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Advancing forest management modelling for next-generation Earth system models

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Abstract

Managed forests occupy a large area of land, with almost 30% of the world's forests designated primarily for production. Management can alter a forest's carbon storage to a considerable extent, via tree species selection, planting and thinning density, selective logging, and wood harvesting. Forest management can also impact biophysical variables like canopy roughness, evapotranspiration, and surface albedo, which can produce strong effects on local warming or cooling. In addition, forest management is increasingly seen as a key component of many countries' climate mitigation planning and a component of Net Zero targets. However, Earth System Models (ESMs) used to produce climate projections have historically contained limited functionality to represent processes relevant to forest management, meaning that the coupled-system consequences of these interventions remain underexplored. In recent years significant advances have been made to simulate forest management in dynamic global vegetation models (DGVMs) and land surface models (LSMs), the offline land surface components of ESMs. These include adding features to represent wood harvest; options to allow users additional control over forest plantation; plant functional types (PFTs) tuned specifically to represent common tree species used in forestry; and more detailed representation of forest demography (allowing for age- or size-specific growth, harvesting and mortality). In this paper, we summarize these developments and make the case for their usage in operational ESM configurations, so that the impacts of forest management on the climate, and the importance of forest management for climate mitigation, are properly represented in next generation climate projections.

Keywords

forest management, forest management practices, land surface models, Earth system models, dynamic global vegetation models, forestry, climate change

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Introduction

Forests cover 32% of the global land area (4.14 Gha) (FAO 2025a) of which 43% is under some form of management (1.18 Gha in “production” and 0.61 Gha in “multiple use”, FAO 2025a). Globally, approximately 4 billion m^3 of wood is harvested each year, of which about half is used for fuel (FAO 2024). More than 1.6 billion people depend on forests for subsistence, livelihood, employment and income (IUCN 2021). In response to environmental changes, the terrestrial biosphere, primarily through forest biomass and soils, has absorbed around 21% of the carbon dioxide (CO_2) that humans have added to the atmosphere in the past decade (Friedlingstein et al. 2025); Pan et al. (2024) put this estimate at 1.89 ± 0.24 Pg C year^{-1} for 2010-2019 (in established forests, excluding regrowth resulting from deforestation).

Afforestation and reforestation (creating new forests or restoring forests to recently deforested lands) is an important consideration in pathways towards greenhouse gas neutrality because carbon sequestration in forests and via long-lived harvested wood products can form a key component of a balanced portfolio of options to remove CO_2 from the atmosphere and provide sustainable carbon-neutral energy (Smith et al. 2016, Lomax et al. 2025). Currently, afforestation, reforestation, and carbon sequestration in long-lived wood products provide an annual sink of 2.2 billion tons of CO_2 (Pongratz et al. 2024). The potential is much greater if carbon capture and storage (CCS) can be achieved at scale or if a massive global afforestation effort can take place, such as the “Green Wall” initiative in China (Jin et al. 2020). At least 55% of countries plan to use afforestation and reforestation for carbon dioxide removal to meet their National Determined Contributions as part of the Paris agreement, in total implicating ~1 billion ha (~10% of all habitable land) for additional CO_2 uptake (Dooley et al. 2024) from the atmosphere, with forest management practices being used to maximise carbon sequestration and other ecological objectives. Furthermore, afforestation efforts must carefully balance the competing demands of food production and forest expansion (Doelman et al., 2020), and proper planning is required to ensure that habitats and biodiversity are enhanced rather than harmed by forest creation (Bond, 2016).

Globally, deforestation remains a major concern, though its rate has slowed in recent decades. An estimated 489 Mha of forest has been lost worldwide through permanent deforestation since 1990, but the rate of loss has slowed (FAO 2025b). The rate of global deforestation was estimated at 10.9 Mha per year in 2015–2025, down from 13.6 Mha per year in 2000–2015 and 17.6 Mha per year in 1990–2000 (FAO 2025b). This has released around 500 billion tonnes of CO_2 to the atmosphere since 1900 (Friedlingstein et al. 2025), destroyed many unique habitats (Brooks et al. 2002), and reduced the capacity of the Earth system to absorb additional atmospheric CO_2 in the long term. Forest degradation is also devastating ecosystems: in the Amazon, long-term degradation has been surpassing deforestation (Matricardi et al., 2020) and 38% of all remaining forest in the Amazon is degraded (Lapola et al., 2023). Forests are also severely threatened by climate change, through increased risks of wildfires, intense droughts, and widespread pest outbreaks. Rising temperatures and changing rainfall patterns stress trees, reducing their productivity and ability to recover (Gessler et al. 2026). These combined stressors are rapidly shifting habitats faster than trees can adapt (Jia et al. 2019; Anderegg et al. 2022; Grünig et al. 2026). Finally, deforestation is increasingly understood to drive reductions in regional rainfall (Cattelan et al. 2026; Cui et al. 2026; Portmann et al. (2022)).

Increasing demand for timber and biomass, coupled with the impacts of climate change and rising conservation needs, make forest management more complex than ever. Forest management practices will need to adapt and evolve in the coming decades in order to protect forests’ health, protect the carbon stored in forests, provide more fuel and food and timber for a growing global population, and mitigate biodiversity loss.

All these concerns motivate the further development of models of the global environment, in order to assess where and how to improve forests' health and their capacity to counteract climate change (Migliavacca et al., 2025). In particular, process-based models such as LSMs and ESMs are necessary to project plant growth and climate evolution under future conditions for which there are no observed historical precedents. At the same time, such models will need to improve the fidelity with which they simulate managed systems in order to achieve the predictive capabilities of empirically based forest dynamics models that presently dominate operational forest carbon uptake forecasting (Pilli et al. 2018; Lerink et al. 2023; Cattaneo et al. 2025). Process-based land surface models (LSMs), the land components of climate and Earth System Models, and Dynamic Global Vegetation Models (DGVMs), which simulate growth and distribution of vegetation in time and space, were principally developed to represent the future evolution of the terrestrial biosphere. Their simplified assumptions around ecosystem dynamics have meant that representation of forest management has historically been challenging. Thus, the majority of operational LSMs do not yet have a comprehensive or realistic implementation of forest management practices. However, substantial advances have been achieved in this class of models in recent years, including models that represent forest age and size structure (demographic models). This new capability improves these models' usefulness for understanding the full set of linkages between human processes, carbon and water cycling, and climate system evolution. To enable a wider appreciation of the capabilities of this new generation of models, we here provide an overview of the current state of forest management modelling in Dynamic Global Vegetation Models (DGVMs), Land Surface Models (LSMs) and Earth System Models (ESMs), and discuss how forest management practices should be represented in ESMs in order to more realistically represent the interactions between forestry and the climate system.

Climatic effects of forest management

Forests exert a strong influence on the climate system, not only through carbon storage and, more broadly, biogeochemical processes, but also through biophysical forcings and feedbacks which combine to influence surface temperature (Luyssaert et al. 2014): water, surface albedo, surface roughness, latent and sensible heat fluxes (Figure 1). Many of these processes scale with leaf area index (LAI), tree size, or forest biomass density, all of which are affected by changes to forest management regime (Otto et al. 2014). Forest management practices also affect the vulnerability of forests to risks such as fire, drought, pests and diseases, and the resulting impact on forest mortality will itself exert an influence on climate (Yan et al., 2026). This motivates the case for including at least some representation of forest management within ESMs: even if the level of detail useful to a land manager is not possible, valuable insights into the interactions between forest management and the climate system may be produced.

Needleleaf and broadleaf trees differ significantly in surface albedo and rates of evapotranspiration, which affects surface temperatures through changes to sensible and latent heat fluxes (Otto et al. 2014). Naudts et al. (2016) compared European forests in 2010 to a pre-industrial baseline of 1750 (using ORCHIDEE-CAN) and found that changes to European forests contributed 0.12 °C of warming to summer air temperatures due to replacement of broadleaf trees with needleleaf and increased management intensity. Yao et al. (2025) showed that replacing current needleleaf forests in Continental Europe with broadleaf forests could reduce summer daily maximum temperatures by 0.6 °C due to changes to albedo and latent heat flux. The difference in albedo between broadleaf and needleleaf forests, during winter where there is snow on the ground, can be even more significant (Betts 2000; Li et al. 2015).

Selective removal of biomass (including clear-cutting, thinning or regular low-intensity harvesting) from an existing forest stand can alter its canopy structure, causing an immediate reduction in leaf area index (LAI). In turn this can reduce evapotranspiration from the canopy (Miller et al. 2011), though evaporation from the soil may increase. Changes to LAI will also affect albedo, depending on the albedo of the surface below the canopy. This may cause local warming, but the effects are mixed (Otto et al. 2014). Ahlswede and Thomas (2017) found that decreasing the maximum LAI of broadleaf deciduous trees in CESM, over eastern North America, from 4 to 2 caused summer warming in the south and summer cooling in the northeast, in the range of 0.5-1 °C change in surface air temperature; winter effects of decreased LAI were smaller and more variable. Changes to canopy structure can also alter surface roughness, which in turn affects properties like surface wind speeds and evaporation rates. The effects are complex and the direction of change does not show a clear pattern (Shu et al. 2025).

Management of forests also changes their carbon storage and carbon cycle dynamics. Planting density, thinning and wood harvest can all affect the quantity of standing biomass, litter, deadwood and soil carbon. In general, this will result in forests that are lower in carbon (Collalti et al. 2018) and higher in annual carbon turnover (O'Sullivan et al. 2026).

Forest management can also contribute to carbon storage outside the forest, depending on the end use of the harvested biomass. Fuelwood remains an essential source of energy for heating and cooking to 2.3 billion people (FAO 2024). As an energy source, fuelwood can be carbon neutral (or close to it), or, combined with negative emissions technologies such as biochar or geological CO_2 storage, have the potential to produce a net drawdown of CO_2 from the atmosphere (Smith et al., 2016; Smith et al., 2024) – a crucial component of future scenarios in which global warming is halted or reversed (Fuss et al. 2014). Forests can also be harvested for materials (e.g. paper products, furniture, structural timber), in which case, the timeline over which this carbon is returned to the atmosphere ranges from a few months to a few centuries (Zhao et al., 2022). Species selection for plantation forestry is influenced by end use, though end uses for both coniferous and non-coniferous wood products span the range from shorter- to longer-lifetime products (FAO 2025c).

In all these cases, these impacts can be amplified by feedback loops between terrestrial ecosystems and the climate system (Cox et al., 2000; Friedlingstein et al., 2006, 2014; Arora et al., 2020). This emphasises the value of studying these processes through consideration of the Earth system as a whole, as opposed to simulating individual components separately.

Current state of forestry processes in ESMs

ESMs are global in scope and focused on useful representations of the Earth's climate and biogeochemical cycles and their responses to external perturbations (e.g., anthropogenic emissions of greenhouse gases). As such, their representation of forests focuses on large-scale biophysical and biogeochemical effects like energy, water, and carbon exchange with the atmosphere. The CMIP6 generation of ESMs (Arora et al. 2020) features simplified representations of anthropogenic land use-related processes: vegetation is typically represented as averaged biogeophysical and biogeochemical properties for each Plant Functional Type (PFT). Trees are represented not by species but by a small number, fixed globally, of PFTs, grouped by broad eco-physiological characteristics and behaviour such as leaf shape, biome, and deciduous habit, aggregating trees of all ages and sizes into one average pool and preventing the representation of species-specific management practices and geographies (Fisher et al., 2018; Argles et al., 2022). ESMs also typically are not run at fine enough spatial resolution to resolve forest management processes at the stand level and instead need to model large, representative grid boxes for reasons of computational efficiency, availability of driving data at appropriate resolution, and scale compatibility with other model components.

Land management can be simulated in ESMs, giving the user some degree of control over which PFTs grow in a designated area. This is an essential precursor to simulating forest plantations. Agriculture is generally simulated by features which exclude trees and other woody vegetation types from a specific area. Where models use dynamic vegetation (in which the model determines the proportion of PFTs), manipulation of the PFT fractions by the user is not straightforward and must be done indirectly such as by prescribing land use e.g. natural or cropland. Where models do not use dynamic vegetation (with user-prescribed PFT fractions), other problems can arise: PFT coverage can diverge from the natural capacity of the environment to support that vegetation, resulting in unrealistically low productivity or carbon fluxes. Given these restrictions, DGVMs can most easily represent "afforestation" as natural regrowth, i.e. abandonment of agriculture allowing trees to grow, but no active plantation of new trees. For example, the Land Use contribution to the Coupled Model Intercomparison Project Phase 6

(CMIP6) (LUMIP) featured natural regrowth of natural forests only to represent afforestation (Lawrence et al. 2016; Hong et al. 2022).

Given these limitations, and the critical need to understand responses to land cover change to understand the global carbon cycle in the past (Sitch et al. 2024) and future (Harper et al., 2018), the LSM components of ESMs are being continually developed to include more useful representations of anthropogenic land use and land use change (Pongratz et al., 2018; Fisher and Koven, 2020). Many LSM components of ESMs now include some accounting of wood harvesting as part of their tracking of carbon cycle impacts of land use and land cover change (Egerer et al., 2025), and some also now include the ability to add forest plantations (Harper et al., in prep). However, no ESMs contain a dedicated process for new forests to be directly planted, or ongoing anthropogenic management of forest areas. All of the forest management modelling described in the next sections has taken place in standalone (or “offline”) land models, and many of these features are still in development for inclusion into main-version models.

Application of model results to forest management decision making

A further motivation to include forest management practices in LSMs and ESMs is that output from model simulations is frequently consulted by forest managers and planners, since it can quantify useful indicators that can facilitate decision making, help improve forest health and mitigate risks. The work of Linser et al. (2026) identifies 21 key forest indicators through a participatory stakeholder and expert consultation process, categorising them into: forest area; primary production; carbon storage; forest health; climate change adaptability; biodiversity; and regional climate regulation.

Some of these indicators are already well represented in DGVMs and LSMs. LSMs have been extensively used in the past to evaluate the overall biogeochemical processes that are essential to understanding the overall contribution of (natural) forests to the carbon cycle and climate system: leaf area, forest area, forest carbon, carbon storage in various major pools, water cycling and surface energy exchange. LSMs explicitly represent forest area, carbon stored in forest biomass, and carbon stored in soils. Apportionment of carbon into specific pools varies between LSMs; for instance, in the JULES land surface model, deadwood is only included implicitly as recalcitrant plant litter (a soil C pool) (Clark et al. 2011). However, deadwood (often single objects lying on the forest floor) can have considerably different properties and decay dynamics, such as carbon-to-nitrogen ratios or decay rates, compared to incorporated plant litter (Harmon et al. 2020, Neumann et al. 2023). In the CLM-FATES demographic LSM, dead wood is represented as five different size classes of 'fragmenting' material (trunks, large branches, small branches, twigs and leaves) that are available to be burned before they enter the soil (Shuman et al. 2022). LAI is a variable of primary importance in vegetation models, directly affecting the rate of photosynthesis, water cycling and energy exchange, as well as plant allometry (including tree height and carbon density). LAI is a useful indicator of regional forest health, but has its shortcomings; for example, remote sensing products frequently underestimate LAI and carbon fluxes in dense forests, which can cause many other biogeochemical processes to be underestimated if models are calibrated using remote sensing data (Neumann et al. 2016). Although many ecological disturbances are difficult to represent individually, many DGVMs and LSMs now include wildfire processes (Li et al., 2024): these estimate fire direction and spread, and diagnose burned area, CO_2 release and other emissions. Many, but not all, CMIP6-participating ESMs include a fire process model, of which about half can calculate burned area. These models can reproduce observations much more accurately than the previous generation of fire models, though significant potential remains for further improvement (Li et al., 2024). Surface meteorology and hydrology measurements are also relevant to forest management planning; LSMs require near-surface air temperature, precipitation, and atmospheric humidity as inputs, and calculate soil moisture, evapotranspiration, and runoff as output variables.

While forest management depends on understanding of carbon dynamics in managed forests, DGVM and LSM development has historically prioritised natural forests only, resulting in patchy or inconsistent representation of functional diversity and carbon cycling. Wood harvests are included in some DGVMs (for a table, see Sitch et al., 2024), though in many cases this is only used to represent forest clearing. All DGVMs can represent natural regeneration – forests will grow or regrow wherever the climate and soil are suitable. However, plantation of forests is technically difficult to achieve within a dynamic vegetation scheme. Forest plantations are mostly even-age stands where stand age is a key determinant of carbon accumulation. Non-demographic DGVMs, which lack size and age components, will struggle to capture this accumulation especially at the coarse resolutions demanded by LSMs and ESMs (Nabel, et al., 2020; Argles, et al., 2022). However, a new generation of demography-enabled DGVMs has recently been developed that aim to simulate the statistical distribution of tree sizes (Argles et al., 2020), and in some cases ecosystem age-since-disturbance (Fisher et al. 2018; Koven et al. 2020). As well as allowing these models to be evaluated against individual tree (Moore et al., 2018, 2020) and forest regrowth data (Eckes-Shepherd et al., 2025), these models can represent tree size and age dependent variations in growth, mortality and forest management. For example, growing stock, represented as the biomass content in the stems and wood of living trees, is used as an output, although restricting it to a minimum diameter at breast height requires tracking of the distribution of trees across trunk diameter. Changes in tree cover density and multi-layered stand or canopy structural diversity can be modelled in forest demographic models. Stand age and stand density can be captured by demographic models but are absent in standard DGVM configurations.

Some indicators of forest health, though crucial to land managers, remain fundamentally challenging to represent in DGVMs and LSMs. Because of the way that PFT properties are aggregated and averaged in non-demographic DGVMs, models generally lack the granularity to represent the biodiversity of forests or their responses to environmental disturbance. Biotic disturbances are modelled only implicitly as part of tree mortality and biomass turnover (although the LPJ-GUESS DGVM has recently been used to simulate spruce bark beetle infestation (Lagergren et al. 2025)). Abiotic damage is more mixed: DGVMs model the effects of water stress and drought mortality on plants (e.g. Jones et al. 2022; Meyer et al. 2025), and development of fire modelling has progressed significantly in recent years (e.g. Burton et al. 2019), but not the effects of external physical damage such as wind damage (Egerer et al. 2025). However, LPJ-GUESS has some capacity to represent storm damage (Lagergren et al. 2012), and there are ongoing developments in the FATES demography module to represent wind damage (Needham et al. 2022; Shi et al. 2025). Species richness and diversity of forest canopy structure is vital to the maintenance of ecosystem services of forests, as well as their resilience to shocks (Vangi et al. 2024). DGVMs typically use only a few PFTs, rather than individual tree species, and as such have limited capacity to represent species richness within a given forest area.

Information provided by ESMs and LSMs, such as climate projections of temperature and water resources, or environmental risk assessments such as fire indices, are increasingly used by forest managers and other stakeholders to guide land use decision-making (Bateman et al., 2023). These communities could be better served by more realistic representation of forest management practices in the ESMs used to make these projections, and explicit results for all essential indicators.

Representations of forest management in DGVMs and LSMs

Forest Management Practices (FMPs) are methods of planting, harvesting, and tending to trees within a forest stand, aimed at achieving specific outcomes such as maximising timber harvest or protecting forest health (Figure 1). Some involve rotation harvesting with clearcutting. Others include selective removal of specific classes of tree within an existing stand, (i.e. thinning or selective logging) for the purpose of long-term improvement of forest growth, timber yield, or forest health. Other forest management practices might focus on choice of tree species at plantation stage; soil treatments such as application of fertiliser or irrigation; or selective removal of biomass for other purposes such as fire prevention, disease control, or pest management. Other forest management practices focus on mitigating other risks such as flooding or wind damage. Forest management practices may be applied with the aim to prevent forest degradation; though unsustainable levels of forest management (such as overharvesting) may cause or accelerate forest degradation. There are FMPs that remove the entire forest stand, such as clear-cutting, while others retain some trees growing in lower layers of the forest, such as shelterwood, and these vary significantly between different regions (Suvanto et al. 2025). Management decisions about tree species and planting density affect many important ecosystem services, such as carbon sequestration and storage, conditions for natural regeneration or transpiration demand. Thus, FMPs are applied in different intensities (e.g. light and heavy thinning in Testolin et al., 2023; Vangi et al., 2026).

In this section, we will discuss how each of these forest management practices have so far been implemented and studied using DGVMs and LSMs. There are many DGVMs and LSMs currently in active use: 22 DGVMs contribute to the land carbon flux component of the Global Carbon Budget (Friedlingstein et al., 2025), and ten LSMs participated in LUMIP, the Land Use contribution to the Coupled Model Intercomparison Project Phase 6 (CMIP6) (Lawrence et al. 2016; Hong et al. 2022). All of these models include representation of plant physiology and biogeochemistry, many with advanced features such as nitrogen fertilisation, fire dynamics, and wood harvesting following land use change (for a table see Sitch et al. 2024). Here we will not attempt to describe how all these DGVMs and LSMs represent forests and their processes, but highlight a few notable cases in which development of these models has explicitly focused on a relevant aspect of forest management modelling. Five families of models are discussed here: the standalone dynamic global vegetation model, LPJ-GUESS, and four land surface models that are used standalone or as part of an Earth system model: JULES (part of UKESM); JSBACH (part of MPI-ESM and ICON-ESM); ORCHIDEE (part of IPSL); CLM (part of CESM, NorESM and E3SM).

Choice of tree species or plant functional types for forest plantations

Many important factors influence the selection of tree species for a forest plantation: environmental suitability, ecosystem co-benefits, and expected yield or profits from end products. LSMs and DGVMs are global in scope and thus typically configured with ‘plant functional type’-based aggregations of plant diversity. Individual PFTs often have the capacity to be configured with any level of specificity the user desires, but standard global configurations will generally only use a few generic PFTs –

grouped by broad characteristics e.g. broadleaf or needleleaf, deciduous or evergreen, tropical or temperate or boreal, related to the degree to which these characteristics have typically been observable using Earth Observations. This is likely insufficient for detailed representation of species diversity within a single mixed forest stand. However, DGVMs contain the architecture for additional tree PFTs to be developed and adapted. For example, 19 of the most common tree species in Europe are represented in the LPJ-GUESS model, a DGVM with many features dedicated to simulation of forest management (Lindeskog et al., 2021; Hickler et al., 2012). In contrast, JSBACH, the land surface model component of MPI-ESM and an implementation within the ICON-Land framework of ICON-ESM, only uses four tree PFTs globally to represent both natural and plantation forests, but can simulate plantation forestry by user specification of the total forest area (Egerer et al. 2024).

Clear-cutting

Clear-cutting refers to the practice of removing all the trees in a section of forest, typically when a designated age (rotation length) is reached and followed by replanting. JULES-BE (Littleton et al., 2020) introduced options to JULES (which are now available in its main version) that facilitate representation of forest plantations and harvesting of plants for biomass. While developed primarily with perennial bioenergy crops in mind, these options also have some applicability to short-rotation coppicing, agroforestry (Littleton et al., 2021) and forestry. These options allow trees (or any other PFTs) to be planted on a user-specified fraction of managed land class from which all other PFTs are competitively excluded, in the same way that areas allocated to cropland and pasture only allow specific PFTs to compete. Each PFT may be left unharvested or subjected to one of two harvesting styles: periodic or continuous. Periodic harvesting reduces the PFT's height (which then recalculates biomass and LAI) to a user-specified height at regular intervals (also specified by the user), representative of fixed rotations of clear-cutting. The harvested biomass is removed from the ecosystem and converted into a harvest flux.

LPJ-GUESS (Lindeskog et al., 2021) contains many options to represent forest management, including clear-cutting. Stands can be felled at time intervals specified by the user, or clear-cutting can be triggered once stands fall below species-dependent density thresholds.

ORCHIDEE-MICT (Yue et al. 2018) is a branch of ORCHIDEE (the LSM component of the IPSL ESM) that incorporates forest age classes, harvesting and shifting cultivation, building on earlier work representing forest management in ORCHIDEE-CAN (Naudts et al. 2016) and ORCHIDEE-FM (Bellassen et al. 2010). ORCHIDEE-MICT-BIOENERGY (Li et al., 2018) builds on this to incorporate harvest rotations of tree PFTs for bioenergy use (a tropical bioenergy tree PFT based on Eucalyptus, and a temperate PFT based on poplar and willow). These allow a harvest of woody biomass that approximates clear-cutting and replanting, or short-rotation coppicing (discussed below). Forest-related PFTs are divided into six age classes, and harvesting occurs beginning by default with the second youngest age class, then sequentially through the older age classes until the harvest index (proportion of aboveground biomass harvested at each harvest event, specified by the user) is reached. However, the starting age cohort and sequence for harvest can also be defined by the user.

FATES (Fisher et al. 2015; Koven et al. 2020), is a demographic vegetation scheme that operates within the framework of both the Community Land Model (CLM) and the E3SM land model ELM. CLM-FATES is the land surface scheme of the Norwegian Earth System Model v3 (NorESM3). Shu et al. (2025) describe the implementation of wood harvest dynamics in ELM-FATES using clear-cutting, and the full description of LUH3-driven dynamic land use change will be described as part of the CMIP7 documentation of CLM-FATES (Koven et al., in prep). In FATES, vegetation that is converted from primary to secondary land is subject to clear-cut harvesting, and in addition, harvesting for rotation forestry on secondary land also drives the ecosystem dynamics in those systems. CLM-FATES tracks age classes of vegetation, so clear cutting (as well as any other mortality of canopy trees) results in the creation of newly disturbed non-spatially-explicit patches, which are followed through their regrowth trajectory. Multiple ‘cohorts’ of plants with similar size (diameter) and of the same PFT exist on each patch. In some configurations of FATES, PFTs compete for light within a patch, and in others (notably the version that will be used for NorESM3) the area of each PFT is an input to the model and each age patch only contains cohorts of one PFT. Irrespective, the model tracks the legacy of disturbance as a part of the grid cell that is subject to harvest and the time lags associated with regrowth following that harvest. Harvested biomass is sent to product pools which turnover and release carbon to the atmosphere with a pre-determined half-life.

Thinning, partial felling, and selective removal of whole trees

Instead of clear-cutting, forest managers often remove trees selectively based on size – either thinning out smaller individuals or harvesting larger trees once they reach a threshold size. Not all LSM/DGVMs have the capacity to represent this usefully, as to do so, models must include some diversity of either tree size or tree age. Non-demographic models only track average or uniform height, biomass and LAI across all the plants of the same PFT within a grid cell. Other vegetation models can represent individual trees (e.g. Sato et al., 2007), but these are both computationally expensive and stochastic in nature, so require multiple ensembles to constrain vegetation dynamics. Several other approaches (described below) track cohorts or patches of plants defined by their age or size.

For example, the JSBACH4-FF model uses a tile-based scheme to include forest age classes (Nabel et al., 2020), which allows a specified age class to be targeted for harvest, but does not track tree size within each age class.

JULES-BE (Littleton et al., 2020) provides a way to simulate some forest management practices within the JULES LSM, although many aspects limit its utility for representing forest management. The basic functionality only allows for a forest area to be clear-cut, rather than thinned, with rotation length specified at initialisation. This could be worked around; for example, by prescribing a fraction of the grid cell as grass to simulate lower-density forest, or by splitting a stand into several grid cells and staggering clear-cutting events.

In contrast, the JULES-RED forest demography model (Argles et al. 2020) tracks trees of different size within a single-PFT stand, but does not follow different age classes. JULES-RED is a development branch of JULES incorporating forest demographics. JULES-RED partitions PFT number density into “mass classes”, using allometric relationships to estimate changes to physical proportions across mass. The distribution of number density is updated by size-dependent growth and mortality through time. JULES-RED has been used to simulate an even-age Sitka spruce plantation with thinning applied after a given amount of time has elapsed since the stand was planted (Argles et al., 2023).

Perhaps the most detailed, useful and flexible representation of forest management in a modified DGVM comes from the LPJ-GUESS model (Lindeskog et al., 2021). Thinning can be implemented on selected tree age or tree size classes or PFTs as prescribed by the user, through thinning intervals, or via automated processes based on self-thinning rules.

In CLM- and ELM-FATES, tracking of both age-since-disturbance patches and size-based cohorts enables harvest to be selected by rules relating to stand age or tree size. The separate tracking of unmanaged ‘primary’ land and secondary land further allows prescribed harvest rates to be applied to secondary land. In addition, separate rules control the transition from primary or secondary land to and within grazing, pasture and crop land use categories. These rules are currently universal (not able to vary by area or over time) and relatively simple, but could be expanded in detail given appropriate inputs.

Shu et al. (2025) note the large discrepancy introduced into vegetation carbon outcomes when switching from area-based harvest targets to mass-based harvest targets, and complexities introduced via contrasting harvest rules are likely to accentuate the degree to which models diverge in their assessment of human impacts on the biosphere (which will ultimately require finer-scale information on harvest regimes to drive or constrain models).

Continuous cover forest management

Continuous cover management retains canopy coverage at every harvest, and harvests are executed on a regular basis every 5-20 years. The result is a multi-layered, irregular forest, where all ages and tree sizes are present.

In practice, most non-demographic models that apply harvests uniformly across an entire PFT (as opposed to those with the capacity simulate clear-cutting), do not ever create an open canopy, and therefore operate as de-facto continuous cover management. For example, while not intended to represent this process in any realistic mechanical way, JULES-BE includes an option for continuous harvesting (Littleton et al. 2020). This does not interfere with the PFT's growth or height, but removes a fixed fraction (currently 30%) of the PFT's litter flux (wood, leaf and root litter), diverting it to a special harvest flux instead of into the soil carbon. This calculation is performed continuously during the simulation period. This may be more representative of forest management practices such as removal of deadwood or other non-timber biomass such as for wildfire mitigation. The CLM5 model (Lawrence et al. 2019) also removes harvest uniformly from across a PFT, typically retaining very similar LAI.

Yousefpour et al. (2019) explored "growth-based" continuous harvesting, using the JSBACH model. The size of the harvest was set equal to the increase in biomass since the previous harvest, thus holding forest biomass constant and sending the additional carbon to an output harvest pool.

Coppice management

Coppice management involves cutting trees to stumps and encouraging the regrowth of woody side shoots which are then harvested on short rotations of up to 15 years (Pommerening et al., 2024). The JULES-BE code described for clear-cutting can also be interpreted as representing coppicing: the plant is resized from a taller height to a shorter one and the surplus biomass sent to the harvest flux. The model makes no distinction between a tree with a single trunk or one with several stems. To simulate coppicing practices accurately, the user must calibrate PFTs specifically for use in simulating short-rotation coppicing in order to capture allometric relationships and biomass yields appropriately. Littleton et al. (2020) includes an example of JULES-BE being used to represent short-rotation coppicing of poplar. The ORCHIDEE-MICT-BIOENERGY model can also simulate short-rotation coppicing with a temperate tree PFT parametrised to represent poplar and willow (Li et al. 2018). Simplified versions of coppice managements were also implemented in specific model branches of ORCHIDEE-CAN (Luyssaert et al., 2018) and LPJ-GUESS (Gregor et al., 2022).

To simulate coppicing explicitly, the dynamics of resprouting vegetation, and the deviation from, and return to, prescribed allometric relationships should be simulated. In FATES, Needham et al. (2022) introduced the potential for ‘damage’ classes to be tracked in addition to age and size-based categories of tree. Defoliation, fire, wind damage and canopy loss during drought can all reduce the size of the crown for a plant whose ‘diameter’ does not change. Coppice harvesting is a similar category of human-induced damage; in a model with fixed allometric functions (diameter-height-crown area-biomass relationships) capturing these processes is not technically possible. The FATES damage tracking capability adds a modifier to the allometric relationships, as well as algorithms that simulate (and parametric controls on) the rate of return to the allometric targets for after disturbance events. Tracking damage requires a multiplication of computational intensity and so is not set on by default in FATES, but could be implemented for coppice-focused experiments.

Soil treatments (fertiliser and irrigation)

Fertiliser and irrigation may be used in plantation forestry, but the prevalence of these practices varies widely between different types of forests around the world. Many LSMs now include nitrogen cycling, allowing for the possibility of nitrogen fertilisation in terrestrial ecosystems (e.g., Lombardozzi et al. 2025; Wiltshire et al., 2021). Irrigation can also be simulated by simply removing soil moisture stress as a constraint on vegetation growth or adding an amount of water to the soil sufficient to eliminate water stress. LPJ-GUESS (Lindeskog et al., 2021) and JULES both contain this functionality. CLM5 has the capacity to simulate irrigation on crop tiles, and many studies have used this capacity to illustrate its impacts on both crops and the climate system (Thiery et al. 2017; Lombardozzi et al. 2020; Yao et al 2022) but this functionality is not yet extended to be compatible with the FATES demographic framework described above.

Key findings from FMP representation in LSMs

Adding new model processes to represent forest management practices has enabled researchers to explore many more environmental impacts of forest management. Using JULES-BE, Littleton et al. (2021) were able to represent agroforestry and silvopasture with biomass harvest, finding that these practices globally could augment other land management practices to produce significant gains in ecosystem carbon sequestration. With the demographic model JULES-RED, Argles et al. (2023) found that introducing thinning significantly improved model performance against observations at a spruce plantation in England. The large number of forest management developments in LPJ-GUESS has given rise to many useful studies: Gregor et al. (2024) found that increased harvesting of timber can enhance the mitigation potential of Bavarian forests, when wood products are used instead of more carbon-intensive alternatives. Rabin et al. (2022) explored prescribed burning and thinning on fire risk in Eastern Europe and Iberia using LPJ-GUESS, concluding that both practices are equally effective for wildfire prevention. Scheel et al. (2022) identified the increased use of thinning practices as a key driver of increasing tree growth and mortality rates in Europe. Bergkvist et al. (2024) found that implementing a “conservation-oriented” management policy on managed forests in southern Sweden could mitigate increases in storm damage vulnerability over the 21st century.

New work in recent years has facilitated exploring FMPs in DGVMs and LSMs, largely focused on the introduction of forest demography, as described in previous sections. Adding more processes and functions to these models allows for new questions to be asked and new insights to be gained. In many areas, such as the Global Carbon Budget (Sitch et al., 2024; Friedlingstein et al., 2025), process-based LSMs have been a valuable tool to identify and explore processes significant to the terrestrial carbon cycle (e.g., wildfire, land use change, how vegetation changes with the environmental drivers). The diversity of models and their included processes has provided a useful range of uncertainty. This progress in model development provides a strong foundation for introducing these practices in ESMs.

Moving FMP developments into ESMs

As forest management practices are developed for implementation in Earth system models, several challenges become apparent. First and foremost, new developments in ESMs must be supported by comprehensive data, for calibration and validation. Data will also be required to initialise and drive models. The FMPs will need to be consistently and efficiently incorporated into the existing code structures and this process must follow the model software development practices.

Given the wide diversity of management styles (Suvanto et al. 2025), detailed information about forest management practices at the global level will necessarily contain many gaps. Because of this, modelling forest management at the global scale will likely require extreme simplification of management practices, and collating and maintaining large datasets of forest properties and management techniques represents a substantial challenge. The Land Use Harmonization dataset (LUH2; Hurtt et al. 2020) is the modelling community standard dataset on land use, from which ESMs are frequently initialised and driven. In addition to agricultural area and land use transitions, LUH2 contains rates of wood harvest and distinguishes between primary and secondary forests. Another highly relevant global dataset is the FAO's Forest Resources Assessment (FAO 2025a), which is updated every five years with data collated from national inventories. This includes forest area, forest area under management, and rates of timber harvest among many other forest health indicators. Because these data are provided at national level rather than gridded, they cannot be used for input to drive gridded models such as LSMs and ESMs, but may still be useful to validate model results (since model grid cells may be aggregated to national level). But site observations and detailed information about local management practices will help drive model development further: data collection efforts such as the PROFOUND database (Reyer et al., 2020) remain essential to future model development. We can also look to Forest Ecosystem Models (FEMs) for validation and calibration: FEMs are process-based models developed to support forest planning and management (Mäkelä et al., 2000), and thus can operate at a higher level of detail and ecological realism than broader-scale models like LSMs and ESMs can support (Collalti et al. 2016). For large-scale validation, data from remote sensing will also be useful, particularly variables such as LAI, net primary productivity and carbon density, especially since these remote sensing data products have some capacity to distinguish between managed and unmanaged forests (Neumann et al., 2016).

For forest management practices which encompass a spectrum of periodic biomass removal ranging from clearing deadwood to clear-cutting areas in rotation, modifying an LSM to simulate these processes may be relatively straightforward. However, some basic limitations of LSMs may constrain the usefulness of these options. Species-based planting, harvesting and replanting options will be limited by the small number of PFTs and incompatibility of dynamic vegetation with user-specified PFT fractions. Additionally, thinning based on tree size or age cohorts can only be possible in models which include ecosystem demographics to some extent; integration of forest demography is an active frontier in LSM development (Eckes-Shephard et al. 2025).

However, integrating these forest management branches into ESMs is a far longer-term project with more stringent requirements. ESMs must conserve all tracked quantities, including energy, water and carbon; forest plantation often starts from seedlings, with minimum tree sizes of 1-2 metres. The addition of this new biomass must be balanced by a subtraction elsewhere (such as a “seed” pool) in order to conserve carbon. Similarly, biomass harvested from forests may seem to disappear from the system, unless it is tracked such as by assignment to pools with defined decay rates, so that its eventual return to the atmosphere is represented with the required level of realism. (Life-cycle assessments of forestry products can facilitate this development, by providing robust empirically sourced estimates of the fate of harvested carbon.) Where irrigation is enabled, the water used must be subtracted from a water source elsewhere in the system such as rivers or groundwater. Models may also have been calibrated to compensate for missing processes, and thus require re-calibration when these processes are later added.

Integrating the development branches into the main version of ESMs also presents significant software engineering challenges. Where developments increase computational expense, they must demonstrate that this is justified by the gain in scientific utility. New code will need to conform to package coding standards, and go through rigorous testing and review (Gregor et al. 2026), potentially involving additional software developers. The impacts of the new developments on the rest of the system (particularly in the case of positive feedbacks) will need to be thoroughly investigated and understood. Often the target of work in development versions aims to demonstrate that the impact of a new process can be significant in some cases, whereas including that new process in an Earth System Model requires knowledge of its behaviour in all cases. Benchmarking suites have been developed for this purpose, and their use is often a requirement for new code developments (Gregor et al. 2026). Such benchmarking systems, however, do not routinely contain data products that test for the validity of carbon pools and fluxes that relate to forest management. And the adoption of more rigorous efforts to quantify and constrain these processes in models should go hand in hand with efforts to illustrate in which domains their performance is superior to their predecessors.

However, the combined policy requirement of meeting national net zero targets and adaptation to climate change is driving demand for higher-resolution ESM simulations. The land components of ESMs are computationally inexpensive compared to other ESM components, so computational cost does not prevent more complex representation of land processes being included in higher-resolution atmospheric models. Moving a model development from LSMs to ESMs ensures the longevity of the code, allows it to be tested and improved by a much larger group of people, so making it more robust and allows it to be connected to other developments.

Priorities and recommendations

Incorporating progress in forest management modelling into Earth system models will improve the accuracy of climate projections and generate useful information to assist forest management decision-making. From the combination of possibility for model implementation, data availability, and importance for the Earth system, one can create a priority list and find “low-hanging fruits” for implementing forest management practices in ESMs (Pongratz et al. 2018). With this in mind, we propose the following recommendations:

- Model development should prioritise simple representations to start with, focusing on the most essential variables: height, LAI, biomass density, gross and net primary productivity, and biomass yield where applicable.
- Ongoing development and integration of demographic models into LSMs should be continued as it will enable many more options for size-based harvesting.
- More detailed land use and management scenarios must be developed and standardised across model development groups. These scenarios should describe rotation harvesting intensity; size selection and frequency; planting densities and PFTs; rules for transitioning between land use classes; and management practices including thinning, fertilizer and irrigation.

- Collection, collation and standardisation of forest growth and management data is essential for supporting this model development, including those derived from national forest inventories and field observations as well as Earth observation and hybrid data products on forest age, size structure and growth rates. This will facilitate development of better metrics to assess how accurately models capture forest management practices and their impacts.

Model development must always be approached with a clear and pragmatic purpose, considering the model's end use. Extending the scope of DGVMs and LSMs to include land management strategies at regional scale, with appropriate development, and their functions may eventually be integrated into ESMs. ESMs on their own are unlikely ever to be particularly useful for diagnosing the best forest management practices for specific sites, but may be used to greater effect with forest ecosystem models and site-specific knowledge. Including representation of managed forests could improve the simulation of forests in ESMs and thus our understanding of the local and global environmental effects of forest management.

Conclusions

With climate change and its associated impacts accelerating (Lenton et al., 2025), it is more urgent than ever to protect, maintain and enhance forests, the ecosystem services they provide, and the carbon sink capacity they represent. For this, we need to understand the linkages between forests and climate and we need reliable indicators for informed decision-making about forest management. Earth system models are vital to these efforts, but their modelling of forests is incomplete because they lack detailed representation of forest management practices. Addressing this is critical to improving our understanding of the evolution of the Earth's climate and biological systems, and to identifying preferred strategies to protect and enhance forests for climate protection, biodiversity protection, human wellbeing and many other critical goals.

New model developments in the last several years have significantly advanced representation of forest management in DGVMs and LSMs. This new functionality allows for new types of modelling studies which have produced valuable insights into how to manage and protect forests through unprecedented global environmental change and changing pressures on land use in the decades to come.

For DGVMs, LSMs and ESMs to help address the most relevant science and policy questions, further development and representation of thinning, clear-cutting and establishment of forestry plantations is critical. Improvements in the ability of these models to assess the direct impacts of humans on the terrestrial carbon sink, and the complex interplay between indirect and anthropogenic forcing is an important element in understanding how to manage the present and future carbon cycle. With integration into ESMs, forest management process modules will also help us to evaluate and quantify the impacts of forest management on the Earth system and climate.

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Figures

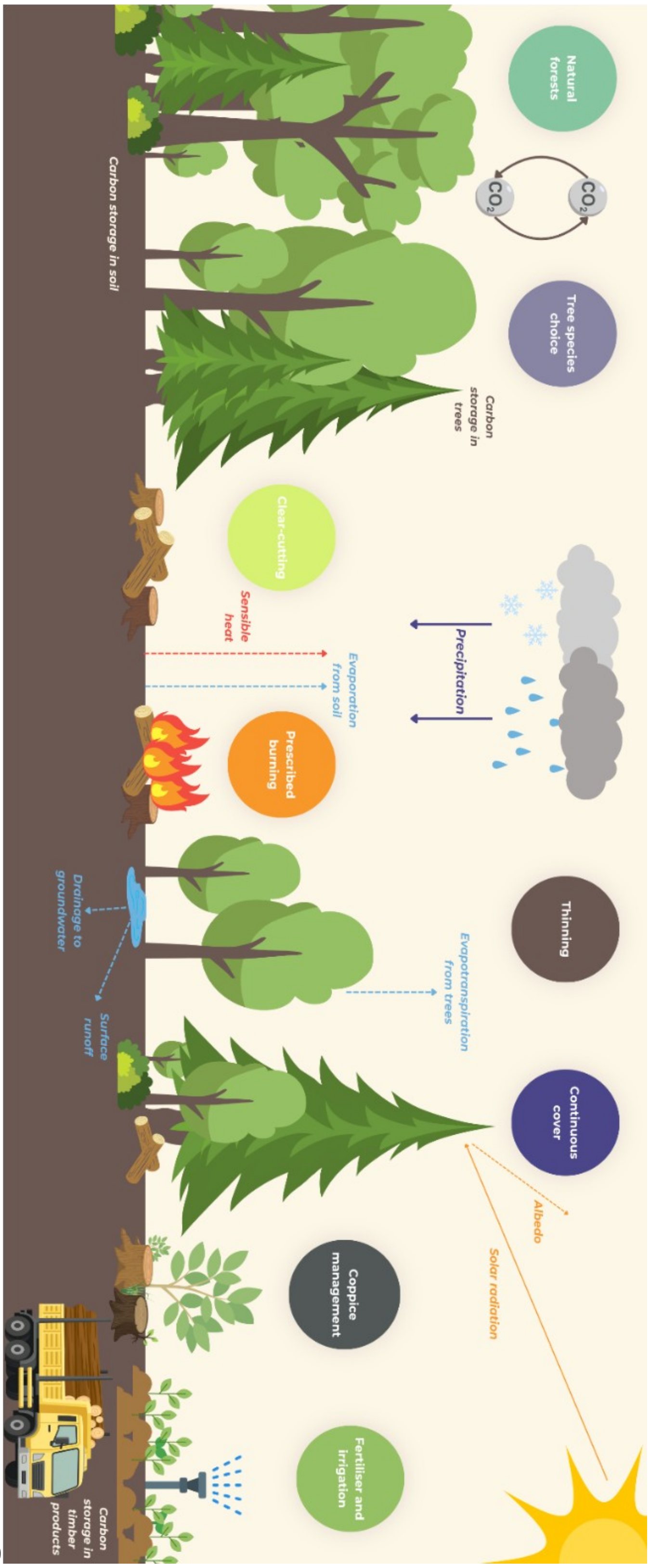
Natural forests
CO_2
CO_2
Tree species choice
Carbon storage in trees
Carbon storage in soil
Clear-cutting
Sensible heat
Evaporation from soil
Precipitation
Prescribed burning
Thinning
Drainage to groundwater
Surface runoff
Evapotranspiration from trees
Continuous cover
Albedo
Solar radiation
Coppice management
Fertiliser and irrigation
Carbon storage in timber products

Figure 1: Linkages between forest management practices and the climate system.

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