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Perspective

Ecological trade-offs of mechanical thinning in temperate forests

David Lindenmayer[a,*], Dominick A. DellaSala[b], Elle Bowd[a], Beverly E. Law[c], Philip J. Burton[d], Chad T. Hanson[e], Philip Zylstra[a,f], William J. Ripple[b,c]

[a] Fenner School of Environment and Society, The Australian National University, Canberra, ACT, 2601, Australia
[b] Conservation Biology Institute, 136 SW Washington Ave, Suite 202, Corvallis, OR, 97333, United States of America
[c] Department of Forest Ecosystems and Society, Oregon State University, Corvallis, OR, 97331, United States of America
[d] Department of Ecosystem Science and Management, University of Northern British Columbia, Prince George, BC, V2N 4Z9, Canada
[e] John Muir Project, a Project of Earth Island Institute, 2150 Allston Way, Suite 460, Berkeley, CA, 94704, USA
[f] School of Molecular and Life Sciences, Curtin University, Kent Street, Bentley, Western Australia, 6102, Australia

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ABSTRACT

Mechanical thinning, the partial removal of stand basal area using tracked or wheeled machines, is a standard silvicultural treatment for whole tree extraction in many temperate forest ecosystems worldwide. It is also increasingly recommended to reduce fire risks in, and increase water yields from, temperate forests. In fire-suppressed forest types, reduced fire risk has been documented in thinned forests under certain conditions. Thinning also may enhance drought resilience in some forest types and assist in habitat restoration for some species. However, we argue there are substantial costs to ecosystems associated with large-scale forest removals from mechanical thinning. Depending on environmental context, scale, frequency, and type of removals, impacts include: (1) loss of ecological integrity in a key successional stage and degradation of habitat suitability for associated taxa; (2) increased susceptibility of thinned stands to fire spread from higher sub-canopy wind speeds and increased fine fuels (slash); (3) soil compaction from heavy machinery; (4) reduced resilience where thinning from above removes naturally competitive dominant trees that may contain adaptive gene complexes; (5) release of carbon stored in forest biomass and soils; and (6) an increase in flammable understorey species, including the spread of invasive plants. Thinning requires an extensive road network that alters hydrology, especially where roads intersect streams and on steep erosive slopes. In addition, the relatively high financial costs of thinning may divert resources from other activities that are more cost-effective and restorative. Forest managers need to carefully consider the multi-facetted costs and environmental trade-offs of thinning operations and not just the benefits in silviculture and restoration projects.

1. Introduction

Mechanical thinning is the process of removing a portion of the trees in a forest stand to limit between-stem competition and boost rates of diameter increase in remaining trees (Fagg, 2006; Helms, 1998). This practice historically has been implemented for silvicultural purposes. However, in recent years, the application of density-dependent management practices, including mechanical "thinning," has increased in response to altered fire regimes and climatic changes such as drought (Bennett et al., 2024; Burton, 2025; Chagnon et al., 2025; Zylstra et al., 2016). Large-scale thinning operations have also been recommended to accelerate the development of habitat for open-canopy and understory dependent species (e.g. (Manlick et al., 2025), and to increase water yields from watersheds (e.g. in the regrowth forests in southwestern Australia) (Clarke, 2016; Hawthorne et al., 2013).

While the benefits of mechanical thinning for fire management and drought resilience have been extensively discussed (Chagnon et al., 2025; Davis et al., 2024; Kalies and Yocom Kent, 2016), the negative environmental and financial impacts of, and carbon emissions associated with thinning are often not fully appreciated. This may mean that trade-offs among the ecological, climate change, and economic effects of thinning are not quantified or appropriately considered in policy and management debates. Given this, we discuss impacts associated with large-scale mechanical thinning in temperate forests and the degree to which they depend on intensity, scale, and frequency of removals as well as environmental context (Fig. 1). We have canvassed topics where

* Corresponding author.
E-mail address: david.lindenmayer@anu.edu.au (D. Lindenmayer).

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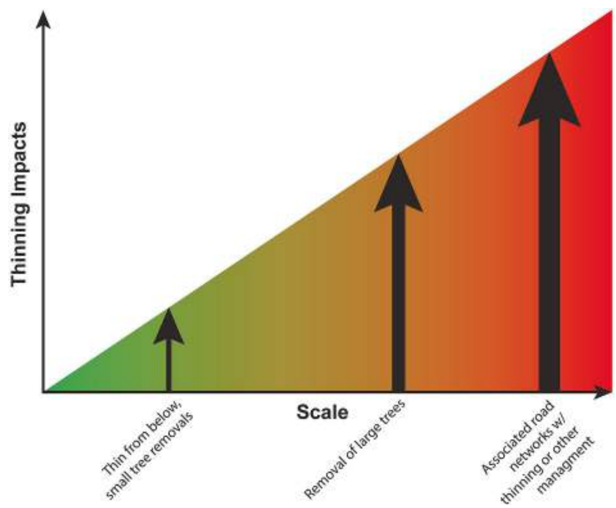

Fig. 1. Predicted increasing impacts of mechanical thinning as a function of increasing intensity and spatial scale of thinning operations. Greater impacts would be expected toward the top right corner (red area) of the diagram with greater thinning intensity over a large area. The schematic has not included frequency effects in which impacts would likely be magnified where the interval between thinning operations is short. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

large-scale mechanical thinning has unintended or underappreciated ecological consequences and where trade-offs merit remedial measures by forest managers. In particular, we examine trade-offs among thinning and: (1) natural self-thinning, successional stages, and habitat for particular elements of biodiversity; (2) wildfire management; (3) carbon emissions and the importance of natural (neither thinned nor logged) forests in climate mitigation and adaptation strategies; (4) reduced genetic variability and resilience resulting from the removal of trees that may possess important adaptative traits; (5) increased soil compaction and the spread of invasive species; and (6) reduced water yields. We also discuss the financial costs of large-scale mechanical thinning operations. Our broad aim is to highlight trade-offs in objectives where thinning is proposed as a large-scale management action, such that impacts are scalable and more readily quantifiable. On this basis, we conclude with commentary on the need for forest managers to more carefully appraise the environmental impacts of widespread thinning. We also underscore the importance of maintaining intact forests as a critical part of climate mitigation and adaptation strategies, as well as enhanced biodiversity conservation.

1.1. *Intensity, scale, frequency and type of removals matter in assessing thinning costs*

While historically framed as a stand-level tree density reduction, contemporary thinning practices are highly variable depending on desired outcome, ranging from uniform row/strip patterns to variable-density thinning with gaps of various sizes. The scale of thinning operations can be highly variable, ranging from the removal of single trees (understory vs. overstory) to entire stands of various ages and across landscapes (Fig. 1). Thinning impacts are therefore dependent on the scale, frequency, type, and environmental context of tree removal operations, all of which vary widely, and contribute to the overall thinning intensity.

Two common types of thinning are thinning from 'above' and 'below'. 'Thinning from below' typically describes the removal of non-dominant trees and can have relatively less ecological impacts, particularly if measures are taken to reduce soil impacts and co-lateral damages to surrounding trees. An exception to this is when the thinned trees originally contributed to the maintenance of a less-windy, moister microclimate that suppressed fire spread (Lindenmayer and Zylstra, 2024; Zylstra et al., 2016). In contrast, 'thinning from above' removes the most dominant trees and is most consequential especially when targeting the removal of critically important large and old trees (Lindenmayer and Laurance, 2017). The ecological effects of thinning scale up and are compounded when applied over large areas that require the use of extensive road networks that have additional impacts. Thus, while there are benefits associated with thinning, there can also be significant costs, especially when thinning is a frequent anthropogenic disturbance superimposed on the background of pre-existing disturbance histories (Fig. 2). We further discuss costs and benefits of thinning (Fig. 2) throughout the remainder of this article.

1.2. *Mechanical thinning vs natural self-thinning*

Mechanical thinning operations are often targeted at densely stocked stands of regrowth forest, typically within a few decades of initial stand-replacing disturbances such as wildfire, epizootic outbreaks, and clearcut logging (Buckley and Cornish, 1991; Fagg, 2006; Kalies and Yocom Kent, 2016; Volkova and Weston, 2019). Such stand conditions generally develop via a pulse of regeneration following prior disturbance/s (Westoby, 1984), some of which are a product of 'active management' (e.g. post-logging seeding or planting). Thus, active management to reduce stem density through mechanical thinning is a fit-for-purpose forestry practice, that usually aims to accelerate the development of a target number of stems per unit area faster than would occur because of natural self-thinning (Burton, 2025). In the Pacific Northwest of the USA, thinning trials are underway to investigate whether the approach can accelerate late-seral conditions in prior clearcuts within late-successional reserves (Dodson et al., 2012). Mechanical thinning has also been used to open tree crowns for understorey development, especially forbs and shrubs for ungulates considered "game" species and other early successional species that do best in more open stand conditions (Betts et al., 2010; Manlick et al., 2025).

1.3. *Natural self-thinning*

Irrespective of the underlying reasons for mechanical thinning intervention, land managers may fail to recognise that densely stocked regrowth is a successional stage in many forest types that will naturally self-thin, leading to a decline in stem density over time (Bowd and Lindenmayer, 2026; Westoby, 1984). Stem density declines because of inter-tree competition for space, light, and other resources (Harper, 1977; Westoby, 1984). The natural process of self-thinning and succession proceeds as resources fluctuate and competition increases until a maximum density of a given tree size is achieved ("self-thinning line" or "maximum size-density limit," Brunet-Navarro et al., 2016; Harper, 1977), that triggers tree mortality (e.g. "self-thinning", Westoby, 1984). Some forests may retain just ~10–15% of early successional stem densities in late successional stages (Freund et al., 2014). For example, just 12–17% of Douglas-fir (*Pseudotsuga menziesii*)/Western Hemlock (*Tsuga heterophylla*) regeneration cohorts may survive to late succession in western Washington and north-western Oregon, USA (Freund et al., 2014). Data from Mountain Ash (*Eucalyptus regnans*) forests in south-eastern Australia subject to previous stand-replacing wildfires show that homogenous sized and densely spaced stems in early successional stages (<10 years old) undergo significant natural thinning, up to ~60% by the time stands reach mature stages (70–80 years old), and then by a further 50% until eventually reaching an old-growth state, leaving stems of a range of sizes (Bowd and Lindenmayer, 2026). In the absence of additional stand-replacing disturbance, early successional forests have the potential to develop into structurally complex late-successional stands that have high values for biodiversity and carbon storage (Keith et al., 2009; Law et al., 2022).

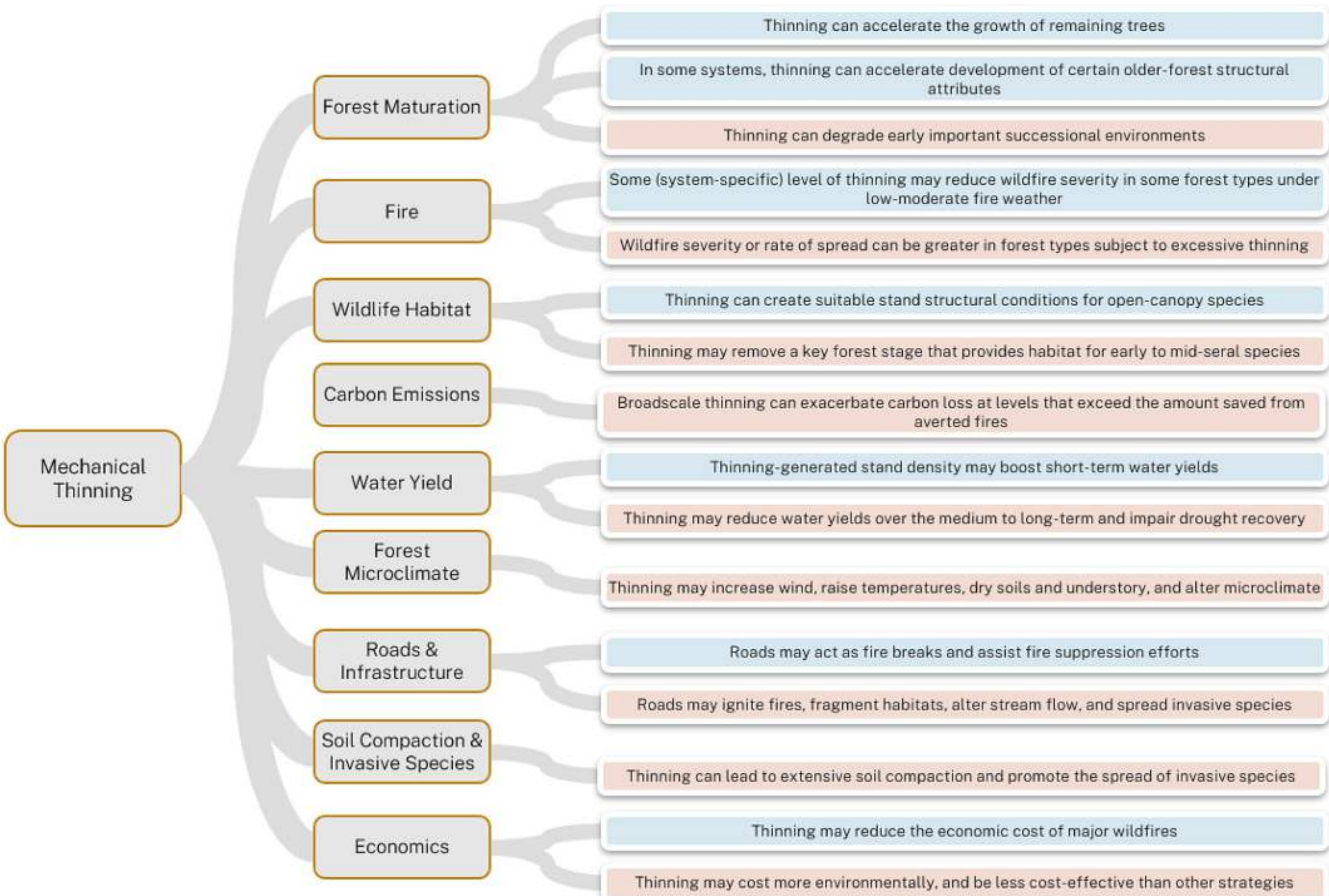

Fig. 2. Summary of the benefits (blue boxes) and environmental impacts (red boxes) that need to be considered as part of key trade-offs in the large-scale application of mechanical thinning. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

1.4. Successional stages

Natural stand-replacing disturbances often trigger a pulse of vegetation regrowth as part of what is termed "complex early seral forests" (Swanson et al., 2011). This successional stage supports high levels of biodiversity (Swanson et al., 2011), including assemblages of species not found in late successional forests, such as in the Klamath-Siskiyou ecoregion, southwest Oregon/northern California (Betts et al., 2010). In the temperate woodlands of inland south-eastern Australia, the bird assemblages associated with densely stocked young regrowth and replanted woodland are markedly different from those found in old-growth woodland (Lindenmayer et al., 2012). Such densely stocked stands (Lindenmayer et al., 2016) provide habitat for an array of species of conservation concern, consistent with the landscape texture hypothesis (Fischer et al., 2008). Similarly, understorey trees in the tall, wet forests of south-eastern Australia (but which can be sometimes removed as part of thinning operations in these environments), provide foraging habitat for arboreal marsupials and birds (Lindenmayer et al., 2009), and act as a substrate to facilitate animal movement (Smith, 1984).

The habitat values of early successional natural regrowth forest means that decisions about whether to thin them need to be carefully considered. Whilst in some cases, thinning may increase vertical heterogeneity, in others it can simplify stand structural complexity through excessive removals of overstory and/or understorey trees (e.g. see Pretzsch and Hilmers, 2025). These impacts need to be weighed against the broader understanding of biodiversity responses to vertical heterogeneity, the associated availability of niches (MacArthur and MacArthur, 1961), and levels of species richness (e.g. Culbert et al., 2013; Sukma et al., 2019).

Thinning of overstory trees in later-successional forests can also pose significant risks to associated species. For instance, in mixed-conifer forests of the Sierra Nevada Mountains, California, thinning has had negative impacts on nesting/roosting habitat of the California Spotted Owl (*Strix occidentalis occidentalis*) (Stephens et al., 2014) and denning habitat of the Pacific Fisher (*Pekania pennanti*) (Garner, 2013). Stephens et al. (2014) documented a 43% decline in California Spotted Owl populations within six years following mechanical thinning. Bond et al. (2022) found that thinning and other logging activities contributed to nest site abandonment for the Northern Spotted Owl (*Strix occidentalis caurina*) in forests also affected by severe fire and Barred Owl (*Strix varia*) encroachment in the Pacific Northwest of the USA. Heavy thinning of stands of Scots Pine (*Pinus sylvestris*) in the United Kingdom also resulted in thinned stands being avoided by species such as the endangered Red Squirrel (*Sciurus vulgaris*) (Gurnell et al., 2002; Shuttleworth et al., 2012).

1.5. Wildfire risks

1.5.1. Thinning alone and/or prescribed fire

Mechanical thinning is increasingly applied with the intention to reduce wildfire extent, intensity, and severity, along with allowing firefighters safer access to forests during fires (Davis et al., 2024; Kalies and Yocom Kent, 2016). There are also examples where thinning has been promoted as a forest restoration tool such as in the frequent-fire Ponderosa Pine (*Pinus ponderosa*) forests of south-western USA (Covington et al., 1997; Friederici, 2003). Recent meta-analyses have found that thinning combined with prescribed burning, or prescribed burning alone, may reduce fire severity, tree mortality, and levels of scorch under certain conditions, and in particular forest types such as some of those in the western USA (Kalies and Yocom Kent, 2016). However, in the absence of prescribed burning, thinning of conifer and mixed conifer-broadleaf forests in parts of North America did not reduce wildfire severity (Davis et al., 2024), unless conducted at very low intensities (Chagnon et al., 2025). Although there is consensus among forest managers on the importance of removing or reducing surface fuels generated by thinning, there are mixed findings as to how much thinning is needed to meaningfully alter wildfire susceptibility and intensity (Banerjee, 2020; Moreau et al., 2022), and whether prescribed fire alone is enough to reduce fire intensity (Kalies and Yocom Kent, 2016). For example, the meta-analysis by Davis et al. (2024) found no significant difference in the effect of thinning plus prescribed fire versus prescribed fire alone on fire severity. Moreover, given that the maturation and growth of overstorey trees is the primary driver of understorey suppression and mortality in some forest types (Vickers et al., 2021), thinning alone can indirectly increase the density of understorey vegetation (White et al., 2025), contributing to the development of more combustible fuels (Zylstra et al., 2022). This effect is evident in eucalypt forests, where the probability of the highest severity fire is greatest in forests thinned within the past 40 years (Taylor et al., 2021).

1.5.2. Mature forests and fire severity

While it may appear intuitive that mature forests with higher densities of trees (including the smaller trees often referred to as "ladder fuels") will experience higher wildfire severity, in certain forest types the opposite has been noted (Lesmeister et al., 2021; Lesmeister et al., 2019; Lydersen et al., 2014). Ostensibly, this is due to differences in forest structure and microclimates (Liu et al., 2019; Zhang et al., 2018). Elevated temperatures and reduced levels of soil moisture render some thinned stands more flammable (Millikin et al., 2024). For instance, in the Pacific Northwest (Frey et al., 2016; Lesmeister et al., 2021), Klamath-Siskiyou Ecoregion (Odion et al., 2004), and Sierra Nevada Ecoregion USA (Stevens, 2020), fire severity generally declines as forests mature, due to changes in forest structure, microclimate, thicker tree bark, higher wood moisture content, and a more humid environment (Frey et al., 2016; Stevens, 2020).

In an analysis of several hundred wildfires spanning three decades in the Pacific Northwest, USA, Lesmeister et al. (2021) found that more open forests with lower tree densities had hotter, drier, and windier microclimates than older forests. They also found that those conditions decreased dramatically over relatively short distances into the interior of unthinned older forests with multi-layer canopies and high tree density (Lesmeister et al., 2021). Fire behavior modelling by Banerjee (2020) suggests that altered microclimatic conditions created by thinning can increase wildfire spread and intensity, but that thresholds exhibit complex interactions with fuel loads, canopy fuel moisture, and wind speed. In an analysis of 42 recent wildfires in California, Hakkenberg et al. (2024) found dense, older forests with higher canopy cover, higher biomass, and lower densities of "ladder fuels" (defined as seedlings and saplings beneath the forest canopy ≤ 10 m tall) had lower wildfire severity, but also found lower wildfire severity at the highest densities of ladder fuels in dense, mature forests (with relatively higher severity at intermediate densities of ladder fuels).

1.5.3. Self-thinning and wildfire severity

The capacity for forest growth and succession to limit fire spread and intensity has been formalised into 'ecological control theory' (Zylstra et al., 2022, 2023). Biological processes such as plant growth, self-thinning, and self-pruning, result in the concentration of biomass away from fuel (low, connected vegetation likely to burn) and into overstorey shelter, or taller plants separated from lower strata that create a slower sub-canopy wind field, rather than burning. This can lead to the development of less-flammable, mesic vegetation and cooler, more moist microclimatic conditions over time (Zylstra et al., 2023). For instance, competition for light that occurs in dense regrowth stands drives faster vertical growth at the expense of increases in stem diameter, so that forests that are allowed to self-thin may grow taller and self-prune, and hence are less likely to experience crown fire (Falster and Westoby, 2003; Zylstra et al., 2023). Mesic understorey rainforest elements also develop in some forests such as those dominated by Mountain Ash in south-eastern Australia (Lindenmayer et al., 2000) – a process of mesophication which has been observed in a range of forest types globally such as oak-pine ecosystems in eastern USA (e.g. Nowacki and Abrams, 2008). The likelihood of crown fire is reduced as self-pruning proceeds naturally, canopy-base heights increase, and the overstory-understory gap widens over a few decades in *Pinus radiata* plantations (Ruiz-González and Álvarez-González, 2011).

1.5.4. Thinning and fire regimes

One of the overarching aims of thinning to reduce wildfire risk may be problematic in forest types where infrequent, high-severity fire and periodic mixed-severity fires are the expected fire regime – and to which many species are well adapted. That is, modifying fire regimes in ways that drive them outside the bounds of natural variability could have substantial negative impacts on a wide range of species and undermine ecosystem integrity (Lindenmayer et al., 2025b). Some examples include areas of tall, wet forest and dry forest in south-eastern Australia, and in mesic and upper elevation forests of North America where mixed severity fire and high-severity fire is expected (Agee, 1993; Lindenmayer et al., 2025b). In some cases, the response of species to a single high-severity fire is far more muted than the negative effects associated with repeated disturbances (e.g. logging, thinning) prior to that conflagration (Driscoll et al., 2024).

In summary, conditions generated by mechanical thinning will alter forest fuel dynamics through related changes in microclimate (e.g. Liu et al., 2019), species composition and structure (Burton et al., 2019), and how these factors interact. There will be specific contexts and locations where thinning will be associated with reduced fire spread, fire intensity, or fire severity (e.g., under low fire-weather), especially when it is combined with prescribed burning, but effectiveness also depends on extreme fire weather (Chagnon et al., 2025; Davis et al., 2024; Kalies and Yocom Kent, 2016). In other cases, thinning can have limited effects on fire behavior, such as in eastern Tasmania, and the Murray Valley National Park, Australia (Bowman et al., 2025; White et al., 2025), or conversely add to fire risk, like that which occurred in central Victoria during the 2009 wildfires (Taylor et al., 2020) and north-eastern Victoria in the 2019–2020 wildfires (Taylor et al., 2021). Indeed, forest management manuals from places such as south-eastern Australia have long recognised the added fire risks that accompany thinned stands (e.g. Buckley and Cornish, 1991; Fagg, 2006). Overall, the effectiveness of thinning in reducing wildfire risk is highly variable across forest types and fire regimes, with potentially different effects on fire intensity, fire severity, and the likelihood of ignition, spread, and crowning. In many forest types, natural succession can confer equal or greater fire resistance than mechanical thinning. Thus, management decisions should be based on ecosystem-specific evidence in conjunction with the trade-offs, rather than generalised assumptions. Finally, extreme fire weather, which is increasing due to climate change, is a major driver of fire spread and intensity that can override fuel treatments (Lydersen et al., 2017; Prichard et al., 2021), including those associated with thinning (Bowman et al., 2025).

1.6. Carbon emissions

Forests are crucial for climate mitigation as they store vast amounts of carbon in vegetation and soils, thereby regulating atmospheric greenhouse gas concentrations. The protection of natural forests is therefore considered to be: "*the highest priority for reducing global greenhouse gas emissions*", as recommended by the Intergovernmental Panel on Climate Change (Portner et al., 2022). To reach these goals, forest management strategies include regional and subregional analysis to identify forests that have high priority for protection of forest carbon, biodiversity, and drinking water (Law et al., 2022). This demands a strategic approach that acknowledges the carbon costs of forest management practices prior to implementation (Pretzsch and Hilmers, 2025).

The carbon emissions resulting from thinning and related activities are often greater than any potential carbon savings from reduced fire emissions (Law et al., 2013). A key finding from a meta-analysis in western North America was that harvest-related emissions were approximately five times greater than fire-generated emissions, in a region with historically high logging levels and wildfire activity (Hudiburg et al., 2019). Broad-scale thinning exacerbates carbon loss, as the amount of carbon removed typically exceeds the amount saved from averted fires (Campbell et al., 2012; Schoennagel et al., 2017).

Following moderate to high-intensity thinning, most analyses indicate a multi-decadal biomass carbon deficit relative to unthinned stands (Pretzsch and Hilmers, 2025; Ruiz-Peinado et al., 2017; Sterman et al., 2018), with the growth of residual trees not immediately compensating for the carbon removed (Hudiburg et al., 2013), and compensation taking decades to occur (Mitchell et al., 2009; Zhou et al., 2013). Thinning for fire severity reduction, which can remove 30–50% of live tree biomass or more, can lead to a rapid release of a large portion of this stored carbon to the atmosphere. For instance, a study in a drought-prone Ponderosa Pine ecosystem showed that removing 40% of live biomass could result in about 60% of the carbon in the biomass being released over the subsequent 30 years (Stenzel et al., 2021). Hence, extensive thinning can conflict with the objective of reducing atmospheric carbon emissions, particularly when considering the decadal-scale carbon debt that is incurred (Law et al., 2022).

In some ecosystems, large, old trees can be relatively more resilient to drought and fire and as such, accumulate the most carbon over decades to centuries (Hudiburg et al., 2009; Hurteau et al., 2019). Focused interventions to protect key carbon pools, such as the maintenance of larger, fire-resistant trees in dry ecosystems will typically be more closely aligned with climate goals than broad-scale thinning.

1.6.1. *Biomass burning of residual thinning by-products for energy production*

In many regions (e.g., south-eastern and western USA, British Columbia, Canada, and south-eastern Australia), the trees thinned from forests are used, or are proposed for use, in biomass burning for energy production (e.g. see Bowman et al., 2025). This has also been recommended (e.g. Clarke, 2016) to offset the financial costs of mechanical thinning (see below) (Bowman et al., 2025). However, any such benefits will be outweighed by the large amounts of greenhouse gas emissions generated by the production of wood pellets and shipping (e.g. from the USA and Canada to the EU) (Booth, 2022; Schulze et al., 2012; Sterman et al., 2018). In addition, there are long lag times between emissions generation and carbon dioxide removals from forest regrowth (Mackey et al., 2025). In fact, biomass burning is more emissive per unit of energy produced than burning coal (Booth, 2018) and may contribute to forest degradation (*sensu* DellaSala et al., 2025), primarily as an outcome of stand simplification and associated habitat modification for forest biodiversity (Mackey et al., 2025).

2. Adaptive capacity and resilience

Forests have numerous adaptations that confer adaptive capacity after disturbance events. That is, the ability of an ecosystem when perturbed to return to the pre-disturbed state or to persist in a modified form better suited to prevailing conditions (Burton, 2025). These adaptations include propagule-related responses such as "serotiny," or well-stocked soil seed banks, that are triggered to germinate by abiotic changes (e.g. fire-triggered germination). Processes like symbiotic relationships (e.g., mycorrhizae networks), epicormic branching, stump and basal resprouting, and gap-phase dynamics following tree death also confer stand resilience to disturbance (Perry et al., 2008). The capacity for forest stands to regenerate following severe (stand-replacing) disturbance is also dependent on the cumulative disturbance burden operating on a particular place and/or species over time (Lindenmayer et al., 2025b).

In some cases, mechanical thinning may increase resistance to droughts, pests, windstorms, and wildfire (reviewed by Chagnon et al., 2025). However, mechanical thinning conducted in an attempt to increase forest resilience by reducing or minimizing tree mortality from drought, native insects, or wildfires, can substantially increase overall tree mortality (i.e., tree mortality from thinning and wildfire combined) relative to natural disturbances alone (Baker and Hanson, 2022; Hanson, 2022). This is because many trees are killed or removed by mechanical thinning operations (Fig. 3). Thus, in the context of forest resilience and adaptive capacity, large-scale mechanical thinning operates as an overall agent of tree mortality, rather than a management tool that prevents or reduces overall tree mortality. In conifer forests of the western U.S., mechanical thinning projects that kill and remove most of the trees and basal area of a given stand have become common on public lands, often producing sparsely treed areas inconsistent with what many people associate with the term "thinning" (Fig. 3).

In contrast with the impacts of mechanical thinning, natural self-thinning (*sensu* Westoby, 1984) may contribute to adaptive capacity (and hence overall forest resilience) at the stand level by typically resulting in the most competitively successful overstorey trees prevailing, and others either dying or persisting in a suppressed form (Bowd and Lindenmayer, 2026; Florence, 1996; Perry et al., 2008). While thinning regimes vary among forest types and management objectives, where thinning from above is employed, dominant (and competitively superior) trees are typically removed, leaving suppressed trees. This approach may mean the most competitive, resilient, and genetically fit individuals are removed from the system, rather than being allowed to reach maturation, which could impair genetic diversity and adaptation processes. This may have long-term consequences for overall stand resilience to disturbances such as insect outbreaks (Baker and Williams, 2015), particularly beetle (Coleoptera) infestations where the survivors may hold important genetic adaptations (Six et al., 2018).

2.1. *Soil compaction and invasive species*

Thinning operations typically employ heavy machinery that can compact soils (Cambi et al., 2015), damage sensitive reproductive organs on plants such as those of tree-ferns (Bowd et al., 2024), and remove other understorey and ground cover components of forests. The extent of soil compaction problems resulting from forestry operations can vary in response to soil types, nutrient levels, soil texture, erodibility and other factors (Cambi et al., 2015). For instance, in south-eastern Australia, up to 30% of wood production areas suffer from soil compaction (Rab, 1998). Thinning-related soil compaction effects may persist for prolonged periods, as shown in a LiDAR analysis of forests in south-eastern Australia that contains evidence of mechanical thinning operations several decades earlier (see Fig. 3).

Mechanical thinning may promote the invasion of exotic plant species. Increased light availability, mineral soil exposure, and altered microclimate conditions following canopy opening can provide a competitive advantage for invasive plants species over native flora (Liu et al., 2019). Roads constructed and maintained for thinning operations also act as dispersal corridors and points of establishment for many exotic and invasive plants (Wace, 1977). Once established, invasive plants can proliferate, outcompete native vegetation, and alter fire regimes by changing understorey fuels (Fusco et al., 2019). These cascading effects can simplify forest structure, reduce biodiversity, and potentially undermine the ecological resilience that thinning is often intended to enhance.

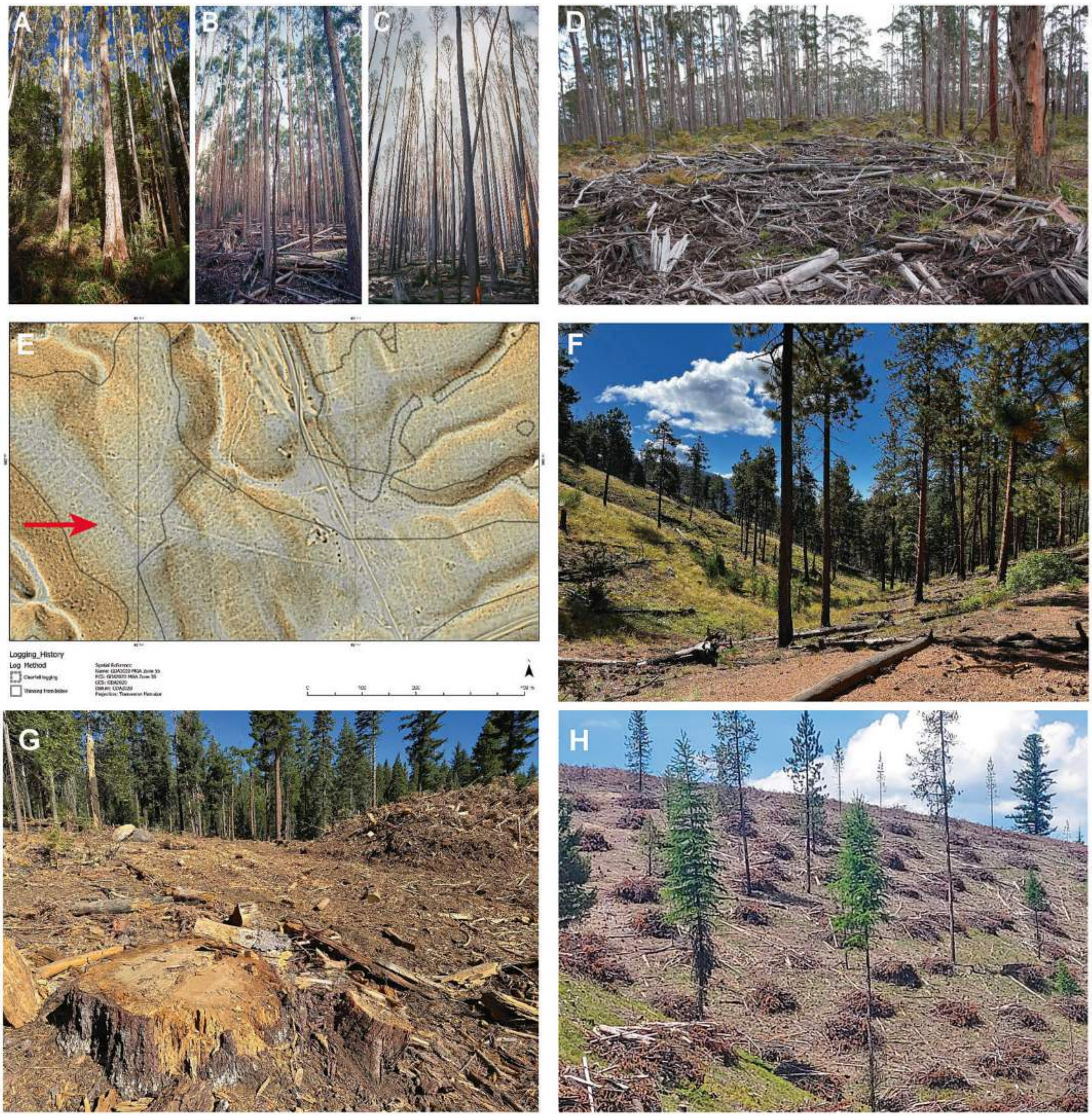

Fig. 3. Montage of images highlighting the environmental impacts of mechanical thinning on forests. A-C. Tall, wet regrowth Alpine Ash (*Eucalyptus delegatensis*) forest in south-eastern Australia that was intact (A), thinned (B), and then burned at high severity (C) (Taylor et al., 2020). (D) Thinned tall, wet forest in south-eastern Australia showing extensive slash piles (Chris Taylor). (E) LiDAR analysis of tall wet forest in south-eastern Australia showing "tramline imprints" (some of which are highlighted by a red arrow) below the canopy resulting from thinning 10–25 years previously (LiDAR image taken in 2016 and extracted by Chris Taylor). (F) Thinned Ponderosa Pine stands in the Santa Fe National Forest, USA showing the conversation of the ecosystem from a mixed-pine forest to a savanna-like environment where open stands on ridge-tops are prone to windthrow (Dominick A. DellaSala). Typical current mechanical "thinning" on public lands in the Stanislaus National Forest in the Sierra Nevada mountains of California (G) (photo by Chad Hanson), and the Wallowa-Whitman National Forest in Washington (H) (photo by George Wuerthner). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2.2. Water relations

Mechanical thinning can sometimes reduce tree stress and mortality due to drought, but there can be complex differences in responses among forest types and stand ages (Elkin et al., 2015; Sohn et al., 2016). A meta-analysis by (Sohn et al., 2016) showed that tree growth reduction during and after drought was mitigated in thinned stands, most likely because of increased levels of soil moisture resulting from thinning operations. However, thinning-enhanced drought resistance tends to be associated with impaired drought recovery (Schwarz et al., 2020). For instance, evidence from some sites suggests that short-term drought avoidance and increased water yields can deplete limited soil water reserves, leading to more severe long-term drought impacts (D'Amato et al., 2013).

Thinning may also influence water yields from forested catchments, defined as the water discharged out of a watershed from surface and subsurface flows through the connected stream network. Water yields are a serious concern where climate change is increasing the intensity and/or frequency of droughts, particularly in areas where soils have limited water holding capacity (Chagnon et al., 2025; Sohn et al., 2016). Thinning-related increases in water yields are likely to be short-lived (<12 years) following vegetation recovery (Vertessy et al., 2001). Gaps in the overstorey associated with tree removal also may modify the local microclimate. For example, understorey vegetation in modified stands (including new regrowth vegetation) can be exposed to increased windspeeds, increased solar radiation (André-Alphonse et al., 2023), and higher air temperatures, as well as greater transpiration rates (Aussenac, 2000), greater soil temperatures (Zhang et al., 2018), and higher levels of soil evaporation (Rosenberg et al., 1983). These changes have the potential to counteract the water conservation effects of reduced canopy transpiration in thinned stands. Therefore, thinning may not result in a net gain in water yield in the medium to long term, especially under drought conditions (Hawthorne et al., 2013).

2.3. Financial considerations

The financial costs of thinning operations are variable and include ecological costs alongside revenues from timber, wood fibre, or biomass that can be sold from such treatments (Table S1). Thinning and related treatments are thought to lower costs in fire suppression activities and limit post-fire sediment flows into water supplies following intense wildfires. However, the economic case for thinning also needs to be weighed against financial outlays, like the construction and maintenance of road networks required to transport machinery and logs, together with the running costs of that machinery. There are also significant ecological impacts associated with extensive road networks needed to support thinning operations that themselves require significant funds to maintain. Costs include soil compaction (Rab, 1998), habitat fragmentation (Laurance and Arrea, 2017), spread of invasive plants (Wace, 1977), unwanted ignitions (Balch et al., 2017), and wildlife mortality (Ibisch et al., 2016).

In western USA, thinning costs for wood production were estimated to average (in 2022) $2075 USD per hectare (Chang et al., 2023). The costs of thinning to reduce fuel levels for wildfires in California were estimated to be $1270 USD per hectare (Wear et al., 2025) (see Table S1). Yet only ~1% of treated forests are subject to wildfire each year in western North America, and hence most Federal Government fuel treatments do not encounter wildfire within their 10–20 year period of treatment effectiveness (Barnett et al., 2016; Schoennagel et al., 2017). This suggests that thinning was not broadly effective and resulted in unnecessary costs. Taken together, the ecological and economic evidence indicates that mechanical thinning often functions as an expensive substitute for natural processes that would regardless occur over time, but with lower collateral impacts.

3. Conclusions

We recognise that mechanical thinning is a way to achieve multiple management goals in production forestry. It has also been applied to manage wildfire risks, insect outbreaks, and drought stress on trees (e.g. Burton, 2025; Chagnon et al., 2025; Davis et al., 2024; Moreau et al., 2022). These applications do not negate the need to evaluate important ecological and economic trade-offs among objectives, many of which have not been fully considered in policy and management debates. Indeed, the impacts of mechanical thinning are influenced by the spatial scale, intensity and frequency of removals (Fig. 1). On this basis, considerations of trade-offs will be important ecologically, climatically, and financially, under proposed intensive, widespread, and repeated implementation of mechanical thinning in forest, wildfire, and climate policies. This is because there will be circumstances where thinning operations actually increase fire risks (Taylor et al., 2021), degrade ecosystem integrity (DellaSala et al., 2025), select against the most adaptive trees in stands (thereby potentially undermining resilience) (Six et al., 2018), release more carbon than a natural disturbance at scale (Hudiburg et al., 2019), and require extensive road systems that contribute to a range of cumulative ecosystem impacts (Ibisch et al., 2016), including increased weed invasion and fire ignitions (Balch et al., 2017; Collins et al., 2015).

We argue that the economic costs and stated benefits of thinning also need to weigh the required investments and damages from extensive road networks and machinery. Those costs can be substantial, especially in situations where repeat treatments are needed, or further interventions are necessary to curtail ecological impacts associated with roads (e.g., weed management, sediment runoff to streams, culvert maintenance, road failure). Given that self-thinning is a natural process (Westoby, 1984), a key question associated with mechanical thinning is: *Is it ecologically beneficial and cost-effective to artificially accelerate the process of stand structure change, when it is going to occur anyway?* For example, in some cases, the artificial reduction in stand density might be only 10–30 years faster than it may have occurred naturally, and without the associated potential ecological, climatic, and financial costs. Hence, investment in, and exploration of, other ecosystem-specific and evidence-based forest management options is warranted and may be more economically viable and less ecologically risky than mechanical thinning. These may include restoration efforts for areas of regeneration failure, weed management, or ecological and/or Indigenous burning practices in specific contexts and ecosystems.

In some cases, the effectiveness of thinning operations (and conversely the potential for perverse outcomes) will be poorly known, and thus it is precautionary to minimise costs and damage to ecosystems. On that basis, we argue that at least five key actions are needed.

First, it is essential to establish rigorous long-term environmental and economic monitoring to quantify the ecological impacts and financial costs of thinning programs before they are implemented, not just their benefits. Where mechanical thinning is proposed in the context of fire management, environmental assessments need to consider its appropriateness relative to the given forest type/s and fire regimes where it is intended for use. For example, thinning that attempts to reduce fire severity may be unsuited to ecosystems where the natural fire regime is infrequent, high severity wildfire, such as coastal temperate rainforests in north-western North America, mixed-intensity fire systems such as the inland forests of western North America, and the tall wet forests of south-eastern Australia.

Second, there will be a need to apply specific prescriptions that mitigate ecological costs of large-scale mechanical thinning operations by, for instance, retaining large overstory trees, minimizing overstory removals to avoid increasing heat loads in the canopy and surface along with soil dessication, and limiting collateral damage to remaining trees, soil compaction, and closed-canopy wildlife species.

Third, it is critical to ensure the maintenance of carbon stores for climate mitigation purposes, especially regarding large amounts of stored carbon in larger, older trees and soils (Stephenson et al., 2014).

Fourth, there is a need for land managers to acknowledge that prescribed fire alone, including Indigenous burning practices, often can be applied on the landscape without thinning (North et al., 2015), and that there is a long history of fire-alone management without thinning, even in very dense and long-unburned forests (Knapp and Keeley, 2006; Knapp et al., 2005).

Finally, we argue that it is essential to ensure there are large protected areas where thinning operations are prohibited, such as high conservation value forests (Lindenmayer et al., 2025a), including older forests, roadless areas, habitat for imperilled species that rely on closed canopy forests, and complex early seral forests that will naturally self-thin over time. The maintenance of intact (unthinned) forests is critical in key climate mitigation and adaptation as natural climate solutions (Law et al., 2022), for biodiversity conservation (DellaSala et al., 2022; Law et al., 2023; Watson et al., 2018), and for reducing overall forest degradation (DellaSala et al., 2025).

We conclude that mechanical thinning has negative ecological impacts in temperate forest ecosystems depending on intensity, scale, and frequency, the type and quantities of trees removed, and other impacts (Fig. 1). Therefore, proposals for its widespread application should be treated with caution to avoid ongoing forest degradation (DellaSala et al., 2025). Active management for "management" sake can have substantial costs and requires context-specific mitigation. This is especially pertinent in forests that have already experienced a substantial natural and/or anthropogenic disturbance burden, are threatened by altered fire regimes, and are subject to novel climatic conditions (Lindenmayer et al., 2025b).

Given there are ecological and financial costs associated with thinning and roads, it should be prohibited in high-conservation value forests because such forests: (1) act as "controls" in active management experiments; (2) provide habitat and/or climate and wildfire refugia for old forest and complex early seral forest species, especially imperilled ones; (3) can be managed as intact, connected blocks of unaltered forest that provide connectivity for climate-forced wildlife migrations and wildlife movements; and (4) can be managed in a manner consistent with climate mitigation (e.g., carbon stored mainly in large trees and soils) and water conservation goals involving reserves and protected area networks (Law et al., 2022) (especially roadless areas). Outside protected areas, thinning can impact larger trees, forest carbon storage and carbon emissions, soils, and water, and result in the accumulation of post-thinning debris. In those situations, assessing the costs of thinning and ways to mitigate those costs, is critical to comprehensive forest management. Assessments are also necessary to determine the extent of roads needed to access sites and other areas where road closure and road removal are needed for restoration purposes. Proper cost accounting would determine when thinning reaches a cost threshold and where it is infeasible or inadvisable ecologically and economically. Recognizing self-thinning as a natural and cost-free process that enhances both carbon storage and biodiversity can help redirect management investments toward restoration of degraded forests and protection of intact forests, while ensuring significant areas act as refugia where active management impacts are absent. We encourage land managers, decision makers, and conservation groups to incorporate comprehensive analyses of the effects of thinning operations before widespread adoption of practices that are otherwise inappropriate or ineffective in certain conditions.

CRediT authorship contribution statement

David Lindenmayer: Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Investigation, Formal analysis, Conceptualization. **Dominick A. DellaSala:** Writing – review & editing, Writing – original draft, Validation, Supervision, Investigation, Formal analysis, Conceptualization. **Elle Bowd:** Writing – review & editing, Validation, Investigation, Formal analysis. **Beverly E. Law:** Writing – review & editing, Validation, Investigation, Formal analysis. **Philip J. Burton:** Writing – review & editing, Validation, Investigation, Formal analysis. **Chad T. Hanson:** Writing – review & editing, Validation, Investigation, Formal analysis, Conceptualization. **Philip Zylstra:** Conceptualization, Writing – original draft, Writing – review & editing. **William J. Ripple:** Writing – review & editing, Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.biocon.2026.111748.

Data availability

Data will be made available on request.

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