Book Section:

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Title: The role of agricultural expansion, land cover and land-use change in contributing to climate change

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Abstract:

Agriculture and land-use change combined account for one quarter of global anthropogenic greenhouse gas (GHG) emissions. In addition to the GHGs emitted directly from agricultural practices (e.g. methane and nitrous oxide), the process of clearing previously forested land often releases carbon into the atmosphere that had been stored by vegetation following photosynthesis. This emission of carbon will increase the concentration of carbon dioxide in the atmosphere and exert a warming impact on the climate.

Land cover change can also affect climate by altering the reflectivity of the land-surface, the efficiency of evapotranspiration, and the emission of biogenic gases into the atmosphere. Modelling studies suggest that forests at high northern latitudes exert an overall warming impact on climate due to their low surface reflectivity, whereas forests at tropical latitudes sequester huge quantities of carbon, giving them an overall cooling impact on the climate.

Keywords: *deforestation, land-use change, carbon dioxide, greenhouse gas, albedo, evapotranspiration, biogenic volatile organic compounds, net zero*

Contents list:

1 Introduction: Agricultural expansion and land-use change

Land-use change has accompanied the arrival and movement of human populations into and between regions of the Earth for thousands of years. The dominant effect of human arrival is the removal of forests to provide land that can be used for agriculture. Reliable land-use surveys exist only from the mid-twentieth century onwards, so the Earth's vegetation distribution must be reconstructed prior to that. On geological time scales, knowledge of climatic conditions and indicators in the fossil record enable a reconstruction of natural vegetation across the globe.

Reconstructing land cover during the period of more substantial human influence (i.e., the past several thousand years) presents considerable challenges and is often based on estimates of human population as well as the assumption that the amount of land "used" per person for agricultural purposes has remained broadly similar over time (e.g., Ramankutty and Foley 1999; Klein Goldewijk 2001; Pongratz *et al.* 2008; Klein Goldewijk *et al.* 2011).

An alternative approach (Boserup 1965; Ruddiman 2003; Kaplan *et al.* 2009), considers the possibility that the amount of land required per capita may have declined substantially over time due to the intensification of agricultural practises. Combining this approach with estimates of population change results in much larger areas of land being under agricultural use over the past two millennia (Figure 1; Kaplan *et al.* 2011).

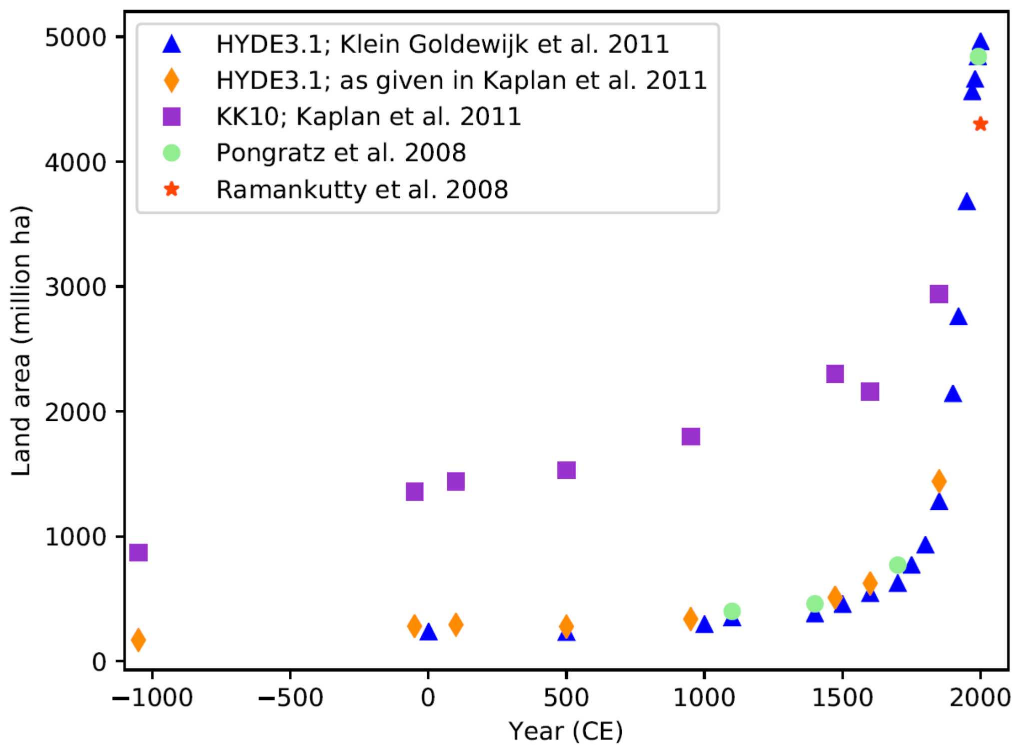

Figure 1: Land area occupied by agricultural activities (i.e., cropland and pastureland combined) in historical reconstructions up to the present day (Pongratz et al. 2008; Ramankutty et al. 2008; Kaplan et al. 2011; Klein Goldewijk et al. 2011).

Up until the Industrial Revolution in the 18th century, there was widespread deforestation across the temperate regions of Asia, Europe and North America on the land considered most suitable for farming (Williams 2003). At the start of the 20th century, deforestation rates in tropical regions began to accelerate (FAO 2012), particularly in South and Central America, Southeast Asia and Central Africa.

Forest clearance in the tropics still occurs predominantly to acquire land suitable for agriculture with more than 80% of new agricultural land acquired across the tropics between 1980 and 2000 coming from the clearance of intact or disturbed forests (Gibbs *et al.* 2010); however, the specific commodities driving agricultural clearance vary from region to region within the tropics.

In South and Central America, beef cattle ranching has been the dominant driver of "modern" forest clearance (e.g. Grainger 1993; Fearnside 2005; Gibbs *et al.* 2010). During the 1960s, 70s and 80s, road building and financial incentives from the Brazilian government encouraged deforestation of the Amazon to create pasture and cattle ranches (Carvalho *et al.* 2002; Fearnside 2005). This process often involves clearance of the forest followed by burning to remove any residual trees. Until the 1990s, Brazilian beef was usually sold domestically but in the early 2000s, international demand for Brazilian beef partly drove a spike in deforestation rates between 2002 and 2004 (Nepstad *et al.* 2006).

During the 1970s, an oil embargo prompted rapid expansion of biofuel crop growth in South America, specifically the growth of sugar cane to produce ethanol. In 1977, the Brazilian government mandated that all gasoline must be blended with ethanol. This mandate is still in place and the current minimum blend level is set at 27% ethanol. As well as directly driving forest clearance, the growth of bioenergy crops can indirectly lead to deforestation if it displaces food production which then moves onto forested land.

During the 1990s and 2000s the growth of soybeans also began to contribute substantially to the clearance of Amazon forests. Rather than being directly consumed by humans, soybean crop is mainly used to feed cattle, pigs and chicken. In the late 1990s, new cultivars enabled farmers to grow soybeans in regions that had not previously been climatically suitable, leading to rapid expansion of soy farms into the Amazon forest (Fearnside 2001; Nepstad *et al.* 2006). In response to growing environmental concerns, a moratorium was announced by the exporters and processors of soybeans stating that they would not buy crops grown on farmland within the Brazilian Amazon that had been deforested since June 2006. Since its implementation the soy moratorium appears to have been successful, with most new soy expansion occurring on previously cleared land (Rudorff *et al.* 2011; Gibbs *et al.* 2015) and has contributed to the overall decline in Brazilian deforestation rates (Hansen *et al.* 2013).

In Southeast Asia, extensive forest loss has been driven by food and fuel crop growth, as well as rubber and timber production (Gibbs *et al.* 2008; Miettinen *et al.* 2011). Malaysia and Indonesia now produce more than 80% of the world's palm oil (USDA-FAS 2019) through both industrial scale and smallholder plantations (Schoneveld *et al.* 2019). Oil palms grow only in humid, tropical conditions but are extremely efficient producers of oil compared to other crops (e.g., soybean, sunflower, rapeseed). The major environmental issue associated with oil palm growth is the conversion of old-growth or peat forests which contain dense carbon stocks; 6% of tropical peatlands in Southeast Asia had been converted to oil palm plantations by the early 2000s (Koh *et al.* 2011). In 2011, the Indonesian government imposed a moratorium on new oil palm and timber plantations on peatlands or primary forests but its effectiveness remains unclear (Busch *et al.* 2015).

In Africa, forests are cleared to provide wood fuel and to make way for smallholder agriculture, but information about the scale and extent of deforestation is less robust than for South America or Southeast Asia due both to a lower reporting capacity and the challenges associated with detecting small-scale forest clearance by satellite (Malhi *et al.* 2013). The lack of industrial-scale land clearance for agriculture means that deforestation rates in Africa have remained lower than those in South America or Southeast Asia throughout the 1990s and 2000s (Achard *et al.* 2002; Mayaux *et al.* 2013). Other pressures on tropical forests include mineral mining (e.g. to obtain gold, copper, tin), coal mining, and oil drilling which have been particularly prevalent in parts of South America and Africa (Grainger 1993).

Monitoring changes to land cover and rates of forest loss relies on either country level statistics of forest area (e.g., FAO 2018) or, in recent years, remote sensing from both airborne (e.g., Asner 2009; Saatchi *et al.* 2011a) and satellite instruments (e.g., Defries *et al.* 2000; Hansen *et al.* 2003; Saatchi *et al.* 2011b; Hansen *et al.* 2013). At the global scale, natural forests were being lost at a rate of 10.6 million hectares per year during the 1990s; between 2010 and 2015 this rate slowed to approximately 6.5 million hectares lost per year (FAO 2015). For the 2010 - 2015 period, the overall rate of forest area change was estimated as a net loss of 3.3 million hectares per year (FAO 2015); this is lower than the rate of direct forest loss due to extensive afforestation, particularly in China (Fang *et al.* 1998; Fang *et al.* 2001; Wang *et al.* 2007), and the natural expansion of forests onto previously managed lands.

2 Impacts of land-use change on climate

When land cover or land use is changed, the fluxes of carbon, energy and water between the land-surface and the atmosphere can be altered substantially (Figure 2; Bonan 2008). Changes to these fluxes can be broken down into radiative (i.e., energy) and non-radiative (i.e., carbon and water) effects. The following sections outline our understanding of the way that these fluxes change, and estimates of the extent to which this has occurred due to agricultural expansion.

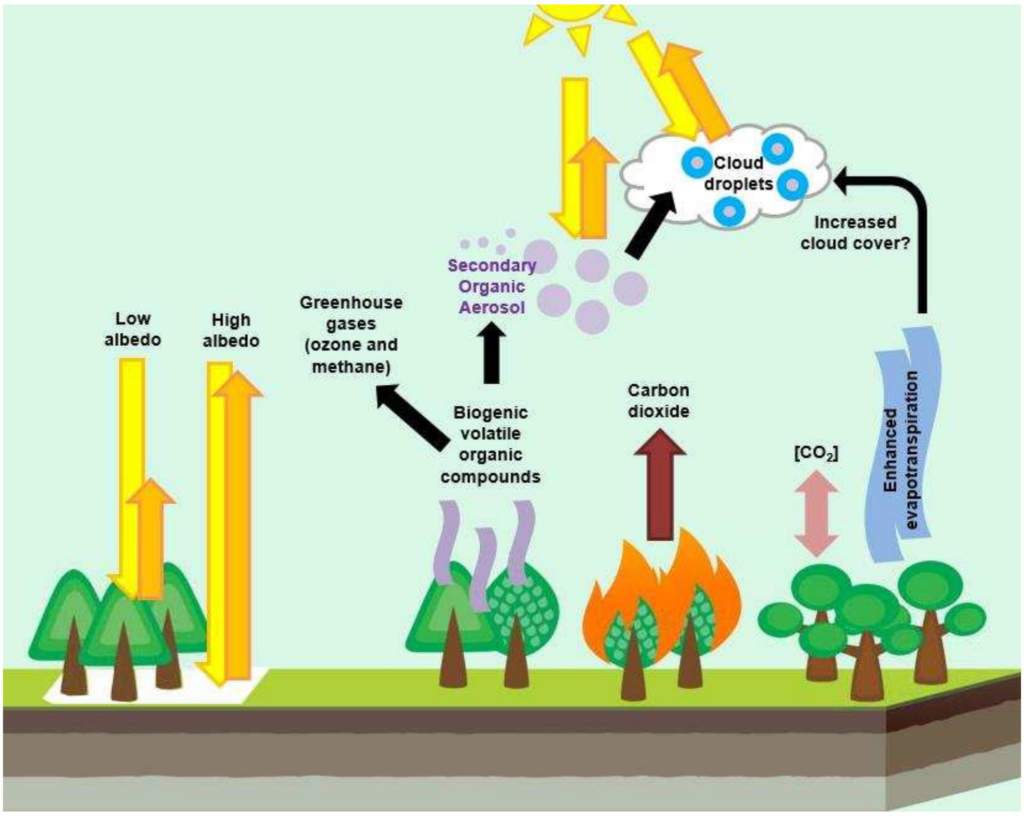

Figure 2: Schematic of the processes described in Section 2 of this Chapter.

2.1 Carbon emission

Plants take in carbon, in the form of carbon dioxide (CO_2), from the atmosphere. Approximately half of this carbon is returned to the atmosphere during respiration, whilst the other half is fixed as plant biomass during photosynthesis. The metabolic activity of ecosystems influences the amount of carbon in the atmosphere, with a marked seasonal cycle evident in measurements of atmospheric CO_2 concentrations.

The total amount of carbon stored in terrestrial ecosystems is uncertain: the tropical forests of Latin America, Sub-Saharan Africa and Asia are estimated to contain between 247 and 553 petagrams of carbon (PgC), temperate forests between 159 and 292 PgC and boreal forests between 395 and 559 PgC (Dixon *et al.* 1994; Prentice *et al.* 2001; Saatchi *et al.* 2011b). As a result of the carbon stored in trees, a considerable emission of carbon can be associated with the process of land-use and land cover change (LULCC), predominantly through the decay and burning of vegetation when forests are converted to agricultural land. Conversely, the process of afforestation will remove carbon dioxide from the atmosphere, generating a carbon sink.

Estimating the net flux of carbon to the atmosphere as a result of LULCC is challenging. Three methods are often used: 1) a “bookkeeping” method that combines country-level forest area data with regionally averaged biomass values (e.g., Houghton 2003; Baccini *et al.* 2012); 2) dynamic global vegetation models (DGVMs) that simulate the fluxes of carbon between the land surface and the atmosphere; 3) regional analyses based on satellite data (e.g., van der Werf *et al.* 2010).

Whilst fluxes of carbon within the carbon cycle are conventionally referred to as an amount of carbon "C", anthropogenic emissions are more commonly referred to in terms of a quantity of carbon dioxide "CO_2", the value of which will be a factor of 3.67 (44 ÷ 12) higher for the same amount of carbon. For the most recent decade available (2008-2017), annual emissions from LULCC are estimated to be 1.5 ± 0.7 PgC (equivalent to 5.5 $PgCO_2$; Le Quéré *et al.* 2018), approximately 14% of the total annual carbon emission from anthropogenic activities. Despite this annual source of carbon emission being generated due to LULCC, globally the land remains a *carbon sink* because vegetation removes more carbon dioxide from the atmosphere than is put back (Jia *et al.* 2019).

The challenges posed by quantifying LULCC emissions in the present-day are further exacerbated prior to the mid-twentieth century where the changes in land-cover must be inferred (see Section 1). It is estimated that since the year 1750 CE, the process of land-use change has resulted in a total emission of almost 200 PgC into the atmosphere, compared to an estimated 27 PgC emitted due to LULCC between 800 CE and 1750 CE (Pongratz *et al.* 2009; Ciais *et al.* 2013). However, Kaplan *et al.* (2011) suggest that over 300 PgC could have been emitted as a result of agricultural land clearance by 1850 CE due to the larger area occupied in their estimates (Figure 1).

2.2 Surface energy fluxes

2.2.1 Reflection of solar radiation

As well as influencing the atmospheric concentration of CO_2, the presence of large-scale vegetation also affects the energy balance at the Earth's surface. Forests are generally darker in colour than other land surface types, particularly cultivated vegetation such as cropland. This dark surface means that forested land absorbs most of the shortwave radiation that it receives from the Sun. The ratio of reflected to incident shortwave solar radiation is known as the *albedo*. A very bright surface e.g., fresh snow, would have an albedo of around 0.9, whereas dark surfaces like the ocean have a much lower albedo of around 0.1. Forests typically have a very low albedo of 0.08 - 0.19 (Betts and Ball 1997; Monteith and Unsworth 2008) whereas grass or cropland have a slightly higher albedo of 0.15 - 0.26 (Monteith and Unsworth 2008).

In the boreal region (above 60°N), snow covers the land surface for several months of the year. If this snow cover is lying on short vegetation, it will completely cover it and the surface albedo will be very high e.g., 0.75 (Betts and Ball 1997). However, if coniferous boreal trees are present, they will protrude from the snow, lowering the albedo to 0.1 – 0.15 (Leonard and Eschner 1968; Robinson and Kukla 1985; Thomas and Rowntree 1992; Betts and Ball 1997).

For an evergreen forest in a snow free region, the albedo will be relatively constant year round. However, for the deciduous forests occupying temperate and boreal regions, the albedo of the forest varies according to the time of year and whether or not the trees are in leaf. In the winter months, the albedo of a deciduous forest will be mainly controlled by the underlying surface, the process of leaf-out tends to increase the albedo of a deciduous forest by 20-50% (Hollinger *et al.* 2010; Richardson *et al.* 2013).

The overall climate impact of land-cover change is explored in Section 3, but the conversion of forest to cropland or other agricultural land will generally result in an increase in the surface albedo. The LULCC that has occurred since 1750 is therefore considered to have increased the overall albedo of the Earth's land, resulting in an overall cooling effect on the climate; this is quantified as a radiative forcing of approximately -0.18 W m^{-2} (Myhre *et al.* 2013).

2.2.2 Evapotranspiration and hydrological impacts

The presence of vegetation also mediates the transfer of water from the land surface to the atmosphere via *evapotranspiration*. Evapotranspiration is the sum of physical *evaporation* from soils and surfaces in the canopy, and biological *transpiration*. During transpiration, water that has been taken up from the soil via plant roots is lost through the stomata on leaves.

Higher rates of evapotranspiration have been measured above forests than other land cover types (Spracklen *et al.* 2018). During the dry season, trees are able to sustain high evapotranspiration rates because their long roots, when compared to other vegetation, facilitate access to deep soil water (Nepstad *et al.* 1994; Canadell *et al.* 1996). Evapotranspiration plays such a strong role in hydrological cycling that parcels of air travelling over forests have been shown to produce at least twice as much rainfall as air that has passed over little vegetation (Spracklen *et al.* 2012).

By modulating water fluxes, forests may also alter the distribution of low-level clouds. Observational studies have reached conflicting conclusions on the impact of deforestation on cloud cover. Wang *et al.* (2009) found that shallow clouds formed preferentially over patches of land in the Amazon that had been deforested, whilst Teuling *et al.* (2017) saw a strong increase in cloud cover over forested regions of western Europe.

As well as being an important part of the hydrological cycle, the process of evapotranspiration plays a vital role in the Earth's surface energy balance. The energy associated with a change from liquid water into water vapour during evapotranspiration is referred to as *latent heat*. The other important energy flux from the surface to the atmosphere is *sensible heat*, which refers directly to the change in atmospheric temperature. The ratio of sensible to latent heat is known as the Bowen ratio (Bowen 1926); by controlling evapotranspiration, vegetation can affect the Bowen ratio and influence local temperatures. Conversion of forests to cropland or grassland is therefore likely to reduce evapotranspiration rates, altering the Bowen ratio and potentially increasing local temperatures.

2.3 Emission of reactive gases from vegetation

In addition to storing carbon, controlling the reflectivity of the land surface and mediating the transfer of moisture to the atmosphere, vegetation present on the land surface can influence the atmospheric concentrations of a number of climatically important non-CO_2 greenhouse gases and particles.

Vegetation emits biogenic volatile organic compounds (BVOCs), into the air; BVOCs include isoprene (with chemical formula C_5H_8), monoterpenes ($C_{10}H_{16}$) and sesquiterpenes ($C_{15}H_{24}$), with their emission rates dependent upon plant species, temperature, sunlight levels and atmospheric CO_2 concentration. Approximately 500 Tg of isoprene is emitted annually by vegetation, with around 100 Tg of monoterpenes and 30 Tg of sesquiterpenes (Went 1960; Rasmussen and Went 1965; Sanadze and Kursanov 1966; Guenther *et al.* 1991; Guenther *et al.* 2012).

Producing BVOCs requires a large investment of energy from plants. This investment suggests that there is some form of advantage to be gained by their emission. Potential benefits to the plant include:

enhancing resilience abiotic stress (e.g. temperature, light and oxidative damage; Loreto and Velikova 2001; Vickers *et al.* 2009), preventing the establishment of competing plants (Muller 1966), altering the climate (e.g. temperature, precipitation and cloud cover; e.g. Spracklen *et al.* 2008; Paasonen *et al.* 2013; Scott *et al.* 2018a), allowing below ground signalling (e.g. Rasmann *et al.* 2005), or reducing insect and herbivore attack (e.g. Oh *et al.* 1967; Kessler and Baldwin 2001; Amin *et al.* 2013).

Once emitted into the atmosphere, BVOCs undergo a series of chemical reactions to give a wide range of products. One consequence of these atmospheric reactions is the formation of biogenic particles. By scattering incoming solar radiation, and acting as seeds for cloud droplet formation (thereby increasing the brightness of clouds), biogenic particles are likely to have a cooling effect on the global climate (Scott *et al.* 2014; Zhu *et al.* 2017; Zhu *et al.* 2019). Recent research suggests that the products of monoterpene oxidation may be involved in the very first stages of new particle formation in the atmosphere, a process that was previously thought to rely on the presence of human made pollution (Gordon *et al.* 2016; Kirkby *et al.* 2016).

Due to the complex atmospheric chemistry in which BVOCs participate, their presence can alter the concentration of some non-CO_2 greenhouse gases (ozone (O_3) and methane (CH_4)) which have a warming effect on the climate (Unger 2014). When evaluated over a 100-year time period, CH_4 is estimated to be between 28 and 34 times more effective at warming the climate than CO_2 (Myhre *et al.* 2013). The ability of O_3 to warm the climate is dependent on its location in the atmosphere so it is not possible to quantify in quite the same way as CH_4. However, the rise in O_3 concentrations in the lower atmosphere due to anthropogenic activity is thought to be the third largest contributor to climate change of all greenhouse gases (behind CO_2 and CH_4; Myhre *et al.* 2013).

The results of the chemical reactions that BVOCs participate in depend upon the concentration of other gases in the atmosphere; whilst BVOCs can react directly with O_3, decreasing its concentration, under certain conditions (in the presence of sufficient nitrogen oxides), the emission of BVOCs contributes to the production of O_3, leading to an overall increase in O_3 concentration (Monks *et al.* 2015).

Unger (2014) found that LULCC since the year 1850 had resulted in a net cooling effect on climate through decreases in BVOC emission and therefore O_3 and CH_4 concentrations. In contrast, Scott *et al.* (2018b), found that the warming effect associated with a reduction in biogenic particles outweighed the cooling effect due to a reduction in O_3 and CH_4, leading to a 10% enhancement of the overall warming due to deforestation.

3 Estimating the impacts of land-use change on climate

The climate impact of land-use change is difficult to isolate from observations, so computer models can be used to explore the effects of converting one land cover type to another in idealised experiments (e.g. Lean and Warrilow 1989; Bonan *et al.* 1992; Betts 2000; Claussen *et al.* 2001; Bounoua *et al.* 2002; Snyder *et al.* 2004; Feddema *et al.* 2005; Gibbard *et al.* 2005; Bala *et al.* 2007; Davin and de Noblet-Ducoudré 2010; Pongratz *et al.* 2010; Arora and Montenegro 2011; Swann *et al.* 2012; Hallgren *et al.* 2013).

Modelling studies find that the overall impact of deforestation on climate is latitude dependent. Bala *et al.* (2007) found that the net climate impact of simulated global forest removal was a temperature reduction of -0.3 °C. Removing *tropical* forest led to a global mean warming (+0.7 °C) due to a reduction in evapotranspiration and high carbon storage in the tropics, whereas the removal of *boreal* forests resulted in a global mean cooling (-0.8 °C) due to the dominance of the surface albedo effect. Davin and de Noblet-Ducoudré (2010) also found that, when looking only at the biogeophysical impacts, simulated global forest removal generated a cooling (-1 °C) with the albedo effect dominant at high latitudes, and the effects of reduced surface roughness and evapotranspiration dominant in the tropics.

In *temperate* regions, the balance between competing biogeophysical effects is less clear than for either boreal or tropical forests (Claussen *et al.* 2001). Bala *et al.* (2007) simulated a global annual mean cooling of -0.04 °C for total temperate deforestation. For the northern hemisphere (NH) alone, Snyder *et al.* (2004) obtained a larger annual mean cooling of -1.1 °C and found that the effect was seasonally dependent, with temperate deforestation causing a cooling during the local winter and a warming during the summer. Swann *et al.* (2012) found a global mean temperature change of between -0.4 °C and +0.1 °C due to northern mid-latitude afforestation, but also simulated a northward shift of tropical precipitation belts and drying of the southern Amazon.

The above studies all used models to examine idealised deforestation or afforestation scenarios. Estimating the climatic impact of historical land-use change combines the challenges associated with understanding the climate impact of specific land-cover transitions, with the challenge of reconstructing historical land-use change. Pongratz *et al.* (2010) estimate that LULCC since 1850 has resulted in a biogeochemical warming of 0.16-0.18°C and biogeophysical cooling of -0.03 °C, giving a combined overall warming.

4 Role of the land sector in climate change mitigation

The 2015 Paris Agreement on Climate commits signatories to "hold the increase in the global average temperature to well below 2°C above pre-industrial levels" and to "pursue efforts to limit the temperature increase to 1.5°C". Globally, anthropogenic CO_2 emissions are still rising; emissions from fossil fuel combustion have increased from 3.1 ± 0.2 PgC (11.4 $PgCO_2$) per year during the 1960s to an average of 9.4 ± 0.5 PgC (35 $PgCO_2$) per year between 2008 and 2017 (Le Quéré *et al.* 2018). Future emission projections that are able limit the global temperature increase to 1.5 °C tend to require that global CO_2 emissions peak around 2020 and reach *net zero* by mid-century (Rogelj *et al.* 2018).

Achieving *net zero* emissions means that any remaining CO_2 emissions are balanced by processes that remove CO_2 from the atmosphere. This can be achieved in a number of ways, but the most frequently cited strategies are an increase in afforestation or reforestation, and the large scale deployment of bioenergy with carbon capture and storage (BECCS). BECCS involves the deliberate growth of crops that can be burned to generate energy, and the subsequent burial of the CO_2 emitted during their combustion; estimates suggest that BECCS could remove around 3 PgC (11 $PgCO_2$) per year by 2100, requiring up to 0.7 billion hectares of land (Smith *et al.* 2016).

By 2050, the world's population is projected to reach nine billion and the Food & Agriculture Organisation predict that a 70% increase in food production will be required (Food and Agriculture Organisation of the United Nations (FAO) 2009). This is unlikely to be achieved by improving agricultural yields or intensifying livestock production alone, suggesting that expansion of current agricultural land area would occur (Bajzelj *et al.* 2014). Taking the requirements for food and bioenergy production together gives a complex set of possible future land-use change scenarios; a combination of increasing population, potentially increasing meat consumption and a requirement for BECCS will place enormous demands on global land that may not be sustainable (Benton *et al.* 2018). Over 75% of current agricultural land is used to raise livestock; future dietary changes, such as a reduction in meat consumption therefore have the potential to reduce the amount of land required (Stehfest *et al.* 2009), as well as the greenhouse gas emissions associated with agriculture (Springmann *et al.* 2016).

In conjunction with the Paris Agreement on Climate, countries around the world prepared *Nationally Determined Contributions* (NDCs) to state what they would do to mitigate, and adapt to, future climate change. Initial assessments of the NDCs suggest that countries are currently expecting approximately one quarter of their mitigation targets by 2025-2030 to be met by the land-use sector, through reduced deforestation and increased afforestation (Forsell *et al.* 2016; Grassi *et al.* 2017).

4.1 Reducing deforestation

The UN-REDD (Reducing Emissions from Deforestation and forest Degradation) programme, and the extension REDD+, aims to reduce forest loss in developing countries by introducing financial mechanisms to benefit countries that preserve the carbon stocks in their forests (e.g., Angelsen and Wetrtz-Kanounnikoff 2008). Reducing deforestation rates by 50% by 2050 (relative to rates observed in the 1990s), and maintaining them at that level until 2100 would avoid the direct release of approximately 50 PgC (Gullison *et al.* 2007); equivalent to five years of fossil fuel carbon emissions. Using a dynamic global vegetation model, Gumpenberger *et al.* (2010) found that tropical carbon stocks in 2100 decreased by 35 and 134 PgC, relative to 2012, under a continued deforestation scenario, whereas under a forest protection scenario tropical carbon stocks could be increased by between 7 and 121 PgC.

4.2 Increasing reforestation, restoration and afforestation

Whilst preserved or increased forest cover would enhance CO_2 sequestration and storage, forests also exert the biogeochemical and biogeophysical impacts discussed in Sections 2 and 3; as such the overall climatic impact of modifications to forest area will be complex and location specific.

Pongratz *et al.* (2011) found that the majority of historical anthropogenic LULCC in temperate and boreal regions has occurred on the most productive land, thereby generating higher than average (i.e., for a particular latitude) CO_2 emissions. Subsequently, reforestation of these areas could potentially induce a cooling effect from CO_2 sequestration that would outweigh any warming effect due to an albedo increase. Arora and Montenegro (2011) found that gradually replacing cropland in an Earth system model with forests reduced the simulated global mean temperature at the end of the 21st century by 0.45°C because the impact of increased carbon sequestration outweighed the warming from biogeophysical effects.

Using photo-interpretation of satellite imagery, Bastin *et al.* (2019) identified 0.9 billion hectares of land globally that could support forests; their analysis suggested that these additional forests could potentially store 205 PgC, but did not consider the biogeophysical impacts of the additional forests and may have overestimated the capacity for above ground and soil carbon increases (Friedlingstein *et al.* 2019; Lewis *et al.* 2019; Veldman *et al.* 2019).

4.3 Growth of crops for bioenergy

Since vegetation takes in CO_2 during photosynthesis (see Section 2.1), it is theoretically possible to generate carbon neutral energy by harvesting and burning crops and other plants. This is often done using fast-growing perennial grasses such as Miscanthus (also known as silvergrass) or coppicing short-rotation trees such as poplar, willow and eucalyptus. Whilst the use of bioenergy crops can potentially displace fossil fuels and therefore reduce carbon emissions, bioenergy crops grown on former high carbon forest or peat land may struggle to repay the carbon debt associated with their initial establishment (Harper *et al.* 2018). If combined with carbon capture and storage (CCS) the global mitigation potential of BECCS is estimated to be up to around 3 PgC per year (Smith *et al.* 2016; Jia *et al.* 2019).

Whilst motivated by the need to reduce carbon emissions, the large scale growth of bioenergy crops could also have substantial impacts on surface energy fluxes and therefore local climate. Modelling studies indicate that expansion of perennial bioenergy crops onto land previously used to grow annual crops would lead to an increase in both surface albedo and evapotranspiration, and therefore a localised cooling effect (Georgescu *et al.* 2011).

Many bioenergy crops emit higher levels of isoprene than the food crops they may have replaced. Ashworth *et al*., (2012) found that, whilst the impacts on global climate were negligible, replacing food crops with oil palm and short-rotation coppice resulted in localised increases in both O_3 and secondary organic aerosol concentrations.

5 Future land-use trajectories

As discussed in Section 3, computer models are often used to explore the impact of changes in land cover on the climate. The same approach is taken to assess future potential climate change as a result of different levels of greenhouse gas, and other anthropogenic, emissions.

A set of Shared Socioeconomic Pathways (SSPs; Riahi *et al.* 2017) have been developed that describe five different future narratives for society. The SSPs reflect a range of levels of possible global challenges around mitigation and adaptation to climate change (Table 1), but do not include specific climate policies. Integrated Assessment Models are then used to realise the SSPs in the context of different levels of climate change along multiple Representative Concentration Pathways (RCPs; Moss *et al.* 2010; van Vuuren *et al.* 2011). Each RCP reaches a specific level of anthropogenic radiative forcing by 2100, for example RCP6.0 reaches a level of +6.0 W m^{-2} and RCP1.9 reaches +1.9 W m^{-2}.

Table 1: Summary of the Shared Socioeconomic Pathways (Riahi et al. 2017) and their implications for future land-use change (Popp et al. 2017).

Shared Socioeconomic Pathway	**Overview of pathway**	**Description of agriculture and land-use sector**

SSP1	Sustainability: Taking the Green Road (*low challenges to mitigation and adaptation*)	Strong land-use regulation. Improvements in agricultural productivity, low meat diets and low growth in food consumption. Full participation of land-use sector in mitigation.
SSP2	Middle of the Road (*medium challenges to mitigation and adaptation*)	Medium land-use regulation. Material-intensive consumption and medium meat consumption. Slow decline in deforestation rate. Partial participation of land-use sector in mitigation.
SSP3	Regional Rivalry: A Rocky Road (*high challenges to mitigation and adaptation*)	Limited regulation. Resource intensive consumption. Continued deforestation. Limited participation of land-use sector in mitigation.
SSP4	Inequality: A Road Divided (*low challenges mitigation but high challenges to adaptation*)	Uneven regulation. High deforestation rates in low income countries. Unequal consumption. Partial participation of land-use sector in mitigation.
SSP5	Fossil-fuelled Development: Taking the Highway (*high challenges to mitigation but low challenges to adaptation*)	Medium regulation. Material-intensive consumption and meat-rich diets. Slow decline in deforestation rate. Full participation of land-use sector in mitigation.

Land-use is of great importance in these pathways because of its potential to contribute to continued CO_2 emissions, and capacity to remove CO_2 from the atmosphere; the pace of land-use change described in these pathways over the 21st century is much more rapid than has been seen historically. The median annual global carbon emission from land-use change across the SSPs is 0.8 PgC (3 $PgCO_2$) in 2030, 0.5 PgC (1.9 $PgCO_2$) in 2050 and -0.2 PgC (-0.7 $PgCO_2$) in 2100 (Jia *et al.* 2019).

In the resulting matrix of SSP and RCP combinations (O'Neill *et al.* 2016), the change in global forested area in 2100 (relative to 2010) varies by over two billion hectares (Figure 3), equivalent to half of the present-day forested land area. The greatest increases in forested area are seen in pathways that follow SSP1, which includes strong regulation of the land-sector, increased agricultural productivity, low food waste, and a shift towards lower meat consumption. Accordingly, SSP1 scenarios see reductions in the amount of land used for pasture, and cropland in some realisations (Figure 3), which allows for forests to regenerate naturally on abandoned land and deliberate afforestation. In the pathways with the most stringent climate target (i.e., RCP1.9) afforestation is a sink of -0.6 PgC (-2.4 $PgCO_2$) per year by 2100 (median value across all SSPs in five IAMs). However, the warming biophysical impacts (i.e., decreased albedo) of forest expansion under some pathways (i.e., RCP4.5) may outweigh the cooling induced by carbon uptake (Davies-Barnard *et al.* 2014).

The area used for cropland includes both food and energy crops; here the decline in demand for food crops in most SSP1 scenarios is offset by an increased demand for biofuel crop growth. In the pathways with the most stringent climate target BECCS is a sink of -4 PgC (-14.9 $PgCO_2$) per year by 2100. The greatest increases in cropland and pasture, coupled with a decline in forested area, are seen in SSP3 scenarios (Figure 3), where deforestation occurs due to limited regulation and continued competition for resources.

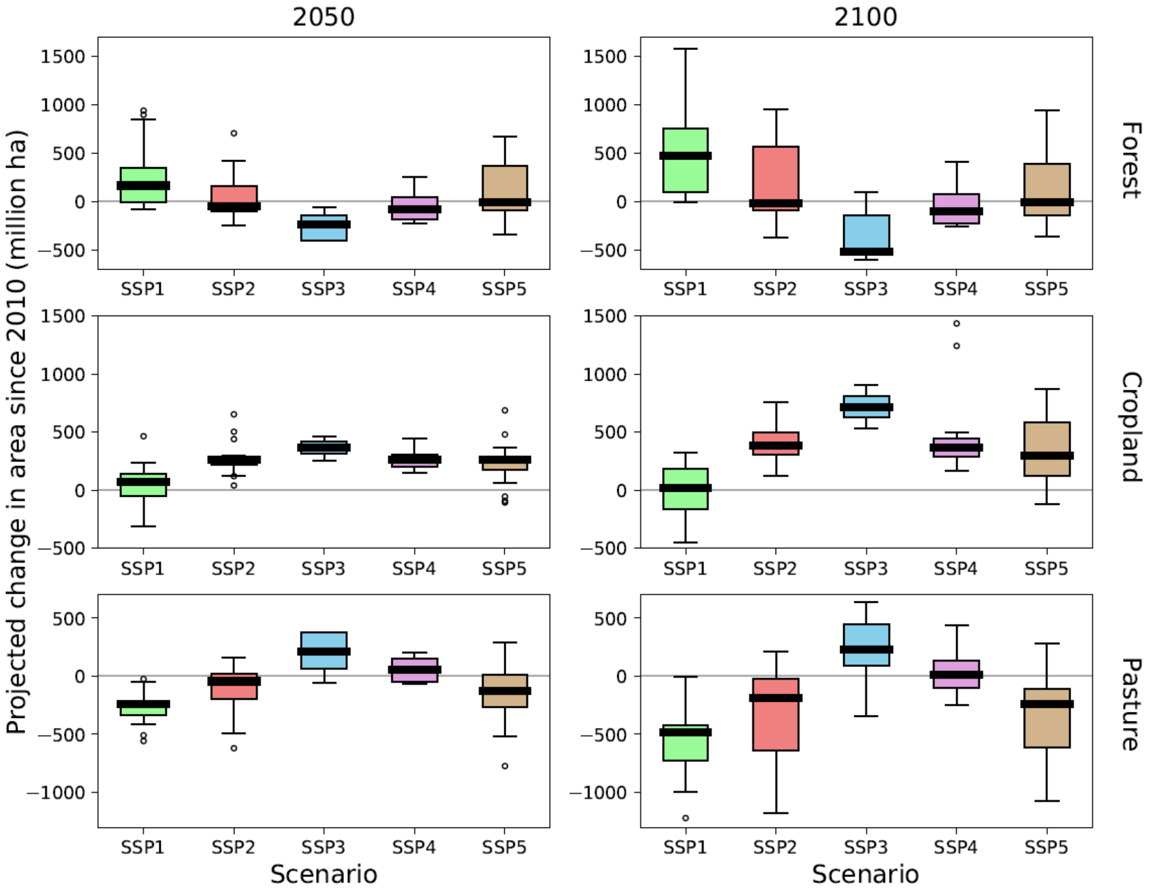

Figure 3: Projected change in land area covered by forest (top panels), cropland (central panels) and pasture (lower panels) in 2050 (left) and 2100 (right), relative to the year 2010, under five Shared Socioeconomic Pathways (Riahi et al. 2017). Each SSP is realised with five Integrated Assessment Models (AIM, GCAM, IMAGE, MESSAGE-GLOBIOM and REMIND/MAgPIE; as described in Popp et al. 2017) under five Representative Concentration Pathways (van Vuuren et al. 2011); data obtained from the IAMC Scenario Explorer (Huppmann et al. 2018).

Rather than being *predictions*, the RCPs and SSPs explore possible future scenarios and are being used by the global climate science community during the Coupled Model Intercomparison Project Phase 6 (CMIP6) to determine the impacts on climate, beyond carbon emissions, associated with different trajectories for the coming century.

6 Outlook and conclusions

Agriculture is currently the main driver of global forest loss, which occurs mainly in the tropics, with land cleared predominantly to grow crops or raise livestock (Gibbs *et al.* 2010). The specific drivers of land-use change vary regionally and temporally however, with livestock and soybean growth currently dominating in South America and oil palm growth dominating in Southeast Asia.

Although reconstructing historical land-use change is challenging (Pongratz *et al.* 2009; Kaplan *et al.* 2011), it is estimated to have resulted in the emission of around 200 PgC (730 $PgCO_2$) since the year 1750 with current annual emissions estimated at 1.5 ± 0.7 PgC (or 5.5 $PgCO_2$, approximately 14% of total anthropogenic emissions; Le Quéré *et al.* 2018). Aside from the direct emission of CO_2, the process of land-use change has substantial impacts on the fluxes of energy, moisture and volatile gases between the land surface and the atmosphere.

Computer simulations can be used to assess the overall impact of a particular land-use change; modelling studies find that the overall impact of forests and land-use change on climate is latitude dependent. Forests at high northern latitudes exert an overall warming impact on climate due to their low albedo (Betts 2000; Davin and de Noblet-Ducoudré 2010), whereas forests in tropical latitudes sequester huge quantities of carbon, giving them an overall cooling impact on the climate (Bala *et al.* 2007). The climate impacts of forests at temperate latitudes are less clear (Claussen *et al.* 2001; Swann *et al.* 2012), but recent observational studies indicate that temperate forests may have a stronger cooling impact on climate than model simulations have previously suggested.

When combined, the agriculture and land-use sector contribute around one quarter of current anthropogenic GHG emissions, highlighting the crucial role that land management practices must play in climate change mitigation over the coming decades. Meeting the commitments outlined in the Paris Agreement on Climate, to "hold the increase in the global average temperature to well below 2°C above pre-industrial levels" and to "pursue efforts to limit the temperature increase to 1.5°C", is likely to require global CO_2 emissions to reach *net zero* by around 2050. Achieving *net zero* will necessitate a complete, or almost complete, elimination of all GHG emissions from agriculture and the land sector, with any remaining emissions being balanced by processes that remove carbon dioxide from the atmosphere.

In addition to reducing direct GHG emissions from agriculture, reducing the amount of land used for food production could enable the natural regeneration, or deliberate replanting, of forests. Scenarios designed to allow the climate science community to explore the impacts of different global futures indicate that a very wide range of land-use trajectories are possible, depending on levels of regulation and cooperation between regions. By 2100, global forested land varies by around two billion hectares between different realisations of five Shared Socioeconomic Pathways (SSPs) combined with Representative Concentration Pathways (RCPs). Current and future research is exploring the impacts of such substantial land-use changes using fully coupled Earth System Models. These models will enable scientists to go beyond quantifying carbon emissions and diagnose the impacts of land-cover change on surface reflectivity, evapotranspiration and the composition of the atmosphere.

7 Where to look for further information

- "Ecological Climatology" by Gordon Bonan (2016) provides an excellent overview of interactions between the land-surface, atmosphere and climate.

- Global Forest Watch provides up-to-date information on rates of land-cover change around the world: https://www.globalforestwatch.org/

- Intergovernmental Panel on Climate Change (IPCC) published a Special Report on Climate Change and Land (2019) to collate the latest scientific evidence on the role of LULCC in climate change: https://www.ipcc.ch/report/srccl/. Chapter 2 in particular discusses the links between land-use and climate (Jia *et al.* 2019).

References

Achard, F., *et al.* (2002). "Determination of Deforestation Rates of the World's Humid Tropical Forests." **297**(5583): 999-1002.

Amin, H. S., *et al.* (2013). "Monoterpene emissions from bark beetle infested Engelmann spruce trees." Atmospheric Environment, **72**(0): 130-133.

Angelsen, A. and S. Wetrtz-Kanounnikoff (2008). "What are the key design issues for REDD and the criteria for assessing options?" in Moving Ahead with REDD. A. Angelsen, CIFOR. p11-22.

Arora, V. K. and A. Montenegro (2011). "Small temperature benefits provided by realistic afforestation efforts." Nature Geoscience, **4**(8): 514-518.

Ashworth, K., *et al.* (2012). "Impacts of near-future cultivation of biofuel feedstocks on atmospheric composition and local air quality." Atmos. Chem. Phys., **12**(2): 919-939.

Asner, G. P. (2009). "Tropical forest carbon assessment: integrating satellite and airborne mapping approaches." Environmental Research Letters(3): 034009.

Baccini, A., *et al.* (2012). "Estimated carbon dioxide emissions from tropical deforestation improved by carbon-density maps." Nature Clim. Change, **2**(3): 182-185.

Bajzelj, B., *et al.* (2014). "Importance of food-demand management for climate mitigation." Nature Clim. Change, **4**(10): 924-929.

Bala, G., *et al.* (2007). "Combined climate and carbon-cycle effects of large-scale deforestation." PNAS, **104**(16): 6550-6555.

Bastin, J.-F., *et al.* (2019). "The global tree restoration potential." **365**(6448): 76-79.

Benton, T. G., *et al.* (2018). "Designing sustainable landuse in a 1.5°C world: the complexities of projecting multiple ecosystem services from land." Current Opinion in Environmental Sustainability, **31**: 88-95.

Betts, A. K. and J. H. Ball (1997). "Albedo over the boreal forest." Journal of Geophysical Research: Atmospheres, **102**(D24): 28901-28909.

Betts, R. A. (2000). "Offset of the potential carbon sink from boreal forestation by decreases in surface albedo." Nature, **408**(6809): 187-190.

Bonan, G. B. (2008). "Forests and Climate Change: Forcings, Feedbacks, and the Climate Benefits of Forests." Science, **320**: 1444-1449.

Bonan, G. B., *et al.* (1992). "Effects of boreal forest vegetation on global climate." Nature, **359**(6397): 716-718.

Boserup, E. (1965). The Conditions of Agricultural Growth: The Economics of Agrarian Change Under Population Pressure. London, G. Allen & Unwin.

Bounoua, L., *et al.* (2002). "Effects of Land Cover Conversion on Surface Climate." Climatic Change, **52**(1-2): 29-64.

Bowen, I. S. (1926). "The Ratio of Heat Losses by Conduction and by Evaporation from any Water Surface." Physical Review, **27**(6): 779-787.

Busch, J., *et al.* (2015). "Reductions in emissions from deforestation from Indonesia's moratorium on new oil palm, timber, and logging concessions." **112**(5): 1328-1333.

Canadell, J., *et al.* (1996). "Maximum rooting depth of vegetation types at the global scale." Oecologia, **108**(4): 583-595.

Carvalho, G. O., *et al.* (2002). "Frontier Expansion in the Amazon: Balancing Development and Sustainability." Environment: Science and Policy for Sustainable Development, **44**(3): 34-44.

Ciais, P., *et al.* (2013). "Carbon and Other Biogeochemical Cycles" in Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. T. F. Stocker, D. Qin, G.-K. Plattneret al. Cambridge, United Kingdom and New York, NY, USA, Cambridge University Press.

Claussen, M., *et al.* (2001). "Biogeophysical versus biogeochemical feedbacks of large-scale land cover change." Geophysical Research Letters, **28**(6): 1011-1014.

Davies-Barnard, T., *et al.* (2014). "Full effects of land use change in the representative concentration pathways." Environmental Research Letters, **9**(11): 114014.
Davin, E. L. and N. de Noblet-Ducoudré (2010). "Climatic Impact of Global-Scale Deforestation: Radiative versus Nonradiative Processes." Journal of Climate, **23**(1): 97-112.
Defries, R. S., *et al.* (2000). "A new global 1-km dataset of percentage tree cover derived from remote sensing." Global Change Biology, **6**(2): 247-254.
Dixon, R. K., *et al.* (1994). "Carbon Pools and Flux of Global Forest Ecosystems." Science, **263**(5144): 185-190.
Fang, J.-y., *et al.* (1998). "Forest Biomass of China: An Estimate Based on the Biomass-Volume Relationship." Ecological Applications, **8**(4): 1084-1091.
Fang, J., *et al.* (2001). "Changes in Forest Biomass Carbon Storage in China Between 1949 and 1998." Science, **292**(5525): 2320-2322.
FAO (2012). State of the World's Forests. Rome, United Nations.
FAO (2015). Global Forest Resources Assessment 2015: How are the world's forests changing? Rome, United Nations.
FAO (2018). The State of the World's Forests 2018 - Forest pathways to sustainable development. Rome, United Nations.
Fearnside, P. M. (2001). "Soybean cultivation as a threat to the environment in Brazil." Environmental Conservation, **28**(1): 23-38.
Fearnside, P. M. (2005). "Deforestation in Brazilian Amazonia: History, Rates, and Consequences." Conservation Biology, **19**(3): 680-688.
Feddema, J., *et al.* (2005). "A comparison of a GCM response to historical anthropogenic land cover change and model sensitivity to uncertainty in present-day land cover representations." Climate Dynamics, **25**(6): 581-609.
Food and Agriculture Organisation of the United Nations (FAO) (2009). How to Feed the World in 2050. Rome, United Nations.
Forsell, N., *et al.* (2016). "Assessing the INDCs' land use, land use change, and forest emission projections." **11**(1): 26.
Friedlingstein, P., *et al.* (2019). "Comment on "The global tree restoration potential"." Science, **366**(6463): eaay8060.
Georgescu, M., *et al.* (2011). "Direct climate effects of perennial bioenergy crops in the United States." **108**(11): 4307-4312.
Gibbard, S., *et al.* (2005). "Climate effects of global land cover change." Geophysical Research Letters, **32**(23): L23705.
Gibbs, H. K., *et al.* (2008). "Carbon payback times for crop-based biofuel expansion in the tropics: the effects of changing yield and technology." Environmental Research Letters, **3**(3): 034001.
Gibbs, H. K., *et al.* (2015). "Brazil's Soy Moratorium." **347**(6220): 377-378.
Gibbs, H. K., *et al.* (2010). "Tropical forests were the primary sources of new agricultural land in the 1980s and 1990s." Proceedings of the National Academy of Sciences.
Gordon, H., *et al.* (2016). "Reduced anthropogenic aerosol radiative forcing caused by biogenic new particle formation." Proceedings of the National Academy of Sciences, **113**(43): 12053-12058.
Grainger, A. (1993). "The Causes of Deforestation" in Controlling Tropical Deforestation, Earthscan. p49-68.
Grassi, G., *et al.* (2017). "The key role of forests in meeting climate targets requires science for credible mitigation." Nature Climate Change, **7**(3): 220-226.
Guenther, A. B., *et al.* (2012). "The Model of Emissions of Gases and Aerosols from Nature version 2.1 (MEGAN2.1): an extended and updated framework for modeling biogenic emissions." Geosci. Model Dev., **5**(6): 1471-1492.

Guenther, A. B., *et al.* (1991). "Isoprene and monoterpene emission rate variability: Observations with eucalyptus and emission rate algorithm development." Journal of Geophysical Research: Atmospheres, **96**(D6): 10799-10808.
Gullison, R. E., *et al.* (2007). "Tropical Forests and Climate Policy." Science, **316**(5827): 985-986.
Gumpenberger, M., *et al.* (2010). "Predicting pan-tropical climate change induced forest stock gains and losses - implications for REDD." Environmental Research Letters, **5**(1): 014013.
Hallgren, W., *et al.* (2013). "Climate impacts of a large-scale biofuels expansion." Geophysical Research Letters, **40**(8): 1624-1630.
Hansen, M. C., *et al.* (2003). "Global Percent Tree Cover at a Spatial Resolution of 500 Meters: First Results of the MODIS Vegetation Continuous Fields Algorithm." Earth Interactions, **7**(10): 1-15.
Hansen, M. C., *et al.* (2013). "High-Resolution Global Maps of 21st-Century Forest Cover Change." Science, **342**(6160): 850-853.
Harper, A. B., *et al.* (2018). "Land-use emissions play a critical role in land-based mitigation for Paris climate targets." Nature Communications, **9**(1): 2938.
Hollinger, D. Y., *et al.* (2010). "Albedo estimates for land surface models and support for a new paradigm based on foliage nitrogen concentration." Global Change Biology, **16**(2): 696-710.
Houghton, R. A. (2003). "Revised estimates of the annual net flux of carbon to the atmosphere from changes in land use and land management 1850-2000." Tellus B, **55**(2): 378-390.
Huppmann, D., *et al.* (2018). IAMC 1.5°C Scenario Explorer and Data hosted by IIASA, Integrated Assessment Modeling Consortium & International Institute for Applied Systems Analysis.
Jia, G., *et al.* (2019). "Land-climate interactions" in Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems.
Kaplan, J. O., *et al.* (2011). "Holocene carbon emissions as a result of anthropogenic land cover change." The Holocene.
Kaplan, J. O., *et al.* (2009). "The prehistoric and preindustrial deforestation of Europe." Quaternary Science Reviews, **28**(27): 3016-3034.
Kessler, A. and I. T. Baldwin (2001). "Defensive Function of Herbivore-Induced Plant Volatile Emissions in Nature." Science, **291**(5511): 2141-2144.
Kirkby, J., *et al.* (2016). "Ion-induced nucleation of pure biogenic particles." Nature, **533**(7604): 521-526.
Klein Goldewijk, K. (2001). "Estimating global land use change over the past 300 years: The HYDE Database." **15**(2): 417-433.
Klein Goldewijk, K., *et al.* (2011). "The HYDE 3.1 spatially explicit database of human-induced global land-use change over the past 12,000 years." Global Ecology and Biogeography, **20**(1): 73-86.
Koh, L. P., *et al.* (2011). "Remotely sensed evidence of tropical peatland conversion to oil palm." **108**(12): 5127-5132.
Le Quéré, C., *et al.* (2018). "Global Carbon Budget 2018." Earth Syst. Sci. Data, **10**(4): 2141-2194.
Lean, J. and D. A. Warrilow (1989). "Simulation of the regional climatic impact of Amazon deforestation." Nature, **342**: 411-413.
Leonard, R. E. and A. R. Eschner (1968). "Albedo of Intercepted Snow." Water Resources Research, **4**(5): 931-935.
Lewis, S. L., *et al.* (2019). "Comment on "The global tree restoration potential"." Science, **366**(6463): eaaz0388.
Loreto, F. and V. Velikova (2001). "Isoprene Produced by Leaves Protects the Photosynthetic Apparatus against Ozone Damage, Quenches Ozone Products, and Reduces Lipid Peroxidation of Cellular Membranes." Plant Physiology, **127**(4): 1781-1787.
Malhi, Y., *et al.* (2013). "African rainforests: past, present and future." Philosophical Transactions of the Royal Society B: Biological Sciences, **368**(1625).

Mayaux, P., *et al.* (2013). "State and evolution of the African rainforests between 1990 and 2010." Philosophical Transactions of the Royal Society B: Biological Sciences, **368**(1625).
Miettinen, J., *et al.* (2011). "Deforestation rates in insular Southeast Asia between 2000 and 2010." Global Change Biology, **17**(7): 2261-2270.
Monks, P. S., *et al.* (2015). "Tropospheric ozone and its precursors from the urban to the global scale from air quality to short-lived climate forcer." Atmos. Chem. Phys., **15**(15): 8889-8973.
Monteith, J. L. and M. H. Unsworth (2008). "Microclimatology of Radiation (i)" in Principles of Environmental Physics, Academic Press. p86-99.
Moss, R. H., *et al.* (2010). "The next generation of scenarios for climate change research and assessment." Nature, **463**(7282): 747-756.
Muller, C. H. (1966). "The Role of Chemical Inhibition (Allelopathy) in Vegetational Composition." Bulletin of the Torrey Botanical Club, **93**(5): 332-351.
Myhre, G., *et al.* (2013). "Anthropogenic and Natural Radiative Forcing" in Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. T. F. Stocker, D. Qin, G.-K. Plattneret al. Cambridge, United Kingdom and New York, NY, USA, Cambridge University Press.
Nepstad, D. C., *et al.* (1994). "The role of deep roots in the hydrological and carbon cycles of Amazonian forests and pastures." Nature, **372**(6507): 666-669.
Nepstad, D. C., *et al.* (2006). "Globalization of the Amazon Soy and Beef Industries: Opportunities for Conservation." **20**(6): 1595-1603.
O'Neill, B. C., *et al.* (2016). "The Scenario Model Intercomparison Project (ScenarioMIP) for CMIP6." Geosci. Model Dev., **9**(9): 3461-3482.
Oh, K. H., *et al.* (1967). "Effect of Various Essential Oils Isolated from Douglas Fir Needles upon Sheep and Deer Rumen Microbial Activity." Applied Microbiology, **15**: 777-784.
Paasonen, P., *et al.* (2013). "Warming-induced increase in aerosol number concentration likely to moderate climate change." Nature Geoscience, **6**(6): 438-442.
Pongratz, J., *et al.* (2008). "A reconstruction of global agricultural areas and land cover for the last millennium." Global Biogeochemical Cycles, **22**(3): GB3018.
Pongratz, J., *et al.* (2011). "Past land use decisions have increased mitigation potential of reforestation." Geophys. Res. Lett., **38**(15): L15701.
Pongratz, J., *et al.* (2009). "Effects of anthropogenic land cover change on the carbon cycle of the last millennium." Global Biogeochem. Cycles, **23**.
Pongratz, J., *et al.* (2010). "Biogeophysical versus biogeochemical climate response to historical anthropogenic land cover change." Geophys. Res. Lett., **37**(8): L08702.
Popp, A., *et al.* (2017). "Land-use futures in the shared socio-economic pathways." Global Environmental Change, **42**: 331-345.
Prentice, I. C., *et al.* (2001). "The Carbon Cycle and Atmospheric Carbon Dioxide" in Climate Change 2001: The Physical Science Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. J. T. Houghton, Y. Ding, D. J. Griggset al, Cambridge University Press, Cambridge, UK and New York, USA.
Ramankutty, N., *et al.* (2008). "Farming the planet: 1. Geographic distribution of global agricultural lands in the year 2000." **22**(1).
Ramankutty, N. and J. A. Foley (1999). "Estimating Historical Changes in Global Land Cover: Croplands from 1700 to 1992." Global Biogeochem. Cycles, **13**(4): 997-1027.
Rasmann, S., *et al.* (2005). "Recruitment of entomopathogenic nematodes by insect-damaged maize roots." Nature, **434**(7034): 732-737.
Rasmussen, R. A. and F. W. Went (1965). "Volatile organic material of plant origin in the atmosphere." Proceedings of the National Academy of Sciences, **53**: 215-220.
Riahi, K., *et al.* (2017). "The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview." Global Environmental Change, **42**: 153-168.

Richardson, A. D., *et al.* (2013). "Climate change, phenology, and phenological control of vegetation feedbacks to the climate system." Agricultural and Forest Meteorology, **169**: 156-173.
Robinson, D. A. and G. Kukla (1985). "Maximum Surface Albedo of Seasonally Snow-Covered Lands in the Northern Hemisphere." Journal of Climate and Applied Meteorology, **24**(5): 402-411.
Rogelj, J., *et al.* (2018). "Mitigation Pathways Compatible with 1.5°C in the Context of Sustainable Development" in Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. V. Masson-Delmotte, P. Zhai, H.-O. Pörtneret al, In press.
Ruddiman, W. F. J. C. C. (2003). "The Anthropogenic Greenhouse Era Began Thousands of Years Ago." **61**(3): 261-293.
Rudorff, B. F. T., *et al.* (2011). "The Soy Moratorium in the Amazon Biome Monitored by Remote Sensing Images." **3**(1): 185-202.
Saatchi, S., *et al.* (2011a). "Impact of spatial variability of tropical forest structure on radar estimation of aboveground biomass." Remote Sensing of Environment, **115**(11): 2836-2849.
Saatchi, S. S., *et al.* (2011b). "Benchmark map of forest carbon stocks in tropical regions across three continents." Proceedings of the National Academy of Sciences, **108**(24): 9899-9904.
Sanadze, G. A. and A. L. Kursanov (1966). "On certain conditions of the evolution of the diene C_5H_8 from poplar leaves." Sov. Plant Physiol., **13**: 184-189.
Schoneveld, G., *et al.* (2019). Environ. Res. Lett., **14**(014006).
Scott, C. E., *et al.* (2018a). "Substantial large-scale feedbacks between natural aerosols and climate." Nature Geoscience, **11**(1): 44-48.
Scott, C. E., *et al.* (2018b). "Impact on short-lived climate forcers increases projected warming due to deforestation." Nature Communications, **9**(1): 157.
Scott, C. E., *et al.* (2014). "The direct and indirect radiative effects of biogenic secondary organic aerosol." Atmos. Chem. Phys., **14**: 447-470.
Smith, P., *et al.* (2016). "Biophysical and economic limits to negative CO2 emissions." Nature Climate Change, **6**: 42.
Snyder, P. K., *et al.* (2004). "Evaluating the influence of different vegetation biomes on the global climate." Climate Dynamics, **23**: 279-302.
Spracklen, D. V., *et al.* (2012). "Observations of increased tropical rainfall preceded by air passage over forests." Nature, **489**(7415): 282-285.
Spracklen, D. V., *et al.* (2018). "The Effects of Tropical Vegetation on Rainfall." Annual Review of Environment and Resources, **43**(1): 193-218.
Spracklen, D. V., *et al.* (2008). "Boreal forests, aerosols and the impacts on clouds and climate." Philosophical Transactions of the Royal Society A, **366**: 4613-4626.
Springmann, M., *et al.* (2016). "Analysis and valuation of the health and climate change cobenefits of dietary change." **113**(15): 4146-4151.
Stehfest, E., *et al.* (2009). "Climate benefits of changing diet." **95**(1): 83-102.
Swann, A. L. S., *et al.* (2012). "Mid-latitude afforestation shifts general circulation and tropical precipitation." Proceedings of the National Academy of Sciences, **109**(3): 712-716.
Teuling, A. J., *et al.* (2017). "Observational evidence for cloud cover enhancement over western European forests." Nature Communications, **8**: 14065.
Thomas, G. and P. R. Rowntree (1992). "The Boreal Forests and Climate." Quarterly Journal of the Royal Meteorological Society, **118**(505): 469-497.
Unger, N. (2014). "Human land-use-driven reduction of forest volatiles cools global climate." Nature Clim. Change, **4**(10): 907-910.
USDA-FAS (2019). Oilseeds: World Markets and Trade. Circular Series FOP July 2019, US Depart of Agric-Foreign Agric Serv, Washington, DC.

van der Werf, G. R., *et al.* (2010). "Global fire emissions and the contribution of deforestation, savanna, forest, agricultural, and peat fires (1997–2009)." Atmos. Chem. Phys., **10**(23): 11707-11735.

van Vuuren, D. P., *et al.* (2011). "The representative concentration pathways: an overview." Climatic Change, **109**(1): 5.

Veldman, J. W., *et al.* (2019). "Comment on "The global tree restoration potential"." Science, **366**(6463): eaay7976.

Vickers, C. E., *et al.* (2009). "A unified mechanism of action for volatile isoprenoids in plant abiotic stress." Nat Chem Biol, **5**(5): 283-291.

Wang, J., *et al.* (2009). "Impact of deforestation in the Amazon basin on cloud climatology." **106**(10): 3670-3674.

Wang, S., *et al.* (2007). "Carbon sinks and sources in China's forests during 1901–2001." Journal of Environmental Management, **85**(3): 524-537.

Went, F. W. (1960). "Organic Matter in the Atmosphere, and its Possible Relation to Petroleum Formation." Proceedings of the National Academy of Sciences, **46**: 212-221.

Williams, M. (2003). Deforesting the Earth, The University of Chigaco Press.

Zhu, J., *et al.* (2017). "Mechanism of SOA formation determines magnitude of radiative effects." **114**(48): 12685-12690.

Zhu, J., *et al.* (2019). "Decrease in radiative forcing by organic aerosol nucleation, climate, and land use change." Nature Communications, **10**(1): 423.