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## Climate benefits of Amazon secondary forests—recent advances and research needs

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## Climate benefits of Amazon secondary forests—recent advances and research needs


















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**Abstract**

A quarter of the deforested Amazon has regrown as secondary tropical forest and yet the climatic importance of these complex regenerating landscapes is only beginning to be recognised. Advances in satellite remote-sensing have transformed our ability to detect and map changes in forest cover, while detailed ground-based measurements from permanent monitoring plots and eddy-covariance flux towers are providing new insights into the role of secondary forests in the climate system. This review summarises how progress in data availability on Amazonian secondary forests has led to better understanding of their influence on global, regional and local climate through carbon and non-carbon climate benefits. We discuss the climate implications of secondary forest disturbance and the progress in representing forest regrowth in climate models. Much remains to be learned about how secondary forests function and interact with climate, how these processes change with forest age, and the resilience of secondary forest ecosystems faced with increasing anthropogenic disturbance. Secondary forests face numerous threats: half of secondary forests in the Brazilian legal Amazon were 11 years old or younger in 2023. On average, 1%–2% of Amazon secondary forests burn each year, threatening the permanence of sequestered carbon. The forests that burn are predominantly young (in 2023, 55% of burned secondary forests were <6 years old, <4% were over 30 years old). In the context of legally binding international climate treaties and a rapidly changing political backdrop, we discuss the opportunities and challenges of encouraging tropical forest restoration to mitigate anthropogenic climate change. Amazon

secondary forests could make a valuable contribution to Brazil's Nationally Determined Contribution provided there are robust systems in place to ensure permanence. We consider how to improve communication between scientists and decision-makers and identify pressing areas of future research.

## 1. Background

Between 1988 and 2023, approximately 850 000 km<sup>2</sup> of Amazon forest had been deforested (data from Instituto Nacional de Pesquisas Espaciais, INPE, 2024) of which around a quarter has regrown (Smith *et al* 2021). We define these regrowing forests as 'secondary' forests, i.e. forests naturally regrowing on land historically covered by forest that has experienced a land cover change (i.e. no longer forest), and subsequent abandonment (Almeida *et al* 2016a). Amazon secondary forests form important carbon sinks (Heinrich *et al* 2021), provide a buffer against primary forest loss (Wang *et al* 2020), improve forest connectivity and protect old-growth forests from edge effects (Smith *et al* 2023a) and help to protect and restore biodiversity (Matos *et al* 2020). Preserving old-growth forests should be the number one conservation priority (Cook-Patton *et al* 2021) as their value in terms of biodiversity, carbon and water cycling, and other environmental benefits is unmatched (Gibson *et al* 2011, Watson *et al* 2018). Secondary forests may accomplish similar characteristics within a few decades to centuries if kept undisturbed (Poorter *et al* 2021a) and promoting tropical forest regrowth is crucial for climate change mitigation and adaptation efforts (Locatelli *et al* 2015). However, secondary forests are distinctive from old-growth primary forests and differ widely in successional stage, species composition, structure, and functionality (Almeida *et al* 2016a, Lennox *et al* 2018, Rozendaal *et al* 2019, Leite *et al* 2023). Understanding the underlying variability in secondary forests is therefore vital when considering how these ecosystems interact with the Earth system.

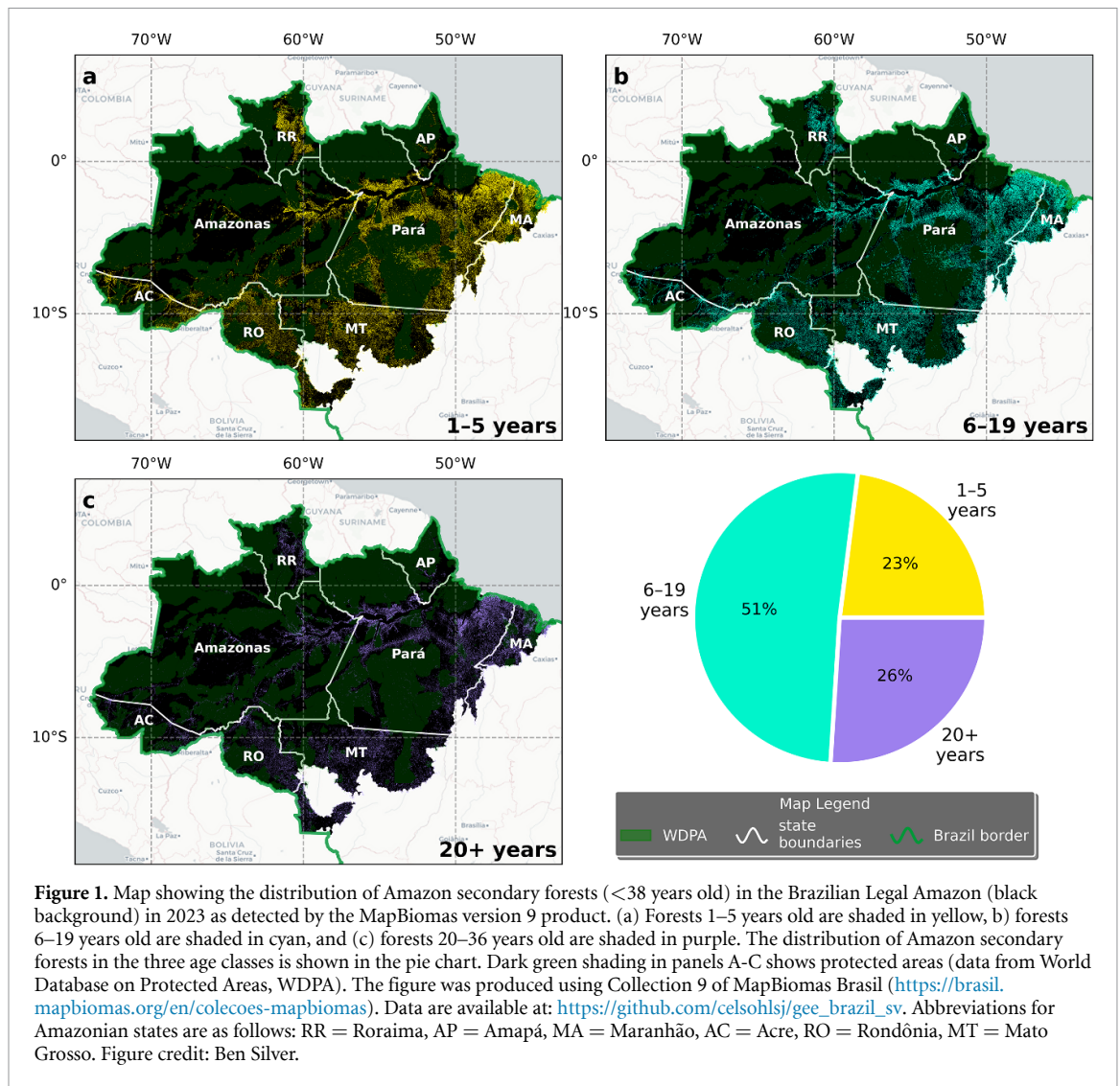
Secondary forest age varies spatially in the Brazilian Amazon (figure 1), which contains around 75% of Amazon secondary forests (Smith *et al* 2021). Forest age is related to the rate of deforestation, with younger forests in more heavily deforested areas (Neeff *et al* 2006, Almeida 2009, Almeida *et al* 2016a, Wang *et al* 2020, da Silva *et al* 2023a). Brazil has the highest potential for tropical forest restoration through natural regeneration, according to a recent analysis (Williams *et al* 2024). Brazil has committed to restoring 120 000 km<sup>2</sup> of forest by 2030 as part of their intended Nationally Determined Contributions (NDCs) under the Paris Agreement (Federative Republic Of Brazil 2016, 2022, 2023). The aim of this agreement is to limit the rise in global mean temperatures to well under 2 °C, with forest restoration and sustainable forest management an essential part

of the mitigation strategy to reduce greenhouse gas emissions (UNFCCC 2015). Reforestation of previously deforested lands offers a way to sequester atmospheric carbon dioxide and increase terrestrial carbon stocks, on the understanding that it must be done in conjunction with preserving old-growth forests.

Analysis of land cover changes in the Brazilian Amazon between 1985 and 2019 revealed complex temporal patterns of loss-regrowth-loss, demonstrating high levels of disturbance in secondary forest ecosystems (Wiltshire *et al* 2022). This explains the dominance of young (<20 years) secondary forests in the region (figure 1). The rate of natural regeneration following the abandonment of agricultural land can vary widely in the Amazon, with aboveground biomass (AGB) recovering within a few decades to well over a century (Gehring *et al* 2005, D'Oliveira *et al* 2011, Heinrich *et al* 2021, Poorter *et al* 2021a), depending on the land use history (see section 3). Secondary forests in Rondônia, Southwest Amazonia had recovered 40%–60% of primary forest biomass after 18 years (Alves *et al* 1997), but rapid recovery is not guaranteed, and much lower rates have been observed in some of the most deforested regions (Elias *et al* 2020) or after mining (Kalamandeen *et al* 2020). Repeated cycles of forest clearance reduce carbon accumulation rates, particularly when fires have occurred (Heinrich *et al* 2021) and have implications for soil health and tree species composition (Villa *et al* 2018, Bauters *et al* 2021).

Restoration of species diversity is more challenging (Jakovac *et al* 2024), with at least 30 years before pioneer species are replaced by late-successional species and more than a century to reach the tree species composition of old-growth forests (Poorter *et al* 2021a, Rosenfield *et al* 2023). Faunal taxa (e.g. dung beetles and birds) recover across similar timescales, with high-conservation-value forest species increasing when forest biomass recovery exceeds 75 Mg ha<sup>-1</sup> (Lennox *et al* 2018). Functional diversity may recover within just a few years to decades of regrowth, with one study of avian communities in 44 secondary forest sites reporting similar levels of ecosystem functioning to nearby primary forests (Sayer *et al* 2017). However, this aspect of diversity is less studied in the Amazon and responses may differ between taxa (e.g. Farneda *et al* 2018).

Smallholder shifting cultivation (where small patches of land are periodically cleared to grow crops before being abandoned) is an important land-management system throughout the Amazon, with many people depending on it for their livelihoods



(Van Vliet *et al* 2013, Curtis *et al* 2018). This practice contributes to the gradual conversion of intact primary forest to secondary forest in areas that are not already protected. Successive cycles of clear cuts under shifting cultivation can reduce forest resilience (Jakovac *et al* 2015), resulting in an alternative stable state (Magnuszewski *et al* 2015). Secondary forests are often targeted for clearance as young forests are easier to cut and are not subject to the same legal protections as old-growth primary forests (Nunes *et al* 2020). In the state of Pará, secondary forests older than 20 years must be conserved (Vieira *et al* 2014) and Mato Grosso state has also approved a bill protecting secondary forests (Secretaria de Estado de Meio Ambiente, SEMA 2016), but no other Brazilian Amazon states legislate to protect secondary vegetation (Wang *et al* 2020).

Current methods for mapping large-scale secondary vegetation areas and estimating their ages rely on optical remote sensing (Almeida *et al* 2016a, Silva Junior *et al* 2020). Significant advances have also been

made in remote sensing involving RADAR (Radio Detection And Ranging) and LiDAR (Light Detection And Ranging), among others. These advances have been used to monitor forest formation, afforestation, degradation and secondary vegetation (Bispo *et al* 2019, Milenković *et al* 2022, Fawcett *et al* 2023, Cooley *et al* 2024). However, these resources do not yet have a sufficiently long time series or complete coverage of the area to be monitored. Current approaches for mapping large-scale areas of Amazon secondary vegetation and estimating their ages therefore still rely on optical remote sensing, and we focus on these in this review.

This article summarises the key advances in secondary forest research in the Brazilian Amazon. We review recent progress in satellite remote sensing and in situ data collection in Amazon secondary forests impact climate at global, regional and local scales, through providing carbon

and non-carbon benefits (sections 3 and 4). We explain how these secondary forest-climate interactions are influenced by drivers of disturbance (section 5) and the importance of accurately modelling forest regrowth for future climate prediction (section 6). We describe two case studies from the Brazilian state of Pará that demonstrate how effective collaboration between scientists and policymakers can lead to successful conservation (section 7). These examples provide a guide for scaling up secondary forest conservation efforts across Brazil and beyond to the wider Amazon. Finally, we look to the future of Amazon secondary forest research and highlight some of the most exciting avenues for further work (section 8).

## 2. Advances in understanding from satellite and in situ data

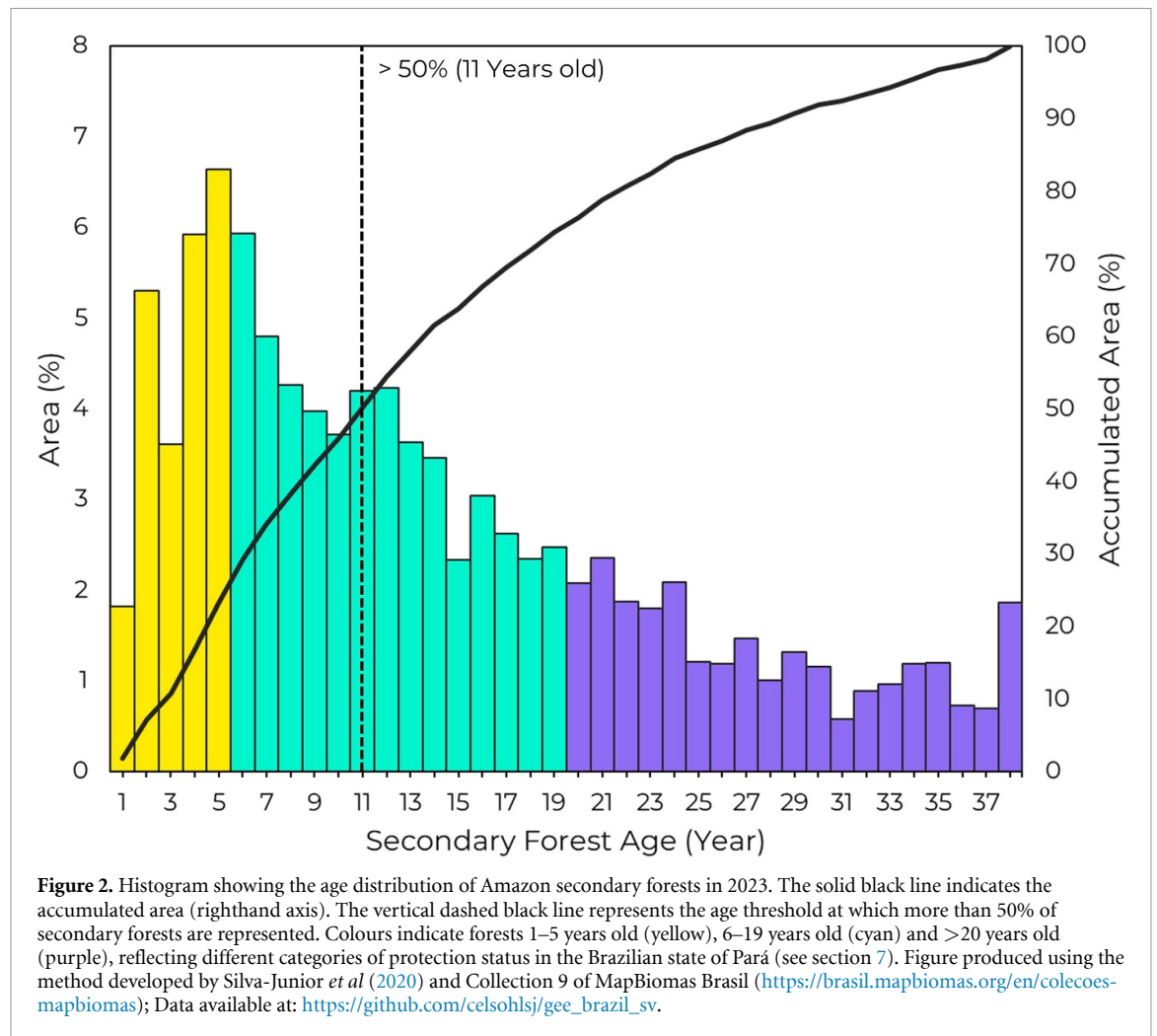
Our understanding of Amazon secondary forests comes from two key sources: satellite remote sensing and field observations. With increasing availability of satellite-based products of land-use and land-cover change, it is now possible to map the extent and ages of Amazon secondary forest (Wang *et al* 2019, Nunes *et al* 2020, Silva Junior *et al* 2020, Smith *et al* 2020, Heinrich *et al* 2021, Vancutsem *et al* 2021), enabling quantification of their role in the global carbon cycle (Harris *et al* 2021, Smith *et al* 2021, Fawcett *et al* 2023, Heinrich *et al* 2023a, Chen *et al* 2024). The European Commission Joint Research Centre has recently mapped global forests, including Amazon secondary forests, in the year 2020 at 10 m resolution, which will enable them to be studied in unprecedented detail (Bourgoin *et al* 2024). Satellite datasets offer spatially comprehensive information, often spanning several decades, but some variables are difficult to measure remotely and calibrating against field data is essential. Detailed information on forest dynamics, including growth rates and compositional changes requires intensive ground data collection at the tree and stand level, but monitoring occurs over smaller areas than possible with remote sensing. In this section, we summarise the importance of satellite datasets for mapping Amazon secondary forests and the vital role of field data for evaluating regrowth rates, ecological succession and climate interactions.

The most challenging aspect of mapping secondary forest is determining whether the area has already been deforested to distinguish it from old-growth primary vegetation. Although it has been possible to identify deforestation and map secondary vegetation with satellite images since the 1970s (Landsat), the data series only became consistent from the mid-1980s with the launch of the Landsat Thematic Mapper sensor (Markham *et al* 2004). Therefore, most satellite-based secondary forest maps are limited to this timeframe. Ongoing efforts using machine

learning to incorporate satellite information with biomass maps, forest inventory data and climate variables may extend secondary forest maps beyond the satellite era in the future (Besnard *et al* 2024).

Brazil has annually mapped primary deforestation since 1988 using optical satellite images through PRODES (Programa de Monitoramento de Desflorestamento na Amazônia Legal), its satellite monitoring program for the Brazilian Amazon. In PRODES, deforestation is defined as the suppression of areas of old growth forest by anthropogenic actions (Almeida *et al* 2021). Usually, its overall accuracy is greater than 90% (Maurano *et al* 2019). To maintain consistency with the historical series, PRODES deforestation rates are calculated for areas larger than 6.25 ha (Kalamandeen *et al* 2018), though since 2017, Brazil's National Institute for Space Research (INPE), has also mapped deforestation smaller than 6.25 ha for Brazil's national Forest Reference Emission Level (data available via the TerraBrasilis Portal). PRODES contributes to the governance and development of policies that seek sustainable production in the Amazon (see section 7) and provides a reliable basis for mapping secondary vegetation.

There have been several attempts to map secondary forests across the Amazon with different methodologies resulting in some differences between data products (Nunes *et al* 2020). The TerraClass project uses the PRODES deforestation map as a base and identifies secondary vegetation using visual interpretation. This is a labour and time-consuming process but remarkably accurate (Almeida *et al* 2016a). Other projects have developed methodologies to estimate secondary forest age based on the MapBiomas map (Silva Junior *et al* 2020). MapBiomas uses fully automated mapping, which reduces the time to obtain the map but does not always show temporal consistency between mapping versions (Souza Jr *et al* 2020). Other methodologies involve machine and deep-learning algorithms to improve the ability to differentiate targets over time (Santos *et al* 2021). Such analysis has only recently become possible with advances in processing infrastructure including cloud computing and storage (e.g. Google Earth Engine, Gorelick *et al* 2017, Amazon Web Services, Chen *et al* 2017; Microsoft Azure and Microsoft Planetary Computer, Luers 2021; and government initiatives such as the Brazil Data Cube, Ferreira *et al* 2020). Nevertheless, improvements in detecting the timing of regrowth are necessary, and satellite-based maps may not reliably detect ground-based restoration (Begliomini and Brancalion 2024). In this review, we present data from MapBiomas Collection 9 (figures 1, 2 and 4), which has a lower area value for secondary forest in the Brazilian Amazon than previous MapBiomas collections (Nunes *et al* 2020, Silva Junior *et al* 2020), likely due to an updated classification approach including better recognition of flooded forests (Mapbiomas 2024). For this reason, it is important to only consider



data within a single collection when evaluating temporal variability. A consistent validation of Amazon secondary forest maps with reference data derived from remote sensing and ground data is urgently required.

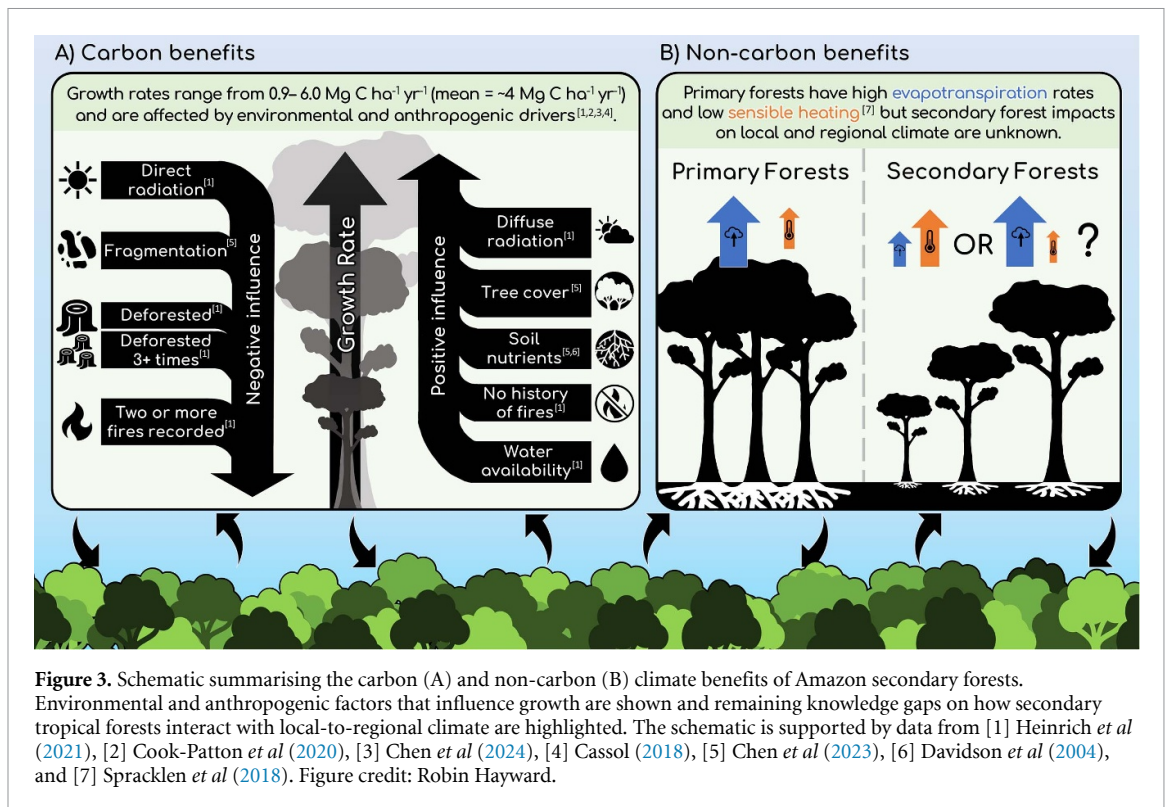
Ground data complement and enhance the insights that can be gained from satellites and are also essential to validate satellite-based maps (Barros *et al* 2018). Secondary forest field inventories and flux tower measurements provide vital information on forest structure, floristic composition, growth rates and climate interactions (see Alves *et al* 1997, Feldpausch *et al* 2005, Silva *et al* 2016, Bentos *et al* 2017, Von Randow *et al* 2020, Heinrich *et al* 2021, Poorter *et al* 2021a and references therein). Secondary forests of different ages that share environmental and soil characteristics are often studied as a chronosequence (i.e. using space-for-time substitution) to assess regrowth rates and forest succession (Feldpausch *et al* 2007, Silva *et al* 2016, Poorter *et al* 2021b). A typical approach is to survey all trees within a sampling plot of known area, recording information such as tree identification, diameter at breast height and tree height, which are used to estimate AGB and carbon accumulation rates (Alves *et al* 1997, Araújo

*et al* 2005, Feldpausch *et al* 2005). Heinrich *et al* (2021) compiled data from 30 field campaigns located across the Amazon and combined this information with six environmental and anthropogenic disturbance drivers to quantify the carbon uptake potential of Amazon secondary forests (see section 3).

An alternative to the chronosequence approach is long-term monitoring at a single location. For example, this may be through repeated plot inventories (Araújo *et al* 2005), or via flux tower measurements (Von Randow *et al* 2020). However, there is only a single flux tower over secondary forest in the Brazilian Amazon. Additional flux tower measurements in forests of different regrowth stages and in different Amazon regions would help to better understand the spatial variability in Amazon secondary forest water recycling and provide valuable ground-truthing for satellite evapotranspiration products (Baker *et al* 2021b).

### 3. Carbon-related climate benefits of Amazon secondary forests

Amazon secondary forests have an important influence on global climate by sequestering and storing



**Figure 3.** Schematic summarising the carbon (A) and non-carbon (B) climate benefits of Amazon secondary forests. Environmental and anthropogenic factors that influence growth are shown and remaining knowledge gaps on how secondary tropical forests interact with local-to-regional climate are highlighted. The schematic is supported by data from [1] Heinrich *et al* (2021), [2] Cook-Patton *et al* (2020), [3] Chen *et al* (2024), [4] Cassol (2018), [5] Chen *et al* (2023), [6] Davidson *et al* (2004), and [7] Spracklen *et al* (2018). Figure credit: Robin Hayward.

carbon, and could play a key role in climate change mitigation efforts (Heinrich *et al* 2021). Figure 2 shows the age distribution of secondary forests in the Brazilian Amazon in 2023. Most of these forests are young, with ~50% younger than 11 years and 90% younger than 29 years. An analysis of 1500 plots in South and Central America found secondary tropical forests took an average of 66 years to achieve 90% of the AGC of old-growth forests (Poorter *et al* 2016). The study found that secondary forests accumulated carbon approximately 11 times faster than old-growth forests, with an uptake rate of 3 Mg C ha<sup>-1</sup> yr<sup>-1</sup> after 20 years (Poorter *et al* 2016). Tropical forest restoration could therefore be important for mitigating climate change (Edwards *et al* 2021). However, carbon accumulation in secondary forests is not uniform across the tropics, with local geography, climate and anthropogenic disturbances influencing regrowth (Cook-Patton *et al* 2020). In this section we summarise the main environmental and anthropogenic factors influencing secondary forest growth variation. These factors are summarised in figure 3. We focus on aboveground carbon (AGC) dynamics as they have been more extensively studied than belowground carbon in Amazon secondary forests.

Variation in environmental conditions is an important driver of variability in secondary forest regrowth rates across the Amazon (Elias *et al* 2020, da Silva *et al* 2023a). In general, AGC accumulation rates are higher in warmer and wetter areas than cooler and drier areas (Cook-Patton *et al* 2020). Regrowth rates of young Amazon secondary forests (<20 years) can

vary by a factor of two with faster regrowth in wetter western regions (3.0 Mg C ha<sup>-1</sup> yr<sup>-1</sup>) compared to drier eastern regions (1.3 Mg C ha<sup>-1</sup> yr<sup>-1</sup>) (Heinrich *et al* 2021). Heinrich *et al* (2021) identified shortwave (SW) radiation as the most important climatic control on growth rate, with higher growth in areas of the Amazon with lower SW radiation, and vice versa. This may be because areas with low SW radiation had high cloud cover and therefore more diffuse radiation, which increases plant productivity (Rap *et al* 2015). Surrounding tree cover and soil fertility also positively influence secondary forest growth (Chen *et al* 2023), while fragmentation has the reverse effect (figure 3). Houghton *et al* (2000) observed uptake rates ranging from 1.5 Mg C ha<sup>-1</sup> yr<sup>-1</sup> for Amazon forests with initial biomass of less than 100 Mg C ha<sup>-1</sup>, to about 5.5 Mg C ha<sup>-1</sup> yr<sup>-1</sup> for forests with initial biomass of more than 190 Mg C ha<sup>-1</sup>. A recent meta-analysis of 452 Amazon secondary forest plots in chronosequence (forests aged between 1–70 years) found carbon stocks ranging from 0.1 to 295 Mg C ha<sup>-1</sup> (Cassol 2018) and a mean growth rate of 4 Mg C ha<sup>-1</sup> yr<sup>-1</sup> (CV = 77%). These findings are similar to those of Chen *et al* (2024), who reported an average regrowth rate equivalent to 3.89 Mg C ha<sup>-1</sup> yr<sup>-1</sup> for the Brazilian Amazon.

Land use history and the magnitude of disturbance are major factors affecting regeneration and biomass accumulation in Amazon secondary forests. Disturbance magnitude is measured by the spatial extent, duration, frequency and severity of use before abandonment (Waide and Lugo 1992, Chazdon 2014). Major anthropogenic disturbances,

such as the conversion of forests to agricultural areas and pastures, have more severe effects on the regeneration of forests than areas abandoned immediately after cutting without cultivation, e.g. due to soil degradation (Moran *et al* 2000, Zimmermann *et al* 2006). Studies have shown that the type of land use (agricultural, pasture, silviculture, or no use), the frequency of clear cuts (number of cycles), and the method used for forest removal (mechanized, with/without fire) can all influence carbon accumulation rates in Amazon secondary forests (Uhl *et al* 1988, Steininger 2000, Wandelli and Fearnside 2015). Abandoned pastures reportedly have slower regrowth rates than other land uses due to the frequent use of fire and higher predation of seeds and seedlings in these areas (Uhl *et al* 1988, Fearnside and Guimarães 1996, Sorrensen 2000). In the central Amazon, secondary forests regenerating on pastures accumulated 25–50% AGB of primary forests in the first 12–14 years (Feldpausch *et al* 2004). Secondary forests growing after a single slash-and-burn cycle showed rapid growth rate saturation, taking an estimated 25 years to reach 50% primary forest AGB and 175 years to restore 75% AGB (Gehring *et al* 2005).

The knowledge of such variation in forest regrowth is important for estimating carbon accumulation potential in secondary forests. Carbon assimilation models often use unrealistically fixed carbon regrowth rates for secondary tropical forests. In their global stocktake, Pan *et al* (2024) estimated carbon uptake in South America tropical regrowth forests to be 4.13 Mg C ha<sup>-1</sup> yr<sup>-1</sup> over a 30 year period, with uncertainty in carbon stocks of around 43%. Cook-Patton *et al* (2020) mapped spatial variation in carbon uptake rate for secondary forests globally, based on 66 environmental covariates and assumed fixed growth rates over the first 30 years of regeneration. They estimated carbon uptake rates of up to 6.0 Mg C ha<sup>-1</sup> yr<sup>-1</sup> with South American rainforest having the highest average uptake rate of 41 ecozones analysed. These studies provide a valuable benchmark for assessing the climate change mitigation potential of reforestation. However, it is important to note that Amazon secondary forest regrowth rates are not linear but decay exponentially with time, and it cannot be assumed that secondary forests will return to the same AGB as primary forests (Gehring *et al* 2005). A long-term repeated assessment in the Eastern Amazon shows 60-year-old forests accumulating just 1.08 Mg ha<sup>-1</sup> yr<sup>-1</sup> (Elias *et al* 2020). Research has shown the loss of resilience of Amazon secondary forest areas due to the intensification of land-use practices (Jakovac *et al* 2015, Chazdon *et al* 2016, Poorter *et al* 2016). Heinrich *et al* (2021) showed carbon accumulation rates may saturate sooner than 30 years, with fire and repeated deforestation substantially limiting regrowth rates (see section 5). The slowest regrowth rates are in Amazon regions with the longest history of deforestation, where there are

almost no primary forests left to provide seed sources (Elias *et al* 2020).

The geographic complexity of regrowth rates in Amazon secondary forest has implications for policies focused on maximising climate mitigation potential whilst enabling secondary forests to be used sustainably. If the current area of secondary forest in the Brazilian Amazon is maintained to the year 2030, the carbon sink could contribute 5.5% of Brazil's NDCs from the Paris Agreement of the United Nations Framework Convention on Climate Change (Heinrich *et al* 2021). Given that in 2017, the area of secondary forests in the Brazilian Amazon (~136 000 km<sup>2</sup>) was equivalent to 1.6% of Brazil's land area, the mitigation contribution is proportionally large (~30%, Heinrich *et al* 2021). Due to the dominance of young (<10 years) secondary forest stands in Brazil (figure 2), preserving only mature (>20 years) secondary forests to 2030 would reduce the mitigation contribution to <1% of Brazil's NDC (Heinrich *et al* 2021). Across the Brazilian Amazon, the Amazon biome and indeed the pantropics, secondary forest carbon regrowth only balances 9%–14% of the carbon lost from ongoing deforestation and degradation (Harris *et al* 2021, Heinrich *et al* 2021, Smith *et al* 2021).

Amazon secondary forests could also contribute to country-level commitments under the Global Biodiversity Framework (Convention on Biological Diversity (CBD) 2022) and are fundamental for achieving the aim of restoring 30% of degraded areas. While secondary forests may take centuries to acquire the largest trees and structural complexity of old growth forests, the colonisation of species of higher conservation value accelerates when they surpass 75 Mg C ha<sup>-1</sup>, which can happen on decadal time scales (Lennox *et al* 2018). Furthermore, even young forests can be important for biodiversity by enabling species movement and gene exchange across the landscape, and one analysis across the Amazon suggests over 2 million fragments are connected by some form of secondary forest (Smith *et al* 2023). Further landscape-level benefits are accrued from the buffering of over 40% of exposed forest edges (Smith *et al* 2023), potentially helping mitigate the edge effects that are a pervasive driver of vertebrate declines (Pfeiffer *et al* 2017) and diminish above-ground carbon stocks (Berenguer *et al* 2014). Keeping pledges on protecting forests, particularly old-growth forests, made on global geopolitical stages remains a priority for addressing the climate and biodiversity emergencies.

#### 4. Non-carbon climate benefits of Amazon secondary forests

Old-growth tropical forests are well known to modulate local and regional climate through mediating exchanges of water and energy between the land and



the atmosphere and altering the surface energy balance (Bonan 2008). Amazon forests, including secondary vegetation, have a lower albedo than pasture and croplands ( $\sim 2\%$  lower), so absorb more incoming solar radiation (Bastable *et al* 1993, Gash and Nobre 1997, Campos *et al* 2021). However, forests also have high rates of evapotranspiration and high surface roughness, which promote the transfer of heat and moisture from the land to the atmosphere, resulting in low sensible heat fluxes and a net cooling at the surface (Gash and Nobre 1997, Von Randow *et al* 2004, Da Rocha *et al* 2009, Spracklen *et al* 2018). Research estimating the effect of natural regeneration on local temperatures suggested tropical reforestation could cause annual cooling of  $2\text{ }^{\circ}\text{C}$  (Alibakhshi *et al* 2024), though this work was based on an analysis of climate variables over intact forests only.

In the Amazon, 24%–41% of precipitation is sourced from evapotranspiration from within the basin (Baker and Spracklen 2022). When the Amazon is deforested these land-atmosphere interactions are disrupted causing substantial surface warming ( $< 2\text{ }^{\circ}\text{C}$ ) and precipitation reductions (Alkama and Cescatti 2016, Bright *et al* 2017, Spracklen *et al* 2018, Baker and Spracklen 2019, Cohn *et al* 2019, Smith *et al* 2023b). The regional impacts on temperature are extensive, with a recent analysis showing Amazon deforestation causes warming up to 100 km from the site of deforestation (Butt *et al* 2023). The impacts of deforestation on precipitation are scale dependent (D’Almeida *et al* 2007, Lawrence and Vandecar 2015). Small patches of deforestation may increase precipitation over or near to the location of forest loss due to convection initiation (Garcia-Carreras and Parker 2011, Khanna *et al* 2017). At larger scales, deforestation reduces precipitation (Spracklen and Garcia-Carreras 2015, Smith *et al* 2023b) through reduced moisture recycling (Zemp *et al* 2017, Staal *et al* 2018). In addition, air pollution associated with biomass burning, e.g. across the arc of deforestation, exposes nearby secondary forest trees to high ozone levels. These fast growing, high stomatal conductance tree species are likely highly susceptible to ozone air pollution, reducing plant productivity and regrowth (Cheesman *et al* 2024, Brown *et al* submitted).

Amazon secondary forests differ in important ways from primary forests in terms of species composition, structure and hydrological functioning (Peña-Claros 2003, Feldpausch *et al* 2005, Poorter *et al* 2016, Von Randow *et al* 2020), so we might expect that secondary forests would also interact differently with local and regional climate. Fast-growing pioneer tree species that dominate in secondary forests tend to have lower wood densities and invest less in water conservation measures than slower-growing tree species that are better protected against drought (Poorter *et al* 2010). A comparison of flux tower measurements in a primary forest and a 20-year-old secondary forest in Central Amazonia revealed important differences

in land-atmosphere interactions between the two sites (Von Randow *et al* 2020). Over four years of measurements, evapotranspiration was 20% higher in the secondary forest ( $3.6\text{ mm d}^{-1}$ ) than in the primary forest ( $3.1\text{ mm day}^{-1}$ ), while gross primary productivity was only 5% higher ( $8.1\text{ gC m}^{-2}\text{ d}^{-1}$  in the secondary forest,  $7.8\text{ gC m}^{-2}\text{ d}^{-1}$  in the primary forest). The differences in evapotranspiration between primary and secondary forest sites were attributed to higher transpiration rates of the secondary forest tree species. This conclusion is supported by the findings of Kunert *et al* (2015) who observed higher leaf-scale transpiration rates in secondary tree species than in old-growth species in the same region. Von Randow *et al* (2020) estimated that stomatal resistance was 40% lower in the secondary forest than in the primary forest site, highlighting the higher drought vulnerability of secondary forests.

In contrast, a study in the southern Amazon based on remote sensing data reported lower evapotranspiration and higher land surface temperature in secondary compared to intact forest sites, particularly in the dry season (Rangel Pinagé *et al* 2023). They found secondary sites had lower structural complexity (a proxy for surface roughness), and as such transfers of heat and moisture from the land to the atmosphere would be lower than over intact forests. The southern Amazon region has a longer and more severe dry season than the flux tower sites in the central Amazon measured by von Randow *et al*, possibly explaining the differences in secondary forest evapotranspiration between the two studies.

Two studies based on MODIS land surface temperature estimates have drawn opposite conclusions about the relative influence of forest loss and forest gain on surface temperature. Su *et al* (2023) analysed areas that remained classified as ‘forest’ but experienced fine-scale (sub-grid) changes in tree cover. They reported that the cooling from tree gain in the tropics was stronger than the warming due to tree loss, such that grid cells where areas of gain and loss were equal saw an overall cooling effect of  $-0.58\text{ }^{\circ}\text{C}$ . They concluded that this was caused by increases in evapotranspiration from tree cover gains being higher than the decreases in evapotranspiration from tree loss. In contrast, Zhang *et al* (2024) reported a cooling of  $-0.10\text{ }^{\circ}\text{C}$  due to tropical forest gain compared to a warming of  $+0.56\text{ }^{\circ}\text{C}$  caused by tropical forest loss. These authors used a slightly different approach whereby 30 m tree cover data were aggregated to a larger grid and grid cells were categorised as forest (tree cover  $> 60\%$ ) or non-forest (tree cover  $< 60\%$ ) in each year to identify forest gains and losses. This study may have included areas with larger reductions in forest, as they did not limit their analysis to areas that remained classified as forest. Both studies were limited to a period of about a decade (2000–2012 in Su *et al* 2023 and 2003–2013 in, Zhang *et al* 2024), and therefore may not fully capture the climate

interactions of regrowing secondary forests. Overall, the lack of agreement on how regrowing secondary forests influence the local-to-regional climate system and how these interactions change as forests age highlights a need for further research in this area (figure 3).

## 5. Drivers of secondary forest disturbance

Understanding drivers of secondary forest disturbance is crucial, as they impact the dynamics of forest regrowth, carbon sequestration and forest-climate interactions. Currently, there is a lack of information on selective logging in Amazon secondary forests and use of non-wood materials. Although their impacts on forest dynamics are still poorly understood, fires, droughts and repeated deforestation after regrowth are perhaps the most studied drivers of secondary forest disturbance in the Amazon due to the availability of satellite-derived products and we focus our discussion on these here. The impacts of fire, deforestation and water availability on secondary forest growth are summarised in figure 3.

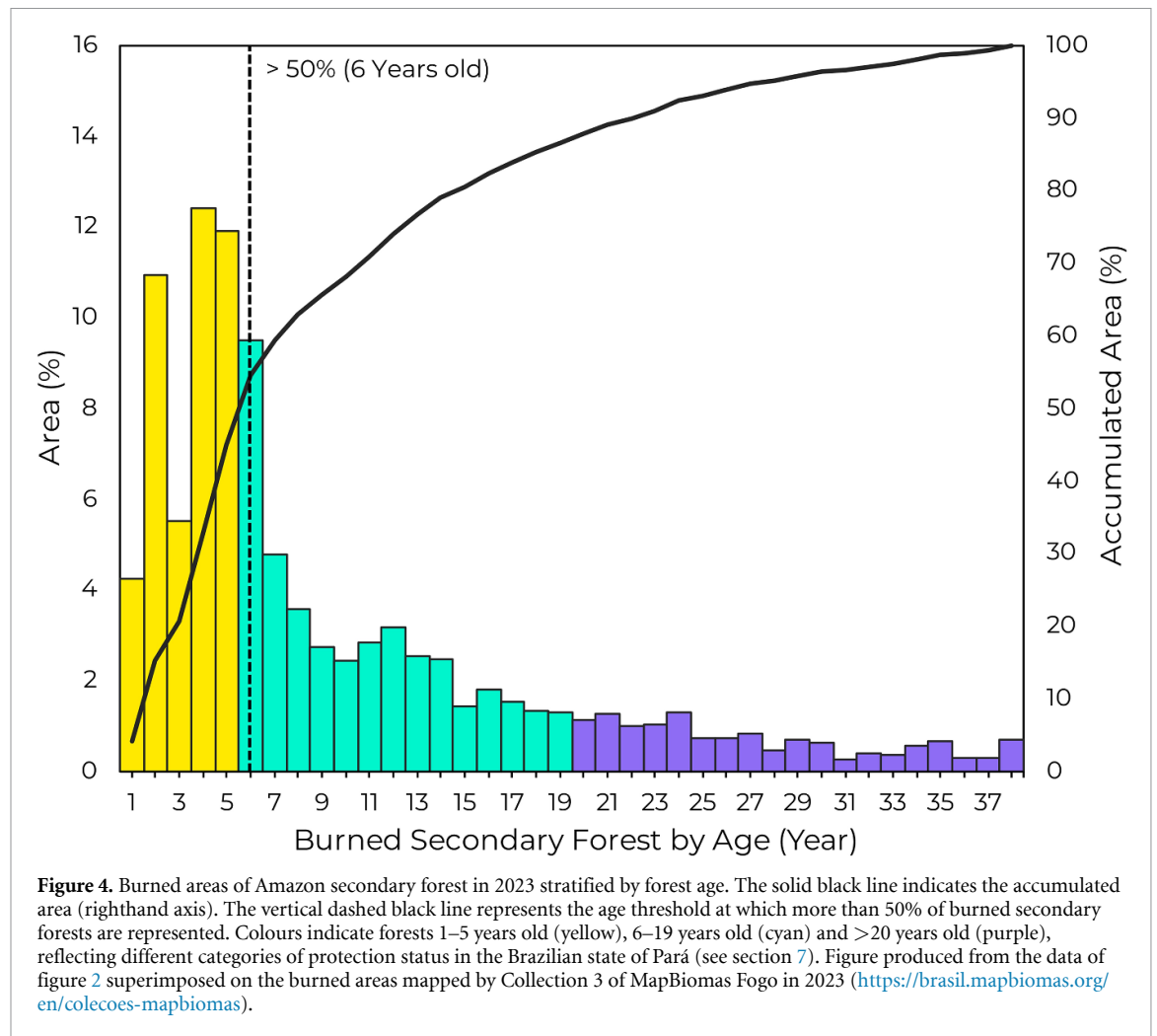
In the humid forests of the Amazon, fire is an anthropogenic driver of secondary forest disturbance and a major source of carbon emissions (Silva *et al* 2020). A recent analysis showed that between 2003 and 2020 on average approximately 79 500 km<sup>2</sup> of land burned annually in the Amazon (including forests, savannas, grasslands and agricultural lands), of which approximately 2% (1862 km<sup>2</sup>) occurred in areas of secondary tropical forest (Silveira *et al* 2022). This represents less than 1% of Amazon secondary forests by area. Most Amazon secondary forest burning occurs in Brazil (89%), where 1%–2% of secondary forests burned each year (Silveira *et al* 2022). In 2023, for example, ~2% of Brazilian secondary forests burned, the majority of which were young forests (55% were <6 years old, figure 4) where the highest carbon uptake rates are found. More mature secondary forests formed a smaller proportion of the burned area, with only 12% of fires occurring in forests older than 20 years and <4% in forests older than 30 years (figure 4). These results have relevance when considering the contribution of secondary forests to NDCs, since permanence is a key requirement when accounting emission reductions (NDC Synthesis Report 2022). With young Amazon secondary forests more likely to burn, safeguards will be required to ensure reforestation for climate change mitigation is effective.

Amazon fire activity in 2020 was the highest in the two first decades of this century with a total burned area of 91 250 km<sup>2</sup> (Silveira *et al* 2022). Major fire events in the Amazon are often associated with extreme meteorological conditions such as droughts (Aragão *et al* 2018, Li *et al* 2021a, 2021b), including the intensive burning of old-growth forests in 2023 (Mataveli *et al* 2024). However, the fires in 2020 were associated with deforestation rather than water

deficit anomalies (Silveira *et al* 2022). Butt *et al* (2022) demonstrated strong positive associations between deforestation and fire across the Brazilian Amazon. An analysis of large fires in Brazil found nearly 30% occurred in near-normal meteorological conditions (Li *et al* 2021b). This highlights the dominance of human activity on the Amazon fire regime (Aragão *et al* 2014). Amazon secondary forests that experienced repeated fire events showed AGC accumulation rates 50%–75% lower than forests with no burning history (figure 3), and long-term reductions in maximum accumulated AGC (Zarin *et al* 2005, Heinrich *et al* 2021). Furthermore, fires can substantially alter microclimatic conditions, hindering regeneration and in some cases completely preventing forest recovery (Almeida *et al* 2016b, Smith *et al* 2023).

Droughts are another important driver of change in the carbon balance of tropical forests. In old-growth forests, droughts affect tree species composition and lead to reductions in biomass (Phillips *et al* 2009, Esquivel-Muelbert *et al* 2019). We might reasonably expect secondary forests to be even more susceptible to drought stresses. Young trees may lack the deep roots known to support old-growth forests (Nepstad *et al* 1994, Broedel *et al* 2017); pioneer species that dominate secondary forests tend to have lower wood density, which is associated with higher drought-driven mortality (Phillips *et al* 2009, Poorter *et al* 2010, Uriarte *et al* 2016); and pioneers are also more vulnerable to stem cavitation (Markesteijn *et al* 2011). Recent work has shown that Amazon forests with more fast-growing tree species take greater hydraulic risks and consequently have higher drought-induced mortality rates than forests with more slow-growing species (Tavares *et al* 2023). On the other hand, if the shift in species composition seen in old-growth forests towards species associated with dry environments (Esquivel-Muelbert *et al* 2019) is also occurring in secondary forests, then the latter may become more resilient to drought. However, secondary forests are often found in regions with little surrounding old-growth forest cover (Silva Junior *et al* 2020) and compositional changes may be limited by seed bank availability.

A growing body of evidence suggests that Amazon secondary forests are indeed vulnerable to drought stress, but via a different mechanism to primary forests (Poorter *et al* 2016, Elias *et al* 2020, Heinrich *et al* 2021). Evidence from repeated forest inventories in the Brazilian Amazon shows that droughts reduce the carbon balance of secondary forests by reducing growth (Elias *et al* 2020). This differs from primary forests, where droughts impact the carbon balance through increased tree mortality (Phillips *et al* 2009). A study using a space-for-time analysis of secondary forests found carbon uptake rates were 44% lower in secondary forests experiencing very high water deficits (>–350 mm yr<sup>–1</sup>)



compared to those experiencing very low water deficits ( $< -180 \text{ mm yr}^{-1}$ ) (Heinrich *et al* 2021). A previous study assessing the impact of 2015 El Niño suggested Amazon secondary forests may be resilient to one-off drought or fire events, reporting elevated regrowth rates in the aftermath of the drought. However, the authors cautioned that their focus on stem growth across a 2.5 year period could overlook longer-term carbon losses (Berenguer *et al* 2018). Meanwhile, repeated drought events are reported to cause canopy damage and reductions in photosynthetic capacity in Amazon secondary forests (Anderson *et al* 2018). With droughts increasing across all tropical continents (Dunn *et al* 2020), these findings are a cause for concern and highlight the importance of understanding the differences in primary and secondary forest responses.

All secondary forests grow on land that was once deforested, but in the Amazon repeated deforestation following regrowth is common, contributing to the predominance of young secondary forests (>50% <11 years old, figure 2). By 2014, clearance of secondary forest accounted for over 70% of Amazon deforestation (Wang *et al* 2020). Repeated deforestation has slightly smaller consequences for

Amazon secondary forest regrowth rates than fire and droughts, reducing regrowth by 20%–55% (Heinrich *et al* 2021). However, when repeated deforestation and fire are combined growth rates are reduced up to 80% and maximum carbon accumulation is suppressed (Heinrich *et al* 2021). In addition to affecting the carbon balance, these anthropogenic disturbances reduce seed availability, impact nutrient dynamics and lower biodiversity resulting in increasingly depleted and dysfunctional ecosystems (Uhl *et al* 1988, Hughes *et al* 2000, Faria *et al* 2023).

## 6. Representation of secondary tropical forests in climate models

Reliable predictions of future climate require accurate representation of secondary forest regrowth, forest resilience and forest-climate interactions in climate models. Regrowth is modelled using Dynamic Global Vegetation Models (DGVMs), which simulate vegetation dynamics within land-surface schemes and Earth system models. The Amazon has an estimated ~16 000 Amazon tree species (Ter Steege *et al* 2013), though only around 1% account for 50% of carbon uptake and storage (Fauset *et al* 2015). By

necessity, DGVMs condense this vegetation diversity into a handful of plant functional types (PFTs)—broad groupings of plants that attempt to capture key differences in vegetation structure and function. For example, in the UK land-surface model JULES-TRIFFID, the number of tree PFTs was recently increased from five to nine (Harper *et al* 2016). At present PFTs do not distinguish between primary and secondary forests. A key knowledge gap is whether secondary forests are functionally different from primary forests, and if so, which key traits (e.g. wood density, bark thickness, evapotranspiration rate etc) need to be differentiated when describing primary and secondary forest PFTs.

DGVMs employ a variety of methodologies to simulate forest mortality, competition, and recruitment (Fisher *et al* 2018, Argles *et al* 2022) and regrowth dynamics are often represented in an oversimplified way (Hanbury-Brown *et al* 2022). Underestimating forest regrowth rates in JULES-TRIFFID has been shown to affect the resilience of tree PFTs to fires, with implications for modelled vegetation cover (Burton *et al* 2019). Furthermore, demographic-dependent disturbances such as drought mortality increasing with tree size (Gora and Esquivel-Muelbert 2021, Oliveira *et al* 2021), are often not fully implemented into land-surface models. Some models have recently incorporated plant hydraulics (Eller *et al* 2018), and the ORCHIDEE land surface model has been updated to explicitly include drought mortality (Yao *et al* 2022). Results show improved simulation of temporal trends and variability in the carbon cycle over Amazonia (Yao *et al* 2023).

To simulate secondary forest regrowth, models need to represent forest demography and variation in tree size through time as prerequisite. Increasingly, land-surface models are representing forest demography through use of cohort DGVMs (Haverd *et al* 2014, Fisher *et al* 2015, Argles *et al* 2020, Weng *et al* 2022). These models partition PFTs into size classes to capture the variation of forest size-structure, and/or rely on using patch age classes to represent spatial variation of forest. Cohort DGVMs have the potential to capture heterogeneous sub-grid processes for evaluation at the landscape scale to improve our understanding of forest ecosystem resilience. The cohort DGVM has been used to investigate important dynamics, such as forest-fire-fragmentation feedbacks (Longo *et al* 2019) and the impact of rooting depth on tree hydraulic water-stress and mortality (Chitra-Tarak *et al* 2021).

Although implementing forest demography in models is challenging, changes in forest cover have an important effect on climate through energy partitioning and land-atmosphere moisture fluxes (see section 5). Modelling studies have shown the major impact of Amazon deforestation scenarios on the regional water cycle, with reductions in

evapotranspiration impacting precipitation, runoff and river discharge (D’Almeida *et al* 2006, Costa and Pires 2010, Júnior *et al* 2015, Spracklen and Garcia-Carreras 2015, Guimberteau *et al* 2017, Baker and Spracklen 2022, Luo *et al* 2022). Errors in model representation of forest-climate interactions can result in unrealistic climate projections under future land-use-change scenarios (Baker *et al* 2021a, Robertson 2019). The CMIP6 climate models showed substantial variability in their ability to capture increases in temperature and decreases in precipitation caused by historical tropical deforestation, with some models simulating the opposite response to observations (Smith *et al* 2023c).

A modelling study examined the potential effects of Amazon secondary forest growth on regional climate and hydrology (Von Randow *et al* 2019). The authors simulated future discharge in the Tocantins river basin in Brazil under multiple climate and land-use-change scenarios. In their model, reductions in river discharge caused by climate change were exacerbated when secondary regrowth scenarios were included, due to the high evapotranspiration of secondary forests. It is important to note that the model simulations used in this study considered the direct effects of climate and land-use change on discharge but did not include feedbacks between forest change and rainfall production. For instance, deforestation (reforestation) might impact regional climate in the long term by reducing (increasing) precipitation recycling in the region, which may then feedback reducing (increasing) discharge (Lima *et al* 2014). An analysis of rain gauge data from Europe found realistic reforestation could increase summer rainfall by 7.6%, partially offsetting reductions due to climate change (Baker 2021, Meier *et al* 2021). These studies highlight that accurate representation of secondary forests in fully coupled Earth system models would improve climate predictions in areas expected to see large future changes in forest cover, such as the Amazon (Marengo *et al* 2018).

## 7. Applying scientific knowledge to policy for conserving secondary forests

Large-scale restoration of tropical secondary forests has the potential to deliver high ecological benefits at low economic cost (Crouzeilles *et al* 2017), but currently this potential remains largely unrealized. Despite favourable ecological conditions for natural regeneration across much of the Amazon, the absence of robust regional governance to protect secondary forests undermines their permanence within the landscape (Vieira *et al* 2014). In this section we discuss two case studies from the Brazilian state of Pará in the eastern Amazon (figure 1), where evidence from scientific research has directly influenced land-use policies relating to secondary forest conservation. We use these jurisdictional-level cases to explore the

role of science in shaping policy and discuss lessons that can be applied to scale efforts to the regional level.

### 7.1. Case study 1: clarifying legal definitions of secondary forests for conservation

In 2014, the Pará State Environment Secretariat (Secretaria de Estado de Meio Ambiente do Pará, SEMAS) identified a significant public issue: the lack of clarity in state legislation regarding the legal status of secondary forests. This ambiguity was causing conflicts between landowners, the federal monitoring agency, and SEMAS. According to Pará's land zoning regulations, 'late-stage' secondary forests were prohibited from being clear-cut. However, there was no clear definition of what constituted 'late-stage', leaving landowners, decision-makers, and enforcement agencies uncertain about how to apply the rule. To address this issue, the Green Municipality Programme invited a scientific working group coordinated by Embrapa (the Brazilian Agricultural Research Corporation) and the Sustainable Amazon Network (RAS), an international consortium of researchers focused on improving the sustainability of tropical land use and fostering dialogue between scientists and policymakers (Gardner *et al* 2013). The team compiled ecological data across Pará by bringing together local institutions and researchers working in Brazil and internationally.

The working group developed ecological criteria to define 'Early', 'Intermediate' and 'Late' stage forest regeneration, allowing the state to licence the re-use of forests with the lowest ecological value and protect the most ecologically important forests. Specifically, the working group compiled evidence from a range of research to identify when secondary forests begin to hold much higher levels of biodiversity. The final analysis suggested that: all forests above 20 years old should be protected; forests less than 5 years old could be cleared; and forests between 5 and 20 years old should be protected if their basal area sits above a certain threshold (between 5 and 10 m<sup>2</sup> ha<sup>-1</sup>). Forests in these three categories of protection status are indicated in figures 1, 2 and 4. The precise basal area threshold used to decide whether 5–20 year-old forests should be protected is linked to the level of forest cover in the municipality, accounting for the slower growth rates in the most deforested regions.

This analysis formed the basis of a new law that was published in three revisions; in the final revision (Instrução Normativa N°08, dated 28 October 2015) the working group clarified the measurement criteria for field-based assessments of carbon stocks, refined the thresholds between basal area and forest cover at the municipality level, and added clauses to ensure that the legislation guards against perverse outcomes, such as secondary forests being deliberately degraded prior to carbon assessments. As a result of this legislation, secondary forests in Pará older than 20 years

must be conserved (Vieira *et al* 2014). If Pará's legislation were applied to all secondary vegetation in the Brazilian Amazon, around a quarter would be protected at the present (figure 1). The licensing detailed by this law allows farmers to return low-value secondary forests to agricultural use whilst ensuring those with the highest carbon stocks and highest biodiversity values are protected (Vieira *et al* 2014).

### 7.2. Case study 2: the importance of accurate carbon assessments for climate change mitigation

In 2020, members of RAS were invited by SEMAS to provide scientific guidance about the carbon accumulation rates of secondary forests in the eastern Amazon to help formulate the 'State Plan for Amazonia Now' (Plano Estadual Amazonia Agora; PEAA—State Decree no. 941 from the 3rd of August 2020), which aims to achieve carbon neutrality in Pará by 2035. Under the PEAA, the state is planning to reforest over 500 000 km<sup>2</sup> of land, representing almost half of Brazil's NDC. The researchers provided up-to-date and regionally appropriate assessments of the carbon accumulation rates of secondary forests (e.g. Elias *et al* 2020, Lennox *et al* 2018). These were substantially lower than the rates that were initially proposed, which were based on data from other regions of the Amazon. The change therefore increased the extent of secondary forest required to reach carbon neutrality. Forest restoration plans from PEAA are being implemented through the Pará Forest Restoration Plan, launched in 2023, following a comprehensive participatory process in which local institutions and stakeholders have been actively involved.

### 7.3. Lessons for policymaking in the wider Amazon context

These two case studies underscore the importance of creating institutional spaces for sharing knowledge and policy solutions, both within individual Amazonian countries and across the region (Vieira *et al* 2024). Ideally, these spaces should be fostered not merely through the translation of scientific findings but through processes of co-construction, participation, and active engagement (Toomey *et al* 2017). Communication across the science-policy interface is a fundamental challenge, and improving it is key to developing evidence-based decision making and avoiding the potential disregard of available knowledge by policymakers (Bertuol-Garcia *et al* 2018). In the cases above, successful engagement required agility on the part of the researchers; policymakers identified an explicit and time-sensitive need for scientific guidance and local researchers were willing to engage at short notice, work collaboratively, and meet those needs. By highlighting these examples, we aim to inspire more researchers to proactively collaborate with decision-makers, contributing to and strengthening evidence-based policymaking.

Scaling to the rest of the Amazon will require resolving pervasive disparities in knowledge production that persist across the region (e.g. Carvalho and Resende *et al* 2023). For example, a meta-analysis of 362 articles (da Silva *et al* 2023b) found that Brazil, particularly the state of Pará, dominated the number of restoration studies (292 articles), while countries like Peru and Colombia lagged behind (37 and 15 articles, respectively) despite having significant areas of secondary forest recovery (Smith *et al* 2021). Venezuela, French Guiana, Guyana, and Suriname had only 11 restoration articles between them. The success of Brazil's PRODES program, which monitors land-use changes via satellite (see section 2), highlights the importance of robust monitoring systems in fostering knowledge production and enabling effective policy measures. PRODES has supported a range of conservation initiatives, including the soy moratorium and Payment for Ecosystem Services programs (e.g. Rudorff *et al* 2011, Nepstad *et al* 2014, Wong *et al* 2022). There have been efforts to improve forest monitoring capacity outside Brazil. From 2010 to 2017, INPE delivered training in satellite-based forest monitoring techniques to nearly 700 participants from 60 tropical countries through the Capacitree Project (INPE 2021). Establishing a basin-wide monitoring system under the Amazon Cooperation Treaty Organization (ACTO) could greatly enhance integrated research and improve conservation across the Amazon.

## 8. Outlook

Amazon secondary forest research has advanced rapidly in the past decade and this trend promises to continue. We have summarised the climatic importance of secondary forests at global through to local scales, through feedbacks on the carbon and water cycles. However, key knowledge gaps remain. There is a pressing need to provide a consistent validation of secondary forest maps using ground and remote-sensing data, to identify areas of agreement and understand why discrepancies arise (Nunes *et al* 2020, Silva-Junior *et al* 2020). Reliable forest monitoring is essential for conservation and a prerequisite for Amazon secondary forests to contribute to climate change mitigation efforts (Heinrich *et al* 2021). Careful consideration of secondary forest definitions, robust systems to ensure permanence, and transparent methods for reporting land carbon emissions are also required (Wiltshire *et al* 2022, Heinrich *et al* 2023b). Research on Amazon secondary forests outside of Brazil remains scarce (da Silva *et al* 2023b), in part due to insufficient secondary vegetation mapping. Establishing a robust forest monitoring framework under ACTO would improve our understanding of secondary forest dynamics across the whole Amazon and support policies for their conservation.

Further research is also needed to better understand local-to-regional forest-climate interactions and how they change as forests age. Current approaches that predict the impact of tropical forest restoration on local temperature based on relationships with intact forest (Alibakhshi *et al* 2024), or through evaluating relatively short time series (Su *et al* 2023, Zhang *et al* 2024) may overlook the distinct nature of Amazon secondary forest-climate interactions (e.g. Von Randow *et al* 2020) and their unknown responses to succession. Future work should address these crucial unknowns, focussing on how secondary forests modulate local and regional temperatures in space and time, their influence on the water cycle, and understanding secondary forest resilience to long-term climate change.

A new network of permanent monitoring plots in Amazon secondary forests is being established as part of Amazon-SOS: a Safe Operating Space for Amazonian Forests initiative, which will provide valuable new insights about forest regrowth and resilience in a changing environment. Results from Amazon-SOS will help to improve climate model representation of secondary forests, including the potential to describe a new secondary tropical forest PFT. This work is essential to improve predictions of how large-scale tropical forest restoration will influence regional temperature projections. Additional ground observations, including eddy covariance flux tower measurements in different Amazon regions and in forests at different stages of regrowth, and measurements of belowground carbon would further enhance our knowledge of secondary forest functioning and provide essential validation for remote-sensing studies.

The rapid pace of anthropogenic changes in the Amazon threatens the future viability of the ecosystem and urgent action is needed to protect what forest remains (Albert *et al* 2023, Lapola *et al* 2023, Flores *et al* 2024). Since 1985, carbon accumulation in Amazon secondary forests has offset less than 10% of the emissions from destruction of primary old-growth forests, highlighting that strengthening primary forest protection must be a priority to stabilise the basin carbon balance (Smith *et al* 2020). Furthermore, climate models predict the Amazon dry season will become hotter and drier with increased risk of fires (Marengo *et al* 2018), threatening secondary forest growth rates. Better integration of forest conservation and restoration strategies with societal needs could deliver enhanced social and ecological outcomes (Chazdon 2019). Local Amazon populations require access to livelihoods that do not rely on deforestation, for example, by a shift towards socio-bioeconomies that support sustainable forest use and restoration (Garrett *et al* 2024). Revolutionising agricultural practices to improve food production while enhancing environmental benefits would optimise the use of already-deforested landscapes (Maeda

et al 2023). In conclusion, protecting remaining old-growth forests and increasing the area of secondary forests will enhance biodiversity, improve ecosystem resilience and help ensure the persistence of the Amazon ecosystem for decades and centuries to come.

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