the early national parks was highly romantic, with much craggy relief garnished with water or ice features. If national parks became desirable for the construction of dams, or proved to have some loggable forest, their revocation or submergence was not a great political problem up until the 1970s, when resistance to the loss of parks to development became strong in some 'New World' countries, such as Australia.

Attempts to protect viable areas of ecosystems that are approaching extirpation from land clearance began to have some effect in the late twentieth century, with the expansion of both public and private protected areas focused on poorly-conserved elements of biodiversity. These protected areas have proven partially effective in rich countries, but nominal in most poor countries, unless there is strong cross-subsidisation from the rich. It has not been possible

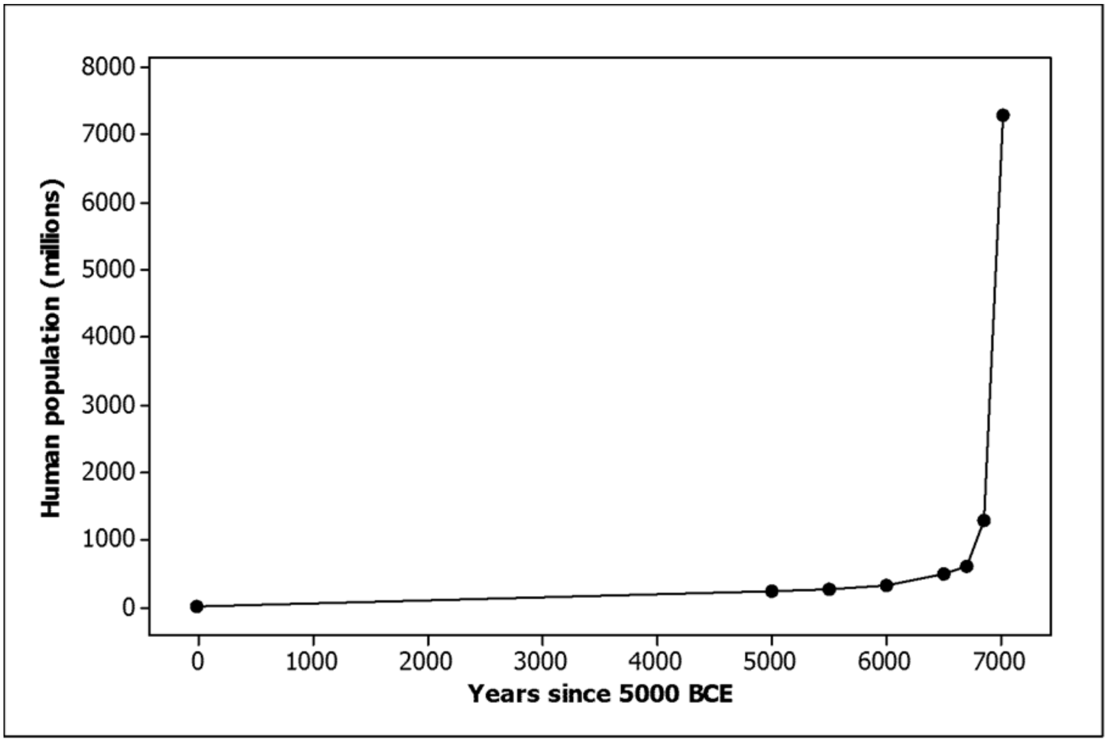

Fig. 4. Changes in the human population since 5000 BCE (data from Goldewijk et al. (2017))

to attain national targets that have gradually increased in many jurisdictions from 10% to 30% for the ecosystems that have been most attractive for land clearance, most notably grassy ecosystems and wetlands in the temprate zone, for the simple reason that these ecosystems are mostly gone.

The idea that national parks and other protected areas should be set aside from development in perpetuity has been honoured more in the breach than the observance in the less than one and a half centuries that they have been a recognised land use. The rate of environmental change is such that protected areas designed for one ecosystem may transition to another. This possibility has resulted in suggestions for increased connectivity of protected areas. when the evidence for the utility of connectivity at all but the longest time scales is scant (Kirkpatrick 2022). There have also been serious suggestions that protected areas need to be moved in space to counteract climate change. The implementation of this suggestion would obviously facilitate more deforestation and clearance and ignores the fact that protected areas are most of the remaining natural cover in a large proportion of countries.

15. Diet and Land Clearance

Human beings are physiologically omnivores, although we can prosper on a diet free of animals, if we are careful to consume enough vitamin B_{12}. The relevance of diet to land clearance is that it takes at least ten times less land or water to support a person on a plant-based diet than to support a pure carnivore, because the loss of energy in any trophic transfer (e.g. plant to herbivore or herbivore to carnivore) is 90 %. The recent explosion of land clearance in Brazil has been largely to grow soy beans to feed to cattle, which are then eaten by humans. A tendency towards more animals in the human diet would necessarily increase land clearance, with approximately a third of cropland dedicated to crops to feed animals in the early twenty-first century (Wirsenius et al. 2010).

Greenhouse Gases and Land Clearance

The realization that the business end of the hockey stick had arrived motivated some governments to encourage the substitution of renewable fuels for fossil fuels. Crops that could have fed humans were converted into alcohol for vehicle fuel. One of the biggest land clearance and deforestation events of the early twenty-first century has been the conversion of the tropical evergreen forests of Malaysia and Indonesia outside protected areas to oil palms, which are partly used to produce fuel, while a substantial proportion of the area devoted to maize in Brazil and the United States goes to the same end. The energetic balance of this crop conversion to fuel is likely to be such that it adds to the greenhouse gas burden, rather than reduce it once the removal of the original forest is taken into account. The proportion of cropland used for energy production has increased from 8.7% in 1995 to 11.7% in 2010 (Wirsenius et al. 2010).

16. Conclusions

The big history of clearance of our planet by humans is an exponential curve from the date of our first transition into agriculture (Fig. 3), with a few almost imperceptible blips in the middle of the flat part of the curve possibly relating to depopulation events, such as that which occurred after the European invasion of the Americas. Our even more exponential population growth (Fig. 4) has been a large part of the explanation for this explosion in clearance, as well as partly being a product of it, but our energy transition to fossil fuels underlay the explosion in both. In the late 20th and early 21st centuries clearance was partly fuelled by an increasing propensity for people to eat other animals that they fed on crop plants, rather than the plants themselves, and to use crops to produce liquid fuels.

The big history of deforestation began well before we transitioned into agriculture. A substantial recession of forests occurred as we used fire to increase the productivity of the landscape, eliminated much of the Pleistocene megafauna, and codeveloped a commensal relationship with *Canis familiaris*. Otherwise, forest loss responded to the same forces as land clearance, of which it was a substantial part.

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