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Perspective

Effects of lag time in forest restoration and management

Klaus J. Puettmann[a,*], Jürgen Bauhus[b]

[a] Department of Forest Ecosystem and Society, Oregon State University, Corvallis, OR, 97331, USA
[b] University of Freiburg, Tennenbacherstr. 4, 79085, Freiburg, Germany

A R T I C L E I N F O

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A B S T R A C T

The increased speed of global change and associated high severity disturbances, in conjunction with the increasing suite of societal expectations on forests, suggest that the timeliness of interventions to encourage the adaptive capacity of ecosystems and to reduce negative impacts in regards to provision of ecosystem services is increasingly relevant. To address this issue, we expand the concept of lag time as used in ecological discussions into a forest management context. In this context, lag times have earlier starting and later ending points and can be separated into different components. These components include the delay till detection, decision making, and implementation, followed by ecological lag time and the time till ecosystem services are provided at acceptable levels. The first three components are influenced by the availability of information, the lack of which can extend lag times. Also, the lengths of components are not simply additive but they interact. For example, treatment preparation due to a quicker detection can lead to shorter decision and implementation lag times. We highlight the benefits of addressing the various components of lag time in forestry operations. Especially when considering adaptive capacity in times of global change, our analysis suggests that all aspects of the forestry sector are challenged to consider how to optimize lag times. Last, we propose that such issues need to be considered with any management action and are especially relevant in discussions whether the best strategy after disturbances or in the light of global change is to adopt a passive approach and let natural ecosystem processes play out on their own or whether active management is better suited to ensure a more rapid and fitting ecosystem response to facilitate the continued provision of ecosystem services.

1. Introduction

Lag time is generally defined as the “interval of time between two related phenomena (such as a cause and its effect)” (https://www.merriam-webster.com/dictionary/time%20lag, accessed 06/11/2023). In an ecological setting, the term focuses on the time between the occurrence of an environmental or biological trigger, often a disturbance event, and the associated response, e.g., “time to rebalancing of a system following a perturbation” (Watts et al., 2020) (Fig. 1, upper bracket). The concept of ecological lag time originated in evolutionary genetics and was directly linked to questions of maladaptation (Levins, 1968). Maladaptation of individuals, species, populations, communities, and ecosystems to changing environmental conditions is becoming more and more of a concern in times of global change (Farkas et al., 2015; Brady et al., 2019, Fig. 1 in Box 1). This is especially relevant in forest and forestry settings, as trees have a very long life cycle and many management decisions have a long time horizon. Consequently, understanding what influences lag time and opportunities to shorten or lengthen lag times through forest management activities becomes increasingly relevant (Rastetter et al., 2021). Lag times express themselves differently at different organizational levels, e.g., for individuals, populations, communities, and ecosystems and they can be due to multiple or a single “bottleneck” process, such as delays in recruitment (Walters, 1986). For a single organism, lag times can often be reduced to settings where a response can be traced directly to a specific event or environmental condition, e.g., leaf shedding as a result of critically low soil moisture availability during drought. In contrast, lag times in ecosystem processes are typically driven by additional factors, especially interactions of various components over time. These interactions may dampen or amplify the response and thus influence lag times. For example, during drought conditions forest structure and composition may change quite differently in response to interactions among tree species, shrubs, and herbaceous vegetation and their resulting effects of trees responding to insect attacks (Rastetter et al., 2021). In such cases, it may not always be possible to attribute an ecosystem response to a single or specific trigger.

Initially, the lag time concept received the most attention in the

* Corresponding author.
E-mail address: klaus.puettmann@oregonstate.edu (K.J. Puettmann).

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ecological community in the context of evolution (Levins, 1968). Already in the 1960s, Levins highlighted that lag time has to be viewed within ecosystem dynamics, as by the time organisms have changed their phenotype in response to environmental triggers, the environment may have changed more in the meantime. This issue has garnered more attention as global change mechanisms lead to an acceleration of environmental changes (Watts et al., 2020) and thus has implications for management efforts to increase the adaptive capacity of ecosystems. Later the concept of lag times received more attention when investigating population and ecosystem dynamics, especially because of concerns that lag times lead to overshoots or oscillations when developing predictive models (Botkin, 1990) and determining harvest levels (Walters, 1986). To account for this, e.g., Leary (1985) suggested to add a delay constant for modeling the effect of herbivore-plant interactions on stand growth.

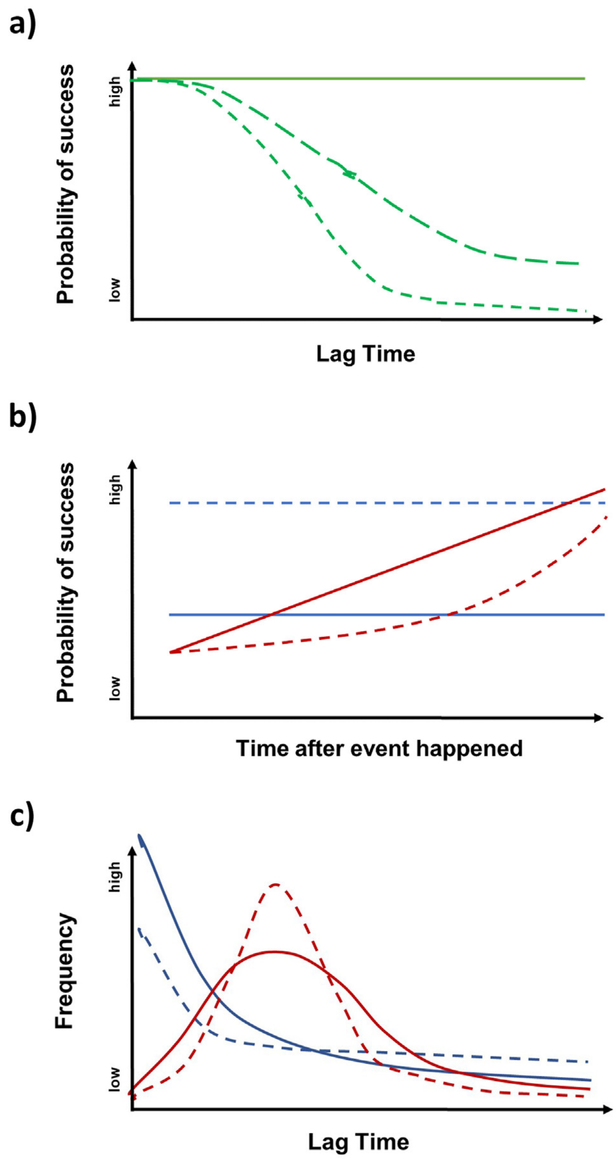
A second argument for paying more attention to lag times is their direct relevance to biodiversity and species conservation. In this context, lag time has received most attention in the discussions about extinction debt (e.g., Duncan, 2021) and the International Union for Conservation of Nature (IUCN) Red list reflects this concern. A longer lag time suggests that our current prediction of populations and species in decline may be an underestimate. This may be the case when the reproductive success declines rapidly in a long-lived species (Jackson and Sax, 2010) and many ecosystem functions are not impacted yet. For example, ecosystem processes associated with mature trees may proceed as before, but the higher sensitivity of germinants and seedlings to environmental changes may prevent tree regeneration that is eventually necessary for continued provision of desired ecosystem services (Martínez-Vilalta and Lloret, 2016). At the same time, a longer time lag may also lead to underestimation of population and species recoveries after damaging practices are halted or conservation treatments have been implemented (Watts et al., 2020). This effect is of sufficient size and concern that the IUCN now accounts for delays in recoveries in the Green Status of Species list. Similarly, studies indicated that the time between the arrival of an exotic species and the recognition of its ecological, social, and economic impact is influenced by numerous factors and can vary from years to centuries (Crooks, 2005).

A third argument to pay attention to lag times is the increased demand of humankind for ecosystem services, both in qualitative and quantitative terms. For example, expectations now include supporting biodiversity (Kok et al., 2018) and a green economy (Sivadas, 2022), as well as counteracting climate change by increased carbon storage in ecosystems (Nunes et al., 2020). These high expectations often can be most efficiently satisfied by forests with a narrow, selected set of conditions, which can deviate from conditions found in natural, unmanaged forests (Bauhus et al., 2010; Parrotta et al., 2016). In the context of novel and high demands for ecosystem services, ecosystem processes and conditions that were considered acceptable or even desirable in the past, may now be viewed as problematic, thus influencing the role of lag times. Examples include the roles of fires and floods, which are natural disturbance agents that are often beneficial in terms of supporting ecosystem dynamics in many natural settings (White and Jentsch, 2001). In the same place, but other settings, these disturbances may now be considered unacceptable and great efforts are made to prevent their impacts, for example in wildland urban interfaces when human and animal lives and structures are threatened (Miranda et al., 2020). In addition, biological conditions have changed over time especially due to past human activities to the extent that the natural processes are not able to provide the desired ecosystem services anymore. For example, global trade or travel has led to introductions of exotic species and a lag time in addressing this issue has led to changes that can greatly influence forest development (red lines, Fig. 2 in Box 1). For example, after the introduction of *Rubus armeniacus* (Himalayan blackberry) into the USA in 1885, it has become a very common and competitive species, among other places in the Pacific Northwest of the USA and western Canada by the 1940s (Bennett, 2007). This exotic species is now widespread in the region and in many areas has formed dense thickets that exclude not only the native forest understory vegetation (Fierke and Kauffman, 2006), but also prevent the regeneration of shade intolerant tree species such as *Pseudotsuga menziesii* (Douglas fir), *Pinus ponderosa* (ponderosa pine) and *Quercus garryana* (Oregon white oak) (Williams et al., 2006; Bennett, 2007). The initial lack of major coordinated efforts to slow down or control its spread in the 19th and early 20th century can be viewed as a long lag time in terms of management responses. Once established these thickets can only be removed through very severe treatments, such as grubbing, repeated mowing, and/or multiple herbicide applications (Soll and Lipinski, 2004; Bennett, 2007). Thus, as a consequence of the extended lag times as described above (see also Box 1), we now need such severe treatments to ensure regeneration of selected plant species for the continued provision of desired ecosystem services. Thus, addressing the issue of lag time is especially urgent in settings and after disturbances when delays in management responses can lead to reductions in ecosystem services. These cases are of special concern because of the increases in the speed of global changes (Osman et al., 2021). Box 1 provides a more conceptual understanding of how the length of lag time influences the probability of success as a function of the speed of environmental change.

The lag time concept is more easily understood, if we assume somewhat simplified ecosystem dynamics, mainly a fairly constant state or trend. This makes it easier to define disturbances or other events that push the ecosystem to deviate from the desired state or trend. In reality, the various aspects of ecosystems are constantly fluctuating following

Box 1
Conceptual description of the relationships between speed of change, lag time, and ecosystem responses.

As we expect increases in the speed of global change (Osman et al., 2021), a more detailed look shows the various implication of such increases, and the consequences if we do not accelerate or modify our management response. Box 1 Fig. 1a shows that an increased speed of global and local changes will result in a lower probability of an outcome where ecosystems successfully adapt to these changes. Successful is defined here as an outcome where the ecosystem maintains ecosystem functions (the end of *ecological lag time*) and/or maintains the provision of desired ecosystem services (the end of *ecosystem service lag time*). To highlight how these patterns come about, Box 1 Fig. 1b shows different hazard functions, including functions where the probability of a successful outcome is constant (blue lines) or increases (red lines) over time at different levels (blue lines) and patterns (red lines). The hazard functions directly influence the distribution, including mean and variation of probability density functions (PDFs) of the length of time (lag time) until such success is achieved (Box 1 Fig. 1c). Understanding these patterns and relationships is especially helpful when discussing management efforts, especially in the context of species or population recoveries (Watts et al., 2020; Duncan, 2021). For simplicity, the figures assume a simple linear time flow and ignore other dimensions of time, such as synchrony and cycles (Ossola et al., 2021). It also is limited to one organizational level and ignores that the influence of lag time is not the same for the same or different processes at different organizational levels, e.g., on recovery of individuals versus populations and species. However, despite that simplicity, the range of probability and time until critical levels are reached highlights that understanding of lag times, the factors that influence them and how they can be managed (either shortened or lengthened) can provide important guidance for the future management of ecosystems (Essl et al., 2015).



Box 1 Figure 1. (a) Probability of treatment success as a function of the amount of lag time (time till treatment), for conditions where environmental and adaptations are in sync, i.e., change at the same speed (solid line) and when environmental conditions change faster than the ability of ecosystem to respond (long and short dashed lines reflect e.g., slow and fast increases in global temperature, respectively). (b) The probability of an outcome such as successful adaptation that provides ecosystem services as a function of the time after an event happened (i.e., after the *Impact*). The blue lines represent conditions with constant probability over time at either lower (solid line) or (higher dashed line) levels. The red lines show conditions where the probability increases over time, either linearly (solid line) or in a convex manner (dashed line). Similar concept as hazard function in survival analysis, modified from Duncan (2021). (c) Probability density function of time till adaptation measures are successful and ecosystems provide desired ecosystem services (assuming a Weibull distribution), based on different hazard functions. The line colors and patterns match Box 1 Fig. 1b. Different patterns of increasing hazard functions result in similar shapes, e.g., convex, linear, and concave increases result in unimodal distributions, with distributions being more peaked and shifted to the left for convex, then linear, and concave patterns (Duncan, 2021). Note, that PDFs are not defined below zero. Thus, conditions were actions are taken in anticipation of events, e.g., based on model simulation, that lead to success prior to the actual event (can be viewed as negative lag time) cannot be displayed.

different, and in some cases discordant trends due to the influence of a variety of natural and human factors (Walters, 1986; Botkin, 1990). In systems in which indicators and variables vary extensively, the points in times that qualify as starting and ending points of lag times may be difficult to define. This makes the application of the lag time concepts more challenging. However, even in those conditions, the major principles still apply, for example the impacts of shortening or extending lag times, making a more detailed understanding of the lag time useful.

The arguments above illustrate also that lag time per se is not a positive or negative factor influencing ecosystem development. Consequently, it may be beneficial or even necessary to distinguish the lag time concept as used in the ecological literature from lag times in managed forests. As a case in point, all three arguments play into the recent and ongoing highly controversial discussions whether, for the sustainable provision of desired ecosystem services, it is better to rely solely on natural processes to prepare ecosystems for global change, even after disturbances, or influence these processes through targeted management efforts (e.g. Jandl et al., 2019; Kuuluvainen et al., 2021). In the restoration community, the same issue is discussed in terms of active versus passive restoration after disturbances or when ecosystems have been degraded through management activities (Chazdon et al., 2021). Against the background of an ever-increasing speed of changes at local to global scales (Watts et al., 2020; Osman et al., 2021), we aim to contribute to this discussion by providing conceptual insights how the lag time concept can be expanded from the ecological interpretation to a management context. Based on these insights, we provide suggestions how the concept can help to develop a more systematic approach how to manage lag times to improve forest management outcomes in highly dynamic and uncertain times.

2. Extending the lag time concept to a management context

In contrast to a purely ecological perspective, management and restoration activities are also driven by human objectives and values (Benayas et al., 2009). In the context of lag time, this is directly reflected in the criteria used to define *impacts*, and *ecosystem responses*. The starting point of an *ecological lag time* is an *impact*, some trigger that critically affects ecosystem functioning. The *ecological lag time* ends with an *ecosystem response*, a reaction that has led to the rebalancing of ecosystem functions and processes (Watts et al., 2020; see Fig. 1, upper bracket). Typical reasons for ecological lag times include delays in recruitment or when selected processes, such as changes in growth rate, are eventually being reflected in mortality or fecundity levels (Walters, 1986).

2.1. When do lag times start and end in a management context?

In managed forests, when exactly an undesirable trend or change (disturbance) is considered an *event*, i.e., when a critical trigger has been reached, is, in contrast to *ecological lag time*, not defined by its *impact* on ecosystem processes, but when an *event* is considered to have an *impact* in terms of consequences to the provision of ecosystem services (Jenkins and Schaap, 2018). Such considerations can result in earlier or later starting times. Also, events and impacts with a high risk to endanger or lower the provision of ecosystem services receive most of the attention and thus are more likely to result in an earlier start of lag time. Similarly, the end of an ecological lag time, when ecosystems may have *responded* to a trigger and "rebalanced" (sensu Watts et al., 2020), may not be sufficient to identify the end of lag time in management contexts. Instead, the end is defined in terms of *ecosystem service provision*.

In a management context (Fig. 1, lower bracket; Eq. (1)), it is more useful to think of the start of *effective lag time* to coincide with the time an *event* happens, where an event is defined as an incident that is later determined to result in an *impact*. For example, the ecological definition starts the clock at a time when an exotic, invasive species, for example the *Agrilus planipennis* (emerald ash borer) started killing trees after it established in a new location (i.e., *impact*). In contrast, in a management

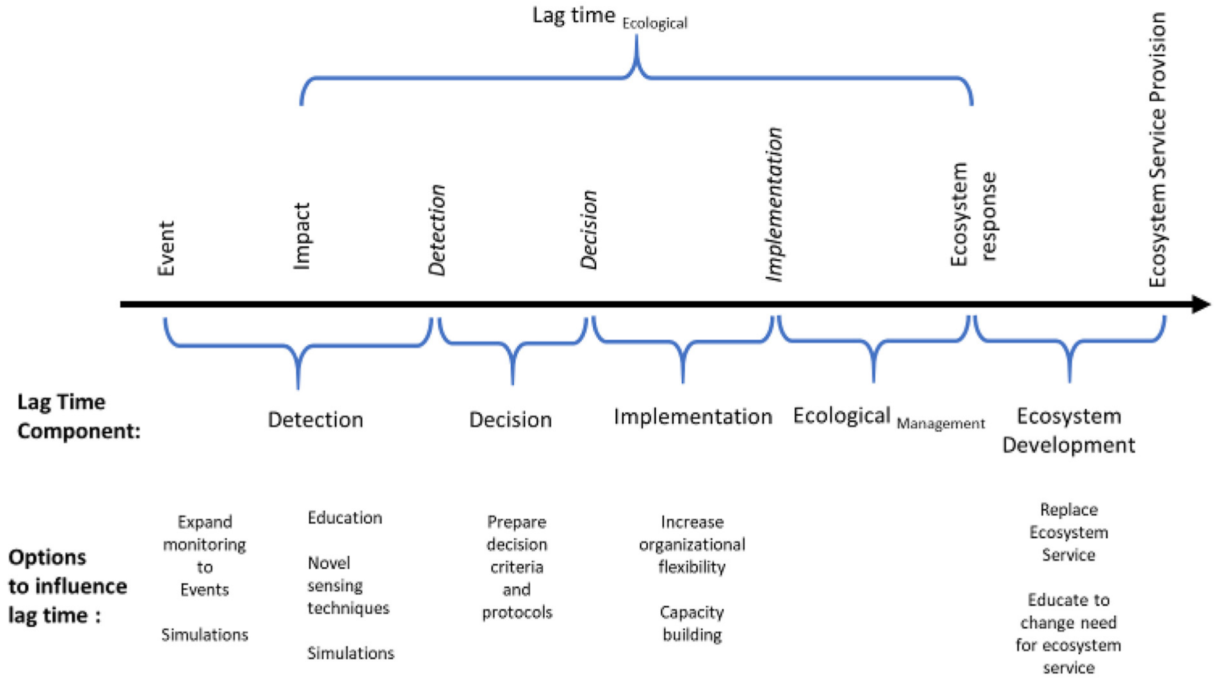


Fig. 1. Additional time steps that are relevant in a management context: An *Event* that by itself has no impact, e.g., seeds or spores of new species attach to a pallet that is then later transported to a new continent. *Detection* is when an impact is formally recognized by managers as sufficiently harmful that it requires intervention. *Decision* is the time when managers agree on a plan whether and how to respond to the impact. *Implementation* is the time when the management plans are implemented, i.e., seedlings are planted or vegetation is removed. In addition, if managers are successful, the *Ecological* lag is defined using the implementation of the management treatment as starting point (trigger) and the ecosystem response as an end point (same endpoint as the generic ecological lag time). After the ecosystem has responded, it may still take time for the *ecosystem* to *develop* to the point where it *provides* the desired *ecosystem services* (the overall end point of lag time in managed settings. Examples of options to influence lag times are listed in their respective lag periods and are discussed in more detail in the text.

context, the *effective lag time* starts at the time when the event initiated, i.e. when the emerald ash borer started its migration, and thus when the later *impact* could be anticipated and long before it actually had a direct *impact* on certain forest ecosystems that were still far away from the initial occurrence of the species. For example, natural resource managers in Oregon knew since 2002 (*Event*), when *A. planipennis* was confirmed in Michigan that this species will eventually kill ash trees in Oregon, which it eventually did starting in 2022 (*Impact*). The Oregon Department of Forestry and Department of Agriculture did not wait for the *ecological impact* but used the earlier *event* to develop and prepare a "Readiness and response plan for Oregon" (https://www.oregoninvasivespeciescouncil.org/eab). One could think of many similar examples of biotic disturbances, especially those caused by introduced pests and diseases, that spread gradually. In selected cases, when more gradual changes lead to conditions that endanger or lower the provision of ecosystem services, scientists have the ability to anticipate future *events* and *impacts*, for example through the use of simulation models, for both biotic and abiotic factors causing stress and disturbances. For example, global circulation models project the effects of climate change on temperatures or precipitation patterns. Based on these simulations, all over the world scientists and foresters are already discussing how best to react to the projections that selected tree species will likely be lost from specific sites or ecosystems. As a consequence, in many places forest managers are already establishing alternative tree species or provenances that are better adapted to future climatic conditions (Butterfield et al., 2017; Palik et al., 2022), rather than waiting for the actual *impact*, such as wide-spread mortality of the species during an extreme drought.

The basic approach (focus on outcomes) is similar, but the criteria used to define the end of lag times varies between *ecological* and *effective* (i.e., managed) *lag times.* In ecological settings, the criterion used is defined in terms of "rebalancing" (sensu Watts et al., 2020) ecosystem structures, processes or functions (Eq. (1)). In contrast, in managed forests the criterion is defined as a specified level of ecosystem services provided by the forest. In both settings, it is not enough that desirable developments have been set in motion, e.g., regeneration of desired species. Instead, these developments have to play out until a sufficient or satisfactory level of ecosystem processes or functions (for *ecological lag time*) or ecosystem services provision (for *effective lag time*) has been reached. Thus, in forests that provide a suite of ecosystem services, there may not be a single, generally accepted end of the lag time, but it may vary depending on the combination of the specific ecosystem services desired at the time. In a managed forest context (Fig. 1, lower bracket) the *effective lag time* is calculated as

$$\mathrm{LT}_{\mathrm{Effective}} = T_{\mathrm{Ecosystem\ Service\ Provision}} - T_{\mathrm{Event}} \quad (1)$$

2.2. Separating lag time in a management context into different components

When considering the environmental, social, and economic costs and benefits of restoration or other management activities, we find it beneficial to separate lag time into different components (Fig. 1, lower bracket, Eq. (2)). Understanding these components and factors that influence each can provide a more robust basis for developing and utilizing effective and efficient opportunities for management to influence or shorten lag times.

1) The lag times in *Detection* can be attributed to several factors. For example, they can be due the spatial segregation of an *event* and its eventual influence on ecosystems, such as introduction of a new insect species in a harbor or transportation hub and its subsequent spread and impact on surrounding forests. Typically, forest monitoring efforts will not cover such areas outside forests. Also within forests, regular monitoring efforts such as national forest inventories that operate at large spatial scales, typically using a grid-based with inventory points that are separated by several kilometers, are not

designed to pick up rare events. For example, new tree species, representing rare events, may not even be recorded but lumped into a category "other species" and only when they have become sufficiently abundant will be recorded as individual species that lend themselves to analysis (e. g. Bindewald et al., 2021). Lag times may thus also result from such events not being detected or the lack of communication between different authorities. Similarly, lag time in terms of detection could be due to ontogeny. For example, organisms are introduced in form of seeds or larvae but may not be detectable until after germination or pupation, respectively. Even with proper monitoring efforts, lag times can be due to misinterpretation of available information by professionals and the public, either by not understanding the cause of events (Noonan et al., 2015) or due a lack of understanding or proper evaluation of the full consequences, for example whether this event eventually leads to changes in ecosystem service provision (Essl et al., 2015). For example, different established risk assessment procedures may lead to very different results when applied to non-native tree species (e. g. Bindewald et al., 2020).

2) Another component of the lag time is due to delayed *Decisions.* After detection and awareness of an *event*, practitioners need to have the ability to make decisions about treatments. Numerous administrative and logistical challenges prevent forest and land managers from implementing management or restoration activities right away. Most public and private enterprises work with strategic and implementation plans and resources are allocated accordingly, including labor and funding. Depending on the flexibility in administrative structures and procedures, it may take time and effort to fight an "insistence on standard operating procedures" (Walters, 1986; page 32) and convince an organization to deviate from such plans and implement previously unplanned activities. For example, the discussion whether to let fires burn in selected places, such as National Parks, should be held prior to fire events. The *decision lag time* is shortened, if clear and generally accepted decision criteria are in place that determine when the risk of letting fires burn is too high. In contrast to private enterprises, public agencies may have to deal with more rules and regulations before such changes are made. Next, it will take time for an organization to agree on a proper management response, especially organizations with a broader scope and an associated wide array of in-house experts and stakeholders with potentially contrasting values and viewpoints. Decisions may for example be delayed when a necessary course of action, such as the application of pesticides or herbicides to control certain invasive species, conflicts with existing legislation or other established rules, for example in forest certification schemes. Besides the ecological implications of the *decision lag time*, other implications can include social conflicts regarding the resource use (Ostrom, 1990).
3) Delays in *Implementation* of the decisions are often attributable to logistics. Especially in larger operations, several steps involving numerous people and administrative levels typically need to be taken before the actual treatment can be implemented. These could include development of information strategies, and contracts that have to be written, put out for bid, and signed. In many instances, this means organizations have to deviate from their standard procedures (Walters, 1986). In addition, tools or equipment may have to be procured or put into place, people may need to be hired and trained, and permits obtained. Recent examples of extended *implementation lag times* include the delays due to the lack of seedlings when forest managers decided to replant land after the 2020 fires in Oregon or the delay in purchasing of harvesting equipment for salvaging in bark-beetle infested forests in parts of Europe (Sanginés de Cárcer et al., 2021).
4) Even in a management context, the *ecological lag time* can be lengthy, even after implementation of the management activities. It is defined as the time until the intended effect has happened, for example through the activation of feedback loops or reversal of trends (Ostrom, 1990). In practical terms, the ecosystem response will be influenced by a combination of the initial *event* and the management activity (i.e., a secondary *event*). Given that the original impact was considered sufficient to warrant management activities, the influence of successful management activities needs to supersede and halt or reverse undesirable ecosystem developments to the point where developmental trends have been initiated that eventually ensure "rebalancing" (sensu Watts et al., 2020).
5) By the time the ecosystems have responded, when the *ecological lag time* has ended, not all desired *ecosystem services* may be *provided* at acceptable levels in managed forests. Examples of this additional delay, i.e., lag time associated with ecosystem development, include the time when trees have been established and are growing, but have not reached sufficient size to be harvestable or provide habitat structures for larger cavity nesters and thus do not yet provide desired ecosystem services (e.g. Bauhus et al., 2009),

$$LT_{\text{Effective}} = LT_{\text{Detection}} + LT_{\text{Decision}} + LT_{\text{Implementation}} + LT_{\text{Ecological}} + LT_{\text{Ecosystem Service}} \quad (2)$$

When separating lag times into these components, several aspects need to be considered. First, any ecosystem response comprises many different responses at different organizational levels such as individuals, populations, meta-populations, and communities. The factors influencing lag times are not necessarily the same for all these different organizational levels. Additionally, processes at and between all these levels likely interact to further add complexity to these responses (Conrad, 1983). For brevity, in the following we briefly highlight selected factors shown to influence *effective lag times* focusing on species (Watts et al., 2020). First, short-lived species with an associated short (generational) turnover time typically show a quicker response. In contrast, species with longer life spans and associated time till sexual maturity have longer generational turnover time, but may have a greater capacity to acclimate to changing conditions. Thus, for selected impacts, these different organisms either have shorter or longer *ecological lag times* (Meyers and Bull, 2002; Watts et al., 2020). Second, habitat requirements of species result in more complicated patterns of influence on lag times. Especially the influence of specificity has been explored, i.e., the range of conditions under which species can survive and prosper. Species with very specific habitat requirements, such as those found in old forests, may have a short *ecological lag time* as they respond relative quickly to habitat loss. At the same time, these species may not respond quickly and thus have long *ecological lag times* in relation to restoration treatments as their habitat takes time to develop (Watts et al., 2020). Third, other species traits, such as fecundity and dispersal distance are especially influential in terms of colonization of newly available habitat (Naaf and Kolk, 2015). For example, species with a high number of propagules that disperse over large distances have a greater capacity to respond quickly to favorable conditions for establishment in the landscape.

Another critical factor influencing the length of numerous lag time components discussed above, specifically the *Detection*, *Decision*, and *Implementation* lag time, is the availability of information (Fig. 1, lower bracket; Eq. (3)). In situations with insufficient information, an additional delay is caused by the process to obtain critical knowledge or robust evidence (Grennfelt et al., 2020). For example, information gaps can result in errors in interpretation of monitoring data and thus lengthen the *detection lag time*. This is further complicated by the type of event. After distinct *events*, i.e., disturbances such as fires or windstorms, changes are obvious and these occurrences are likely interpreted as *events*. In contrast, continuous and gradual changes, such as increasing temperatures or shifts in precipitation patterns are harder to interpret in terms of their ecological relevance and provide special challenges in defining when an *event* has happened. In such instances, the decision is helped by the availability of robust model projections and the determination of threshold values (Scheffer, 2009). In the same context, information may be limited regarding the natural ecosystem development under changing, especially under novel conditions (Hobbs et al., 2013, Eq. (3)). In a management context, additional uncertainty exists in understanding how ecosystems respond to restoration or management treatments under such novel conditions (Puettmann, 2011). Novel conditions are likely to be especially challenging as all these aspects of information gaps may apply simultaneously. Logistic constraints may further influence the affect that lack of information has on lag times. This includes the availability of researchers to develop proposals, obtain funding, implement studies and develop models, analyze and distribute the results. Last, the capacity of educational and training systems determines the lag time till practitioners learn about the new information and become sufficiently educated to decide on forest restoration or management practices.

$$LT_{Effective} = LT_{Detection} \times IN + LT_{Decision} \times IN + LT_{Implementation} \times IN + LT_{Ecological} + LT_{Ecosystem\ Service} \quad (3)$$

Another issue highlighting the benefits of separating the lag time into components for better management is that the components are not simply additive. Specifically, the earlier lag times can influence the length of certain later lag time components (Eq. (4)). For example, quicker detection of an event may allow organizations to start the decision-making process or obtain tools and material earlier, maybe even before an event has actually happened. For example, based on simulation results from global and regional climate change models, researchers have started investigating which tree species or provenances will be suitable in future in selected regions and for certain site types (e. g. Chakraborty et al., 2021). The information may not have shortened the decision and implementation lag time, but the earlier event allowed earlier efforts to choose and establish different provenances or species that are presumably suitable for current and future conditions (e. g. Butterfield et al., 2017; Palik et al., 2022). This moves the *ecological lag time* forward before the actual impact of climate change is evident.

An example of non-linear, threshold-type relationships is to delay decisions to replant after disturbances. A short delay may not necessarily lead to a delay of tree plantings. However, once a threshold has been reached, such as when planting crews are fully booked or nursery stock is sold out, any replanting efforts have to wait at least till the onset of the second planting season. Thus, the implementation lag time is not influenced before the cutoff time, but lengthened once the cutoff time has been reached. Alternative, delays in the early lag time components may also influence the choice of management activities and potentially longer ecosystem response lag times (see description of the invasive species *R. armeniacus* above). Similarly, delays caused by longer discussions about the decision whether or not to salvage harvest and replant disturbed areas after fires or bark beetle damage may result in insufficient regeneration owing to increased competition from early-successional vegetation (Ouzts et al., 2015) and thus a reduction in associated ecosystem services. At the same time, this type of delay may lead to shorter ecosystem response lag times in relation to other ecosystem services, such as provision of selected wildlife habitat (Lindenmayer et al., 2012).

$$LT_{Effective} = LT_{Detection} + (LT_{Decision} \times LT_{Detection}) + LT_{Ecological} + LT_{Ecosystem\ Service} \quad (4)$$

3. Options to influence the lag time in managed ecosystems

We propose that any management intervention benefits from being viewed and evaluated in the context of its influence on lag times. For efficiency purposes, management activities aimed at influencing lag times that can be integrated into management activities already planned to achieve management goals (Box 2) are of special interest. As such, the choice of general management approaches already results in different frequencies of intervention points which offer opportunities to influence lag times. For example, the choice between even-aged and uneven-aged forest management will determine the frequency of stand tending entries and thus of opportunities to influence lag times (Fig. 2).

Investigating opportunities to implement activities aimed at influencing lag times will benefit from considering the components of the effective lag time as listed above and in Eq. (2). Lag time due to delays in *Detection* can be shortened through changes in monitoring efforts. As indicated above, such monitoring efforts for new pests, diseases or other potentially invasive species should expand beyond forested areas, and especially focus on early indicators, e.g., for species invasion on vectors (Ruiz and Carlton, 2003), include different stages of plant or animal development, and be continuously, e.g., not seasonally restricted. A second option to avoid *detection lag times* due to misperception about the relevance of events (Essl et al., 2015) requires education of the professionals and the public. For example, the shift of emphasis from a narrow focus on trees to a more integrative ecosystem view is one example that has shifted the public's perception what factors are important and critical in forest ecosystems, i.e., what should be monitored for potential *events*. One example is the increased interest in studies that investigate harvest or herbicide impacts on structure and functions of communities and ecosystems, for example on insects (Cobb et al., 2007). A third option to decrease the *detection lag time* is utilizing the increased sophistication of detection and forecasting tools. For example, systematic acoustic and camera monitoring may allow quicker detection of new occurrences of animal species (e.g. Pyšková et al., 2016), and global circulation models predict changes in climate, allowing researchers and managers to "detect" potential changes and take appropriate action before the events actually occur (Trasobares et al., 2022). Furthermore, new technologies allow better communication options, e.g., through drone videos, and more efficient communication, both of which should help to shorten *decision lag times* (Franklin, 1999).

The lag time due to delays in *decisions* of management practices can be shortened in several ways. Ostrom (1990) suggests a flexible governance structure which uses the bottom-up, instead of the top-down approach. Major advantages of this approach in terms of *decision lag times* include that quick communication between those with local knowledge and decision-makers is more suitable to support timely decisions. In addition, this approach results in a higher likelihood of political solutions and thus avoidance of conflicts (Ostrom, 1990). Other suggestions to shorten decision times include scenario analyses (Karjalainen et al., 2003; Kahane, 2012) or adaptive management strategies that describe critical thresholds and subsequent management responses before-hand (Walters, 1986). In addition, or as a result of such efforts, having a strategy in place under which conditions and how rules and regulations can be modified or skipped will speed up *decision* processes.

Ensuring there is additional organizational or institutional capacity that can quickly be mobilized and utilized when critical thresholds are reached will help shorten *implementation lag times*. Agreements between countries in the northern and southern hemispheres to share firefighting resources are a prime example. Other examples include excess capacity in nursery operations to increase the speed in which they can ramp up seedling production after large forest dieback events. Alternatively, increasing mobility of loggers and logging equipment de facto shortens the time till salvaging trees takes place to prevent or reduce the buildup of pest populations, for example by bringing loggers and equipment from Scandinavia to harvest beetle damaged trees in Germany (pers. observation). Based on recent trends, increasing and diversifying the workforce is likely to be critical in the future to ensure shorter *implementation* (and *decision*) *lag times*. This can be accomplished by providing incentives and education to ensure sufficient number of qualified forestry professionals, including fellers, truck drivers, forestry and nursery managers, mechanics, and other support staff.

Shorting the lag time for e*cosystem responses* is more difficult as this component is a natural phenomenon inherent in ecosystem processes playing out at a variety of scales and organizational levels, from genetically determined functional traits of species to ecosystem interactions and dynamics (Guo et al., 2022). In the context of global change, any activity that prepares ecosystems for disturbances and to better deal with

Box 2
Traditional management activities and their impacts on lag times.

As an example of natural resource management, forestry has a long history of utilizing management activities to increase the efficiency of ecosystem service provision, mostly wood production, which can also be viewed as management efforts to shorten *effective lag times*. For example, much effort is spent by foresters to shorten the reproduction periods and establish trees and stands quicker than would happen under natural conditions (Shatford et al., 2007; Franklin et al., 2018). Similarly, establishing advance regeneration is a way to shorten rotations or to facilitate forest recovery following disturbances. Basically, these practices result in a shortened *ecosystem service lag time* till forests provide ecosystem services associated with minimum tree sizes or older forests (Bauhus et al., 2010). This is accomplished through artificial regeneration by collecting seeds or propagules before the event (e.g., harvest) and storing them for quick availability (Duryea and Landis, 2012). As in other settings, related management practices can shift the competitive advantage to the advance regeneration of selected crop species (Messier et al., 1999). For example, underburning can improve regeneration of late successional species that are better able to sprout than early successional species (Barnes and Van Lear, 1998; Dey and Hartman, 2005), but only when simultaneous overstory treatments created suitable growing conditions for these species (Hutchinson et al., 2012). As an added benefit, established vigorous advanced regeneration basically eliminates the *decision lag time*, as decisions and efforts to regenerate the disturbed sites have been made and put in place before a possible disturbance *event*. Even more critical may be the elimination of the *implementation lag time* in place when logistic constraints prevent efficient reforestation. Examples include the lack of nursery stock after large-scale tree mortality.

Seedling growth is accelerated compared to growth in unmanaged conditions by providing consistently better conditions for germination and early growth by controlling weeds, water, nutrients, temperature, and light. This can be done either in the field, e.g., through harvest and site preparation in the forest or in more controlled environments, such as in nurseries or greenhouses (Duryea and Landis, 2012). Another option to shorten the *effective lag time* is through a suite of density management treatments. For example, pre-commercial and commercial thinnings are aimed at accelerating growth of the remaining trees so they achieve target dimensions sooner (Ashton and Kelty, 2018). More recent interest has resulted in a suite of management practices aimed at accelerating the development of late successional characteristics (Bauhus et al., 2009), whereby the shortening of *ecological lag time* in terms of the different components of late successional structures and composition may require different management practices (Puettmann et al., 2016). Opportunities for all these practices in regards to shortening *effective lag times* benefit from the use of simulation models. For example, thinning operations can be scheduled based on simulation results, i.e., before competitive conditions would have been "detected" and deemed sufficiently critical to justify treatments.

As ecosystems are dynamic, selected ecosystem services vary with successional or developmental stage, i.e., are only provided during limited time periods. One can view the time after such a stage has passed till the ecosystem again develops to that stage as *effective lag time*. For example, extending early successional conditions in stands (Donato et al., 2012) may be a better alternative to increasing the frequency of disturbances (Swanson et al., 2011), as relying only on natural regeneration and/or limiting weed control will likely ensure longer early successional periods, compared to typical planting practices (Donato et al., 2012; Palik et al., 2020). However, extending early successional conditions will increase the *effective lag times* in other dimensions, for example regarding the provision of ecosystem services associated with large trees (Lindenmayer and Laurance, 2017)

In terms of genetic considerations in response to climate change, assisted migration has received a lot of attention in forestry, as it is one way to reduce *effective lag times*. The rationale for this approach is that the dispersal or migration speed of most tree species is too slow to keep up with changes in climate (Aitken et al., 2008). Thus, foresters can actively move propagules to sites where these plants are genetically adapted to the environmental conditions they are predicted to experience in the future (Aitken et al., 2008). While this appears to be ongoing on an informal basis (https://seedlotselectiontool.org/sst/), more research is necessary to make this a globally reliable practice (Grady et al., 2015). The same argument, i.e., reduced *ecological lag time*, can also be applied to actively encourage selected species mixtures, especially to include species that appear better adapted to future climate conditions (see Liu et al., 2018 and citations therein). Other options to utilize genetics to reduce time lags include to specifically select for traits, such as plasticity, drought tolerance, or tolerance to selected diseases in tree breeding and genetic engineering programs (e.g., Powell et al., 2019), thus shortening the *ecological lag time* in comparison to relying solely on evolutionary forces.

Other trends that can lead to losses of ecosystem services include nutrient depletion after harvesting, especially in forest with short rotations and whole or full-tree harvesting operations. In such settings, foresters have learned from agriculture and fertilize forests. Fertilization can be viewed as shortening the *effective lag time* till nutrients are replenished (and a supportive ecosystem service is provided). In contrast, natural process, such as mineral weathering, atmospheric input or decomposition of organic matter may not be sufficient to maintain productivity (Kimmins, 1997). Also, fuel treatments can be viewed as accelerating decomposition by e.g., burning slash piles. Thus, such practices shorten the *ecological lag time* till forests are not in a condition where live and dead vegetation contributes significantly to fire danger (Stephens et al., 2012). Similarly, sanitation and salvage cutting accelerate development of conditions that are not suitable anymore for selected insects and diseases (Miscicki and Grodzki, 2021).

Just as with silvicultural treatments aimed at increasing adaptive capacity, treatments to shorten lag time are more likely implemented if they can be integrated into ongoing management practices applied to achieve typical ownership objectives, such as timber production, provision of habitat, and recreational values (Puettmann and Messier, 2019). In this context, the typical frequency of management entries is critical (Fig. 2). Silvicultural systems vary greatly in terms of the timing of entries, i.e., possibilities to influence lag times that are financially self-supported. For example, typical even-aged management is characterized by several, often high intensity treatment to ensure stand establishment. After trees are established and free-to-grow, the next entry may not be for a few decades, i.e., till the final harvest for species with relatively short rotations (Fig. 2). For species with longer rotations, intermediate entries may include one or several thinning operations. In contrast, uneven-aged management is characterized by a more or less regular set of entries to tend the stand at relatively short time intervals. At the same time, these entries can be a combination of practices that simultaneously lead to tree establishment, thinning-type density reductions, and final harvests in various portions of stands. Such silvicultural systems not only require but also allow managers more frequent opportunities to shorten lag times using a diverse set of silvicultural treatments and thus react quicker to changing environmental, social, and economic conditions (Fig. 2b). Thus, silviculture approaches with frequent entries have great advantages in terms of flexibility in a changing environment in terms of adaptation, similar to species with short turn-over times (Levins, 1968).

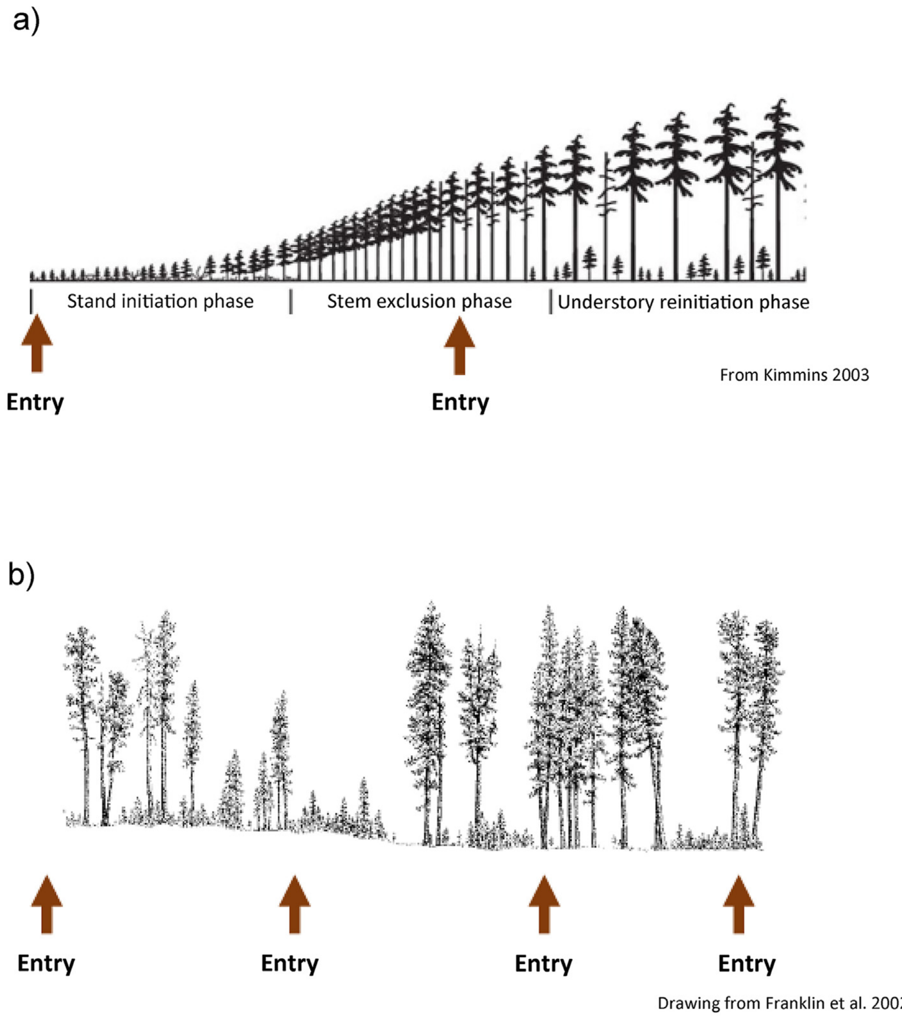


Fig. 2. Frequency of opportunities for commercial entries that influence lag times in forests managed as even-aged forest (**a**) versus with partial harvest operations (**b**). Modified from Kimmins (2003; **a**) and Franklin et al. (2002; **b**).

climate trends increases their adaptive capacity (Puettmann, 2014) and shorten the *ecological lag time*. This can be accomplished through a wide variety of activities that have been organized in three groups: resistance, resilience, and transformation (Millar et al., 2007) and more recently using the Resist-Adapt-Direct concept (Schuurman et al., 2021). For example, the *ecological lag time* can be shorted by encouraging the presence of a diversity of presumably more adapted plant species with a special emphasis on the associated diversity of plant traits (Yachi and Loreau, 1999) in stands (Neill and Puettmann, 2013) and/or in the landscape (Messier et al., 2019). This may be controversial if it involves working against selected ecosystem processes, native species and natural patterns, as would be the case where the natural regeneration following disturbances is dominated by tree species that are maladapted to changed biotic or abiotic conditions. For example, conditions have changed in the north-eastern part of the USA due to the presence of an introduced disease, beech bark disease, that kills larger *Fagus grandifolia* (American beech). After such mortality, the natural regeneration of beech is very prolific due to root suckers. The suckers will die before they can become mature, but in the meantime they basically prevent establishment of other tree species that are better adapted to a world with beech bark disease (Runkle, 2007). In this example, relying on "natural" processes in forests where the conditions have changed significantly leads to a longer *ecological lag time* not only in terms of providing desired ecosystem services (after accounting for *ecosystem service lag time*), but also in terms of the adaptive capacity of these forests to global changes. Shortening the *ecological lag time* would require active removal of much of the regeneration of the maladapted beech through a combination of mechanical and herbicide applications (Myers et al., 2023).

Forest managers have limited opportunities to directly influence the *ecosystem service lag time*. The provision of ecosystem services is derived from the "rebalanced" ecosystem structures and composition (ecosystem service cascade; Zhang et al., 2022). Other professionals and aspects related to the forestry sector are better suited in this regard. For example, the *ecosystem service lag time* can be influenced by changing the expectation of or need for the desired ecosystem services. For example, the time till forests provide a certain level of income to landowners can be shorted by subsidies, tax incentives, or payment for easements. Other examples include removing damaged and dangerous trees after disturbances and thus allowing quicker safe access for the recreating public. Alternatively, educational efforts may be helpful in shortening the *ecosystem service lag time* if they change the expectation of the public, e.g., by creating acceptance that certain areas are unsafe and thus will not provide previous recreational benefits for extended periods.

Impact of insufficient *Information* on the extent of the lag time can be shortened by encouraging forward looking proposals and ideas, flexibility in funding such as National Science Foundation Grants for Rapid Response Research in the USA and institutional and endowed funds that provide researchers with high flexibility. Capacity building also includes ensuring sufficient research expertise, lab space, field sites, analytical expertise, and procedures for efficient publication and distribution of results. Also, technological innovation, such as the ability to spread information via knowledge platforms, emails, and social media have the ability to shorten the delay due to information needs. Several developments in the publishing business have resulted in quicker dissemination of information, such as making pre-prints available or publishing articles online before the actual journal comes out. Also, if robust simulation models are in place, investigating hypotheses through modelling can provide relative quick results compared to field studies (Rahn et al., 2018).

4. What can we learn from the lag time discussion about passive/active restoration?

Viewing lag time in a management context can contribute to discussions about decisions whether to actively manipulate the forests or allow ecosystem dynamics to play out in times of global changes, especially after severe disturbances (active versus passive restoration, sensu Chazdon et al., 2021). As we expect increased impact of global changes including increased frequency and severity of disturbances, managing the *detection*, *decision*, and *implementation lag times* is becoming more and more critical. In this context, the specific role of each desired ecosystem service is important to consider. Here, the implications of the management/no management choice on the length of the *ecosystem service lag time* requires additional discussions.

In selected places, such as wilderness areas or nature parks, the main management focus is often to avoid or minimize all influence of human activities and presence and to allow natural development mechanisms to play out on their own. As long as it was not or little influenced by humans, any ecosystem condition is acceptable. Thus, the provisioning of spiritual or cultural ecosystem services, in this case knowing that there is a forested area where humans had no or little influence, is more important than other ecosystem services. People obtain that benefit instantaneously when the decision is made, there is basically no *ecological* and *ecosystem service lag time*. In contrast, in most multiple-use forests the provision of other regulating, cultural, and provisioning ecosystem services is part of the suite of management goals. Even in "protected areas" the recent discussion about the long tradition and role of indigenous forest management challenges the dominance of the benefits of having no or little human impacts. In these cases, changes in environmental conditions, ecosystem dynamics, or disturbances that are leading to conditions that are less suitable to provide the desired suite of ecosystem services suggest further discussion about the role of management in terms of influencing *effective lag times*.

In the context of multiple ecosystem services, it is important to consider that the provision of ecosystem services varies depending on stand structure and composition (Zhang et al., 2022), and that the provision of many ecosystem services is higher in fully stocked stands and when trees are of larger sizes, with notable exceptions (Bauhus et al., 2010; Swanson et al., 2011). The dominance of the respective objectives and the associated benefits of influencing the *effective lag time* is typically driving decisions in managed forests after disturbances (Lindenmayer et al., 2012). Furthermore, for this discussion it is important to separate any management or restoration efforts into its individual components, as they can have unique impacts on the length of *ecological* and *ecosystem service lag times*. For example, managed post-fire recovery efforts can include salvage logging, tree seeding or planting, and associated weed control practices. One can view salvage logging as shortening the *ecological lag time* by not allowing for processes such as wood decay, and thus all associated ecosystem services to play out longer (Harmon et al., 1986; Thorn et al., 2018). Tree seeding, planting, and weed control practices will shorten the time till fully stocked stands of vigorous trees are established (*ecological lag time*; Shatford et al., 2007) and thus all ecosystem services associated with these types of stands are provided (*ecosystem service lag time*), e.g., signficant carbon sequestration, habitat for large cavity nesters, and economic values (Bauhus et al., 2009). On the other hand, weed control practices cut out specific processes and conditions such as the ecosystem services associated with early successional stand structures and vegetation (Swanson et al., 2011; Donato et al., 2012). For example, in southwestern Oregon the weed control practice of removing deerbrush (*Ceanothus integerrimus*) in regeneration efforts after fires shortens or eliminates the nitrogen fixation by that species, resulting in lengthening the ecological and ecosystem service lag time of nutrient provision to maintain productivity, a supporting ecosystem service (Yelenik et al., 2013). This simplified description of one example highlights the complexity of the management/no management issue and how any decision is reflected in the length of effective lag times.

Many traditional silviculture practices are set up so forest ecosystems recover quicker from a disturbance (tradionally mostly harvests) and thus avoid or minimize the *effective lag time*. Managing forests through partial harvest and associated reforestation efforts to establish advance regeneration is a prime example of a practice that shortens various lag time components, including the *ecological* and associate *ecosystem service lag times* after disturbance that damage or kill the overstory trees (for a more detailed discussion see Box 2). In contrast, decisions to manage or not manage can be aimed at extending the *effective lag time* through management efforts that slow down or stop undesirable process that interfere with the provision of desired ecosystem services. Examples include reducing or restricting the movement of exotic insects, fungi, or plant species that lead to tree mortality, e.g., through quarantine efforts or establishing barriers by removing affected species (Václavík et al., 2010). While such invasions may not be stopped, the practices that extend the *ecological lag time* may allow managers to shorten *implementation lag times* (and allow the implementation of "softer" practices), e.g., by establishing alternative species or resistant varieties, and thus ensure the continuity of ecosystem service provision down the line. In special cases, ecosystem conditions have changed to a point where ecological lag times are lengthened through natural processes (also see discussion about *R. armeniacus* above). In many forests, herbivory by large ungulate browsers is preventing establishment of selected species that are better adapted to future conditions (Angelstam et al., 2017; Redick and Jacobs, 2020), e.g., *Quercus* species that are more drought tolerant than current species (Niinemets and Valladares, 2006). In the latter case, management efforts that lower herbivore populations and/or protect seedlings from browsing (Anderson and Katz, 1993) can shorten the *ecological lag time* and thus accelerate the development of the adaptive capacity of forests. Other examples where management can shorten *ecological lag times* include harvesting and regeneration practices that encourage mixed-species forests by discouraging the potentially dominant role of the natural regeneration of vulnerable species, e.g., *Picea abies* (Norway spruce) in many areas in central Europe (Unkule et al., 2022).

Alternatively, if shortening or extending the *effective lag time* is not possible or sufficient, finding alternative ways to lower the expectations and/or replace the respective ecosystem services may be necessary. In such cases, the practices need to be part of the discussion about the decision regarding active management versus no management as these practices can be viewed as shortening the *ecosystem service lag time* till the "recalibrated" demand for these ecosystem services is satisfied. Obviously, such discussion extends beyond the forestry sector itself and requires a broader discourse about various social issues. Examples of ecosystem services that influence a wide populace include the provision of income, clean water, and wildlife populations and the expectations can be addressed through subsidies, water cleaning facilities, or protecting and establishing critical habitat for rare species in other places, respectively.

These examples highlight the importance of the various dimension of scale. Our discussion above is focused on forestry issues and at the stand level. Expanding the discussions to larger spatial scales and including the social component of natural resource management will better reflect the various dimensions involved in decisions whether to manage selected settings. A better understanding of *effective lag times* will provide a more solid basis for such decisions.

5. Conclusion

The longevity of trees and associated long time horizons of forest management decisions related to the provision of selected ecosystem services highlights that forest managers are aware of the importance of time and timeliness in their management activities, especially in the context of a world with an increasing pace of change. We conclude that in a forestry context it is beneficial, maybe even necessary to go beyond the ecological definition of lag time and consider additional aspects that define when lag times start and end, specifically regarding the provision of ecosystem services. Furthermore, breaking the lag time down into its components highlights specific opportunities how to shorten or lengthen lag times. The more detailed view also indicates that not only foresters and other people in the forestry sector, but the public can influence lag times as well. For example, researchers and decision makers can influence the lag time directly, for example through improved monitoring or better information about potential impacts. Examples of indirect influences include administrators in research and management organizations who establish the capacity to respond quickly to changes. Examples of people outside the direct forestry sectors include hunters, who can shorten or lengthen lag times in relation to the development of forests with high adaptive capacity by their role in influencing the population levels of herbivores. Alternatively, adjustments of expectations by landowners and the general public can also influence *effective lag times*. We conclude that consideration of lag times is not only relevant after disturbance events, but becomes more critical and ever-present in the context of forest management in times of increasing speed of global changes (Hessburg et al., 2021). Last, the benefits of more purposeful discussions of lag time are highlighted using the topic whether the best strategy after disturbances is to let ecosystem processes play out on their own (Leverkus et al., 2020), or whether active management is better suited to ensure more rapid and more complete ecosystem recovery (Jones et al., 2018).

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Authors' contribution

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Data availability statement

NA.

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References

Aitken, S.N., Yeaman, S., Holliday, J.A., Wang, T., Curtis-McLane, S., 2008. Adaptation, migration or extirpation: climate change outcomes for tree populations. Evol. Appl. 1, 95–111.
Anderson, R.C., Katz, A.J., 1993. Recovery of browse-sensitive tree species following release from white-tailed deer (*Odocoileus virginianus* Zimmerman) browsing pressure. Biol. Conserv. 63 (3), 203–208.
Angelstam, P., Pedersen, S., Manton, M., Garrido, P., Naumov, V., Elbakidze, M., 2017. Green infrastructure maintenance is more than land cover: large herbivores limit recruitment of key-stone tree species in Sweden. Lands. Urban Plan 167, 368–377.
Ashton, M.S., Kelty, M.J., 2018. The Practice of Silviculture: Applied Forest Ecology. John Wiley & Sons, New York, NY.
Barnes, T.A., Van Lear, D.H., 1998. Prescribed fire effects on advanced regeneration in mixed hardwood stands. South. J. Appl. For. 22 (3), 138–142.
Bauhus, J., Puettmann, K., Messier, C., 2009. Silviculture for old-growth attributes. For. Ecol. Manag. 258 (4), 525–537.
Bauhus, J., Van der Meer, P., Kanninen, M., 2010. Ecosystem Goods and Services from Plantation Forests. Earthscan, London, Washington, D.C.
Benayas, J.M.R., Newton, A.C., Diaz, A., Bullock, J.M., 2009. Enhancement of biodiversity and ecosystem services by ecological restoration: a meta-analysis. Science 325 (5944), 1121–1124.
Bennett, M., 2007. Managing Himalayan Blackberry in Western oregon Riparian Areas. Oregon State University Extension Service, Corvallis.
Bindewald, A., Michiels, G., Bauhus, J., 2020. Risk is in the eye of the assessor: comparing risk assessments of four non-native tree species in Germany. Forestry 93, 519–534.
Bindewald, A., Miocic, S., Wedler, A., Bauhus, J., 2021. Forest inventory-based assessments of the invasion risk of *Pseudotsuga menziesii* (Mirb.) Franco and *Quercus rubra* L. in Germany. Eur. J. For. Res. 140, 883–899.
Botkin, D.B., 1990. Discordant Harmonies: a New Ecology for the Twenty-First Century. Oxford University Press, New York, Oxford.
Brady, S.P., Bolnick, D.I., Barrett, R.D.H., Chapman, L., Crispo, E., Derry, A.M., Eckert, C.G., Fraser, D.J., Fussmann, G.F., Gonzalez, A., Guichard, F., Lamy, T., Lane, J., McAdam, A.G., Newman, A.E.M., Paccard, A., Robertson, B., Rolshausen, G., Schulte, P.M., Simons, A.M., Vellend, M., Hendry, A., 2019. Understanding maladaptation by uniting ecological and evolutionary perspectives. Am. Nat. 194 (4), 495–515.
Butterfield, B.J., Copeland, S.M., Munson, S.M., Roybal, C.M., Wood, T.E., 2017. Prestoration: using species in restoration that will persist now and into the future. Restor. Ecol. 25, 155–163.
Chakraborty, D., Móricz, N., Rasztovits, E., Dobor, L., Schueler, S., 2021. Provisioning forest and conservation science with high-resolution maps of potential distribution of major European tree species under climate change. Annals For. Sci. 78 (2), 26.
Chazdon, R.L., Falk, D.A., Banin, L.F., Wagner, M., Wilson, S.J., Grabowski, R.C., Suding, K.N., 2021. The intervention continuum in restoration ecology: rethinking the active–passive dichotomy. Restor. Ecol. https://doi.org/10.1111/rec.13535.
Cobb, T., Langor, D., Spence, J., 2007. Biodiversity and multiple disturbances: boreal forest ground beetle (coleoptera: carabidae) responses to wildfire, harvesting, and herbicide. Can. J. For. Res. 37 (8), 1310–1323.
Conrad, M., 1983. Adaptability: the Significance of Variability from Molecule to Ecosystem. Plenum Press, New York, NY.
Crooks, J.A., 2005. Lag times and exotic species: the ecology and managment of biological invasions in slow-motion. Ecoscience 12 (3), 316–329.
Dey, D.C., Hartman, G., 2005. Returning fire to Ozark Highland forest ecosystems: effects on advance regeneration. For. Ecol. Manag. 217 (1), 37–53.
Donato, D.C., Campbell, J.L., Franklin, J.F., 2012. Multiple successional pathways and precocity in forest development: can some forests be born complex? J. Veg. Sci. 23 (3), 576–584.
Duncan, R.P., 2021. Time lags and the invasion debt in plant naturalisations. Ecol. Lett. 24 (7), 1363–1374.
Duryea, M.L., Landis, T.D., 2012. Forest Nursery Manual: Production of Bareroot Seedlings. Springer, Dordrecht.
Essl, F., Dullinger, S., Rabitsch, W., Hulme, P.E., Pyšek, P., Wilson, J.R.U., Richardson, D.M., 2015. Delayed biodiversity change: no time to waste. Trends Ecol. Evol. 30 (7), 375–378.
Farkas, T.E., Hendry, A.P., Nosil, P., Beckerman, A.P., 2015. How maladaptation can structure biodiversity: eco-evolutionary island biogeography. Trends Ecol. Evol. 30 (3), 154–160.
Fierke, M.K., Kauffman, J.B., 2006. Invasive species influence riparian plant diversity along a successional gradient, Willamette River, Oregon. Nat. Area J. 26 (4), 376–382.
Franklin, J.F., Johnson, N.K., Johnson, D.L., 2018. Ecological Forest Management. Waveland Press, Long Grove, Illinois.
Franklin, U., 1999. The Real World of Technology. House of Anansi Press Inc.

Franklin, J.F., Spies, T.A., Pelt, R.V., Carey, A.B., Thornburgh, D.A., Berg, D.R., Lindenmayer, D.B., Harmon, M.E., Keeton, W.S., Shaw, D.C., Bible, K., Chen, J., 2002. Disturbances and structural development of natural forest ecosystems with silvicultural implications, using Douglas-fir forests as an example. For. Ecol. Manag. 155, 399–423.
Grady, K.C., Kolb, T.E., Ikeda, D.H., Whitham, T.G., 2015. A bridge too far: cold and pathogen constraints to assisted migration of riparian forests. Restor. Ecol. 23 (6), 811–820.
Grennfelt, P., Engleryd, A., Forsius, M., Hov, Ø., Rodhe, H., Cowling, E., 2020. Acid rain and air pollution: 50 years of progress in environmental science and policy. Ambio 49 (4), 849–864.
Guo, C., Yan, E.-R., Cornelissen, J.H.C., 2022. Size matters for linking traits to ecosystem multifunctionality. Trends Ecol. Evol. 37 (9), 803–813.
Harmon, M.H., Franklin, J.F., Swanson, F.J., 1986. Ecology of coarse woody debris in temperate ecosystems. Adv. Ecol. Res. 15, 133–302.
Hessburg, P.F., Prichard, S.J., Hagmann, R.K., Povak, N.A., Lake, F.K., 2021. Wildfire and climate change adaptation of western North American forests: a case for intentional management. Ecol. Appl. 31, e02432.
Hobbs, R.J., Hiccs, E.S., Hall, C., 2013. Novel Ecosystems: Intervening in the New Ecological World Order. Wiley-Blackwell.
Hutchinson, T.F., Long, R.P., Rebbeck, J., Sutherland, E.K., Yaussy, D.A., 2012. Repeated prescribed fires alter gap-phase regeneration in mixed-oak forests. Can. J. For. Res. 42 (2), 303–314.
Jackson, S.T., Sax, D.F., 2010. Balancing biodiversity in a changing environment: extinction debt, immigration credit and species turnover. Trends Ecol. Evol. 25 (3), 153–160.
Jandl, R., Spathelf, P., Bolte, A., Prescott, C.E., 2019. Forest adaptation to climate change—is non-management an option? Annals For. Sci. 76 (2), 48.
Jenkins, M., Schaap, B., 2018. Forest Ecosystem Services: Background Analytical Study 1. Background Study Prepared for the Thirteens Session of the. United Nations Forum on Forests, pp. 1–48.
Jones, H.P., Jones, P.C., Barbier, E.B., Blackburn, R.C., Rey Benayas, J.M., Holl, K.D., McCrackin, M., Meli, P., Montoya, D., Mateos, D.M., 2018. Restoration and repair of Earth's damaged ecosystems. Proc. Royal. Soc B: Biol. Sci. 285, 20172577.
Kahane, A., 2012. Transformative Scenario Planning: Working Together to Change the Future. Berrett-Koehler Publishers.
Karjalainen, T., Pussinen, A., Liski, J., Nabuurs, G.-J., Eggers, T., Lapveteläinen, T., Kaipainen, T., 2003. Scenario analysis of the impacts of forest management and climate change on the European forest sector carbon budget. For. Policy Econ. 5 (2), 141–155.
Kimmins, J.P., 1997. Forest Ecololgy: a Foundation for Sustainable Management. Prentice-Hall Inc., Upper Saddle River, New Jersey.
Kimmins, J.P., 2003. Old-growth forest: an ancient and stable sylvan equilibrium, or a relatively transitory ecosystem condition that offers people a visual and emotional feast? answer-it depends. For. Chron. 79, 429–440.
Kok, M.T.J., Alkemade, R., Bakkenes, M., van Eerdt, M., Janse, J., Mandryk, M., Kram, T., Lazarova, T., Meijer, J., van Oorschot, M., Westhoek, H., van der Zagt, R., van der Berg, M., van der Esch, S., Prins, A.-G., van Vuuren, D.P., 2018. Pathways for agriculture and forestry to contribute to terrestrial biodiversity conservation: a global scenario-study. Biol. Conserv. 221, 137–150.
Kuuluvainen, T., Angelstam, P., Frelich, L., Jõgiste, K., Koivula, M., Kubota, Y., Lafleur, B., Macdonald, E., 2021. Natural disturbance-based forest management: moving beyond retention and continuous-cover forestry. Front. For. Glob. Change 4. https://doi.org/10.3389/ffgc.2021.629020.
Leary, R.A., 1985. Interaction theory in forest ecology and management, 19. Springer Science & Business Media.
Leverkus, A.B., Gustafsson, L., Lindenmayer, D.B., Castro, J., Rey Benayas, J.M., Ranius, T., Thorn, S., 2020. Salvage logging effects on regulating ecosystem services and fuel loads. Front. Ecol. Env. 18, 391–400.
Levins, R., 1968. Evolution in Changing Environments. Princeton University Press, Princeton.
Lindenmayer, D.B., Burton, P.J., Franklin, J.F., 2012. Salvage Logging and its Ecological Consequences. Island Press, Washington, D.C.
Lindenmayer, D.B., Laurance, W.F., 2017. The ecology, distribution, conservation management of large old trees. Biol. Rev. 92 (3), 1434–1458.
Liu, C.L.C., Kuchma, O., Krutovsky, K.V., 2018. Mixed-species versus monocultures in plantation forestry: development, benefits, ecosystem services and perspectives for the future. Global Ecol. Cons. 15, e00419.
Martínez-Vilalta, J., Lloret, F., 2016. Drought-induced vegetation shifts in terrestrial ecosystems: the key role of regeneration dynamics. Global Planet. Change 144, 94–108.
Messier, C., Bauhus, J., Doyon, F., Maure, F., Sousa-Silva, R., Nolet, P., Mina, M., Aquilué, N., Fortin, M.-J., Puettmann, K., 2019. The functional complex network approach to foster forest resilience to global changes. For. Ecosyst. 6, 21. https://doi.org/10.1186/s40663-019-0166-2.
Messier, C., Doucet, R., Ruel, J.-C., Claveau, Y., Kelly, C., Lechowicz, M.J., 1999. Functional ecology of advance regeneration in relation to light in boreal forests. Can. J. For. Res. 29, 812–823.
Meyers, L.A., Bull, J.J., 2002. Fighting change with change: adaptive variation in an uncertain world. Trends Ecol. Evol. 17 (12), 551–557.
Millar, C.I., Stephenson, N.L., Stephens, S.L., 2007. Climate change and forests of the future: managing in the face of uncertainty. Ecol. Appl. 17 (8), 2145–2151.
Miranda, A., Carrasco, J., González, M., Pais, C., Lara, A., Altamirano, A., Weintraub, A., Syphard, A.D., 2020. Evidence-based mapping of the wildland-urban interface to better identify human communities threatened by wildfires. Environ. Res. Lett. 15 (9), 094069.
Miscicki, S., Grodzki, W., 2021. Can sanitation cutting contribute to reduced mortality of Norway Spruce (*Picea abies* (l.) h. Karst.) due to infestation by *Ips typographus* (L.)? Sylwan 165 (11), 749–762.
Myers, A.L., Storer, A.J., Dickinson, Y.L., Bal, T.L., 2023. A review of propagation and restoration techniques for American beech and their current and future application in mitigation of beech bark disease. Sustainability 15 (9), 7490. https://doi.org/10.3390/su15097490.
Naaf, T., Kolk, J., 2015. Colonization credit of post-agricultural forest patches in NE Germany remains 130–230 years after reforestation. Biol. Conserv. 182, 155–163.
Neill, A., Puettmann, K.J., 2013. Managing for adaptive capacity: thinning improves food availability for wildlife and insect pollinators under climate change conditions. Can. J. For. Res. 43, 428–440.
Niinemets, U., Valladares, F., 2006. Tolerance to shade, drought, and waterlogging of temperate northern hemisphere trees and shrubs. Ecol. Monogr. 76 (4), 521–547.
Noonan, M.J., Rahman, M.A., Newman, C., Buesching, C.D., Macdonald, D.W., 2015. Avoiding verisimilitude when modelling ecological responses to climate change: the influence of weather conditions on trapping efficiency in European badgers (*Meles meles*). Global Change Biol. 21 (10), 3575–3585.
Nunes, L.J.R., Meireles, C.I.R., Pinto Gomes, C.J., Almeida Ribeiro, N.M.C., 2020. Forest contribution to climate change mitigation: management oriented to carbon capture and storage. Climate 8, 21.
Osman, M.B., Tierney, J.E., Zhu, J., Tardif, R., Hakim, G.J., King, J., Poulsen, C.J., 2021. Globally resolved surface temperatures since the last glacial maximum. Nature 599 (7884), 239–244.
Ossola, A., Cadenasso, M.L., Meineke, E.K., 2021. Valuing the role of time in urban ecology. Front. Ecol. Evol. 9 (152). https://doi.org/10.3389/fevo.2021.620620.
Ostrom, E., 1990. Governing the Commons: the Evolution of Institutions for Collective Action. Cambridge University Press, Cambridge.
Ouzts, J., Kolb, T., Huffman, D., Sánchez Meador, A., 2015. Post-fire ponderosa pine regeneration with and without planting in Arizona and New Mexico. For. Ecol. Manag. 354, 281–290.
Palik, B.J., Clark, P.W., D'Amato, A.W., Swanston, C., Nagel, L., 2022. Operationalizing forest-assisted migration in the context of climate change adaptation: examples from the eastern USA. Ecosphere 13 (10), e4260.
Palik, B.J., D'Amato, A.W., Franklin, J.F., Johnson, K.N., 2020. Ecological Silviculture: Foundations and Applications. Waveland Press.
Parrotta, J., Yeo-Chang, Y., Camacho, L.D., 2016. Traditional knowledge for sustainable forest management and provision of ecosystem services. Int. J. Biod. Sci. Ecos. Serv. Manage. 12 (1–2), 1–4.
Powell, W.A., Newhouse, A.E., Coffey, V., 2019. Developing blight-tolerant American chestnut trees. Cold Spring Harbor Perspect. Biol. 11 (7), a034587.
Puettmann, K.J., 2011. Silvicultural challenges and options in the context of global change: simple fixes and opportunities for new management approaches. J. For. 109 (6), 321–331.
Puettmann, K.J., 2014. Restoring the adaptive capacity of forest ecosystems. J. Sustain. For. 33, S15–S27.
Puettmann, K.J., Ares, A., Burton, J.I., Dodson, E.K., 2016. Forest restoration using variable density thinning: lessons from Douglas-fir stands in western Oregon. Forests 7 (12), 310.
Puettmann, K.J., Messier, C., 2019. Simple guidelines to prepare forests for global change: the dog and the frisbee. Northwest Sci. 93 (3–4), 209–225.
Pyšková, K., Storch, D., Horáček, I., Kauzál, O., Pyšek, P., 2016. Golden jackal (*Canis aureus*) in the Czech Republic: the first record of a live animal and its long-term persistence in the colonized habitat. ZooKeys 641, 151–163.
Rahn, E., Vaast, P., Läderach, P., van Asten, P., Jassogne, L., Ghazoul, J., 2018. Exploring adaptation strategies of coffee production to climate change using a process-based model. Ecol. Model. 371, 76–89.
Rastetter, E.B., Ohman, M.D., Elliott, K.J., Rehage, J.S., Rivera-Monroy, V.H., Boucek, R.E., Castañeda-Moya, E., Danielson, T.M., Gough, L., Groffman, P.M., Jackson, C.R., Miniat, C.F., Shaver, G.R., 2021. Time lags: insights from the U.S. Long term ecological research network. Ecosphere 12 (5), e03431.
Redick, C.H., Jacobs, D.F., 2020. Mitigation of deer herbivory in temperate hardwood forest regeneration: a meta-analysis of research literature. Forests 11 (11), 1220.
Ruiz, G.M., Carlton, J.T., 2003. Invasive Species: Vectors, Management, Strategies. Island Press, Washington, D.C.
Runkle, J.R., 2007. Impacts of beech bark disease and deer browsing on the old-growth forest. Am. Midl. Nat. 157 (2), 241–249.
Sanginés de Cárcer, P., Mederski, P.S., Magagnotti, N., Spinelli, R., Engler, B., Seidl, R., Eriksson, A., Eggers, J., Bont, L.G., Schweier, J., 2021. The management response to wind disturbances in European forests. Curr. For. Rep. 7 (4), 167–180.
Scheffer, M., 2009. Critical Transitions in Nature and Society. Princeton University Press, Princeton, NJ.
Schuurman, G.W., Cole, D.N., Cravens, A.E., Covington, S., Crausbay, S.D., Hoffman, C.H., Lawrence, D.J., Magness, D.R., Morton, J.M., Nelson, E.A., O'Malley, R., 2021. Navigating ecological transformation: resist–accept–direct as a path to a new resource management paradigm. Bioscience 72 (1), 16–29.
Shatford, J.P.A., Hibbs, D.E., Puettmann, K.J., 2007. Conifer regeneration after forest fire in the klamath-siskiyous: how much, how soon? J. For. 105, 139–146.
Sivadas, D., 2022. Pathways for sustainable economic benefits and green economies in light of the state of world forests 2022. Anthropol. Sci. 1 (4), 460–465.
Soll, J., Lipinski, B., 2004. Controlling himalayan blackberry in the Pacific Northwest. In: Lipinski, B. (Ed.), The Nature Conservancy. http://tncweeds.ucdavis.edu/moredocs/rubarm01.pdf. (Accessed 15 June 2023).
Stephens, S.L., McIver, J.D., Boerner, R.E.J., Fettig, C.J., Fontaine, J.B., Hartsough, B.R., Kennedy, P.L., Schwilk, D.W., 2012. The effects of forest fuel-reduction treatments in the United States. BioScience 62, 549–560.

Swanson, M.E., Franklin, J.F., Beschta, R.L., Crisafulli, C.M., DellaSala, D.A., Hutto, R.L., Lindenmayer, D.B., Swanson, F.J., 2011. The forgotten stage of forest succession: early-successional ecosystems on forest sites. Front. Ecol. Environ. 9 (2), 117–125.

Thorn, S., Bässler, C., Brandl, R., Burton, P.J., Cahall, R., Campbell, J.L., Castro, J., Choi, C.-Y., Cobb, T., Donato, D.C., Durska, E., Fontaine, J.B., Gauthier, S., Hebert, C., Hothorn, T., Hutto, R.L., Lee, E.-J., Leverkus, A.B., Lindenmayer, D.B., Obrist, M.K., Rost, J., Seibold, S., Seidl, R., Thom, D., Waldron, K., Wermelinger, B., Winter, M.-B., Zmihorski, M., Müller, J., 2018. Impacts of salvage logging on biodiversity: a meta-analysis. J. Appl. Ecol. 55 (1), 279–289.

Trasobares, A., Mola-Yudego, B., Aquilué, N., Ramón González-Olabarria, J., Garcia-Gonzalo, J., García-Valdés, R., De Cáceres, M., 2022. Nationwide climate-sensitive models for stand dynamics and forest scenario simulation. For. Ecol. Manag. 505, 119909.

Unkule, M., Piedallu, C., Balandier, P., Courbaud, B., 2022. Climate and ungulate browsing impair regeneration dynamics in spruce-fir-beech forests in the French alps. Ann. For. Sci. 79 (1), 11.

Václavík, T., Kanaskie, A., Hansen, E.M., Ohmann, J.L., Meentemeyer, R.K., 2010. Predicting potential and actual distribution of sudden oak death in Oregon: prioritizing landscape contexts for early detection and eradication of disease outbreaks. For. Ecol. Manag. 260, 1026–1035.

Walters, C.J., 1986. Adaptive Management of Renewable Resources. Collier Macmillan, New York, NY.

Watts, K., Whytock, R.C., Park, K.J., Fuentes-Montemayor, E., Macgregor, N.A., Duffield, S., McGowan, P.J.K., 2020. Ecological time lags and the journey towards conservation success. Nat. Ecol. Evol. 4 (3), 304–311.

White, P.S., Jentsch, A., 2001. The search for generality in studies of disturbance and ecosystem dynamics. In: Esser, K., Lüttge, U., Kadereit, J.W., Beyschlag, W. (Eds.), Progress in Botany: Genetics Physiology Systematics Ecol. Springer Berlin, Heidelberg, pp. 399–450.

Williams, K., Westrick, L.J., Williams, B.J., 2006. Effects of blackberry (*Rubus discolor*) invasion on oak population dynamics in a California savanna. For. Ecol. Manag. 228 (1), 187–196.

Yachi, S., Loreau, M., 1999. Biodiversity and ecosystem productivity in a fluctuating environment: the insurance hypothesis. Proc. Nat. Acad. Sci. USA 96, 1463–1468.

Yelenik, S., Perakis, S., Hibbs, D., 2013. Regional constraints to biological nitrogen fixation in post-fire forest communities. Ecology 94 (3), 739–750.

Zhang, C., Li, J., Zhou, Z., 2022. Ecosystem service cascade: concept, review, application and prospect. Ecol. Indicat. 137, 108766.