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Editorial

Virtual Special Issue “Advances in forest hydrology in the light of land use change and disturbances”

1. Introduction

Forests are recognized as primary regulators of the hydrological cycle: they cover over four billion hectares, more than one third of the world’s land surface, and return more than 60000 km^3 of water to the atmosphere through transpiration each year (Wang-Erlandsson et al., 2014). Forest canopy architecture influences atmospheric turbulence, albedo, and mixing of water vapour, thus controlling transpiration and evaporation processes. Forests provide many hydrological benefits and ecosystem services, including favoring rapid infiltration, increasing soil moisture storage capacity, reducing rates of surface erosion and sediment transport, and moderating the effect of precipitation on hydrological responses and flood generation (Keleş, 2019). Forests modify microclimates, stabilizing the temperature of soils and surface waters (Moore et al. 2005), and tree roots influence the redistribution of water within the soil profile and add to slope stability in steep terrain (Schwarz et al., 2010). Forests exhibit unique biogeochemical processes, affecting element cycling and the export of carbon and nutrients from forested catchments. Linking hydrological sciences and forest ecology is therefore the foundation for sustainable and integrated catchment management in forest-dominated ecosystems, even more so in the light of rapid global change. Interactions between forests and their water and energy budget are vital for the distribution of water resources, with important implications for planning and management efforts.

Forest loss is occurring globally, particularly in the tropics. Northern latitudes and large areas of Southern and Eastern Asia are experiencing increased greening due to afforestation and woody encroachment. Disturbance events, including catastrophic fires and drought mortality are impacting forests in places once thought to be secure from such change (e.g., McDowell et al. 2018; Andrus et al 2021). These forest cover dynamics are superimposed on and contribute to climate change and expected frequent weather extremes. The impacts of intersecting land cover and weather variability on the water budget, hydrological regime, and ecosystem services remain poorly understood, as do appropriate and effective measures to mitigate or adapt to these changes.

2. Aim and content of the Virtual Special Issue

This Virtual Special Issue (VSI) “Advances in forest hydrology in the light of land use change and disturbances” was formed to promote research and improve understanding of the effects of forest cover change and forest disturbance on catchments’ hydrological response. The VSI aimed to synthesize the current state of knowledge about physical and biogeochemical processes linking forests to water and how these interconnected systems respond to disturbance and change. The VSI also aimed to highlight new evidence and observations relating knowledge gaps about the role of forests in the water cycle under rapidly changing conditions. The 29 contributions made to the VSI are process-oriented and address the feedbacks linking land use change and disturbances to the hydrological cycle (Fig. 1). They address hydrology, ecohydrology, and ecosystem services across three emergent themes:

1) Quantification of evapotranspiration, transpiration, and analysis of stand-scale processes
2) Effects of land-use and land-cover changes on runoff generation and prediction
3) Disturbance effects, feedbacks, and management implications

The contributions made under each of these themes are summarised in the next sub-sections.

2.1. *Quantification of evapotranspiration, transpiration, and analysis of stand-scale processes*

Transpiration and evapotranspiration are critical hydrological processes in forests, where they couple the hydrological cycle with plant health and water status. Improved transpiration models can enable better understanding of these processes. Komatsu and Kome (2020) provided a review focusing on the historical development of numerical models that predict changes in evapotranspiration associated to forest management (e.g., clearcutting and thinning). The two authors moved from the description of modelling approaches developed in the 1990′s for applications at large scales, such as to assess the impact of forest cover change on the water cycle, to small-scale models used as research tools to investigate the role of forest vegetation on hydrological processes but with limited usefulness for forest managers, to later models created for management applications to a given area. Komatsu and Kume (2020) concluded stating that the primary role of forest hydrology studies in this era is to detect emerging environmental challenges and then develop practical models for connecting different stakeholders for collective policy and decision making.

Along this line, Liu et al. (2019) combined a process-based evaporation model with an empirical, modified Jarvis-Stewart model to simulate transpiration under different levels of soil water deficit. The combined model was tested for subtropical humid and Mediterranean climates, and on daily and hourly resolutions. The hybrid model performance was superior to that of the process-based model alone when

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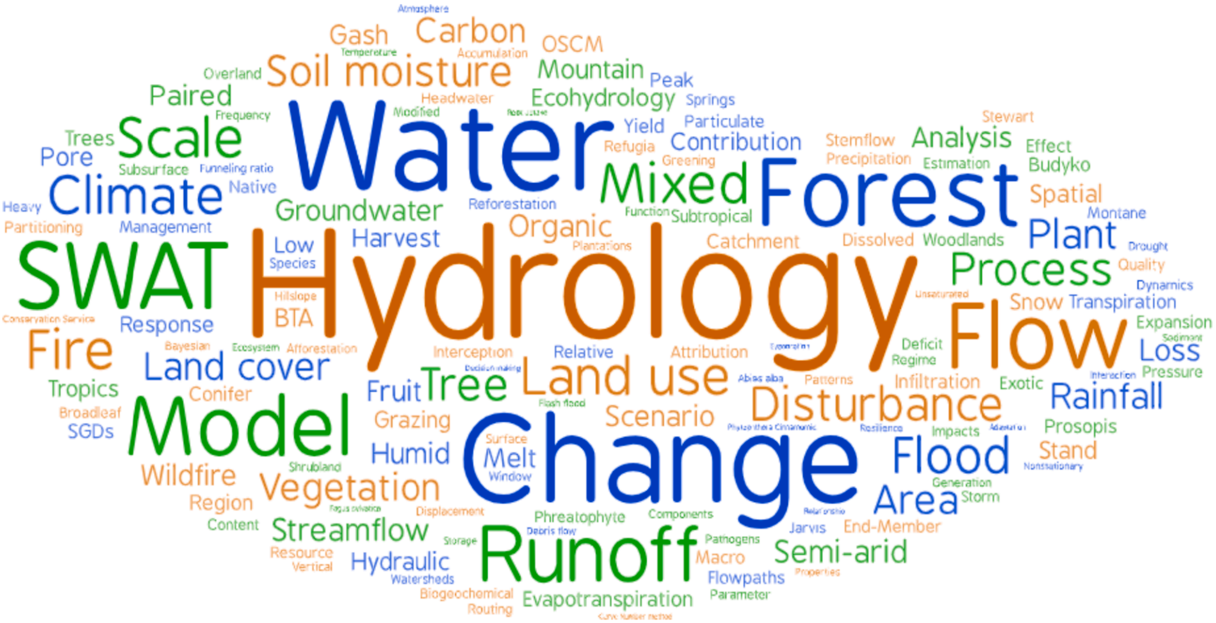

Fig. 1. Word cloud based on the keywords reported by the papers included in the VSI. The word size is proportional to the times that word was reported. The names of the study areas were excluded.

simulating transpiration under different levels of soil water deficit, and was more robust than the purely empirical model in selecting appropriate water stress functions.

Wang et al. (2020) investigated the water-energy cycle response to land use and land cover change in an agro-pastoral ecotone in China through a modelling approach. They quantified evapotranspiration in the period 1993–2010 showing that grassland expansion reduced land surface temperature, which in turn delayed seed germination and the onset of vegetation growth in spring. Increases in seasonal evapotranspiration rates and precipitation decreases affected soil dryness, exacerbating the risks of summer drought (Wang et al., 2020).

Meng et al. (2020) evaluated the effect of large-scale afforestation programs in the arid and semi-arid areas in northern China on the regional hydrological cycles using remote sensing products and the Variable Infiltration Capacity model. They found that increased precipitation (climate change) caused greater changes to the hydrological cycle than afforestation over the 2000 to 2015 study period. However, the hydrological cycle was sensitive to afforestation at small-catchment or sub-regional scales. This discrepancy highlights ongoing difficulties in understanding the scaling behavior of evapotranspiration and its sensitivity to land cover.

In addition to modulating transpiration and evaporation fluxes, forest canopies alter the propagation of precipitation fluxes to the soil surface through interception and stemflow. Belowground, the diversity of plant species leads to interacting, species-specific water use strategies. Some disturbances specifically alter plant canopies and the fluxes they determine. For example, Wei et al. (2020) evaluated how rainfall interception changed following a destructive ice and snow storm in southern China. Rainfall partitioning into throughfall and stemflow were measured and interception losses were modelled. They found that the vegetation leaf area index doubled in the four years after the ice storm, decreasing throughfall and increasing interception, until the interception capacity in the study plots was fully recovered after 5–7 years.

A fraction of intercepted water forms stemflow which is important in forested ecosystems because of its greatly concentrated input at the base of tree stems. Zhang et al. (2020) evaluated the funnelling efficiency (stemflow funnelling ratio) of individual trees at the stand scale for *Quercus acutissima* and *Broussonetia papayrifera* trees in a subtropical deciduous forest. They found that funnelling efficiency was variable across individuals but overall significantly higher for *B. papyrifera* than *Q. acutissima*. For individual trees, projected crown area and diameter at breast height were the two most important factors controlling the funnelling efficiency. At the stand scale, gross precipitation, rainfall duration, and vapor pressure deficit explained most of the variation in funnelling efficiency for both species.

Magh et al. (2020) investigated water use strategies of mature stands of European beech trees (*Fagus sylvatica*) with and without co-cultivation of silver fir trees (*Abies alba*), using a combination of sap flow analysis, water stable isotope labelling, and a simple mixing model. During times of drought, both beech and fir trees displayed high water use plasticity, shifting their water uptake to deeper and moister soil layers. This shift was sufficient to meet the transpiration demand of firs, but not of beech trees. Upon the restoration of soil water supplies, beech trees in monospecific stands were able to recover in terms of the volume of water uptake from shallow soil layers and sap flow rates. In the mixed stand, beech trees were not able to successfully compete with fir trees for water. Thus, the facilitative effect of silver fir on water relations of beech trees, was disrupted by drought resulting in competition for water resources (Magh et al., 2020).

2.2. Effects of land-use and land-cover changes on runoff generation and prediction

This topic covers the largest number (14) of papers in the VSI. The effects of vegetation removal and of afforestation on water quantity and quality, although the subject of study for decades, remain challenging to predict and important to measure for both scientific and operational purposes. One challenge in these predictions is that removing or replacing vegetation alters many hydrological processes, which can confound each other. For example, Peña-Arancibia et al. (2019) considered how forests can act as “pumps” (evapotranspiration fluxes) and as “sponges” (enhanced soil infiltration capacity and moisture retention). Overall hydrological change due to altering forest cover in tropical catchments therefore depends on the extent to which each of these functions is altered. Based on a grid-based land surface hydrological modelling approach, they showed that forest removal increased mean annual streamflow but decreased stream runoff during the dry season. The magnitude of the change depended on pre- and post-forest removal surface conditions and groundwater response times (Peña-

Arancibia et al., 2019).

By contrast, Liu et al. (2020) assessed the effect of reforestation and fruit tree planting on catchment-scale water resources in a subtropical region in China. Neither reforestation nor fruit tree planting had significant effects on total streamflow, but reforestation increased baseflow and fruit tree planting increased surface runoff. Both forms of land cover change amplified hydrological variability – on baseflow and surface runoff respectively – relative to climatic variability alone.

Using data from 663 globally-distributed catchments, Luo et al. (2020) quantified the impact of vegetation change on surface runoff based on the Budyko framework over a period of more than 30 years. They found that, on average on the Earth over the last three decades, changes in satellite-derived leaf area index, precipitation, and potential evapotranspiration produced modifications in surface runoff from −15% up to 15.5%. In arid zones subject to intense revegetation, increases in leaf area index led to substantial declines in surface runoff exceeding changes induced by climate change. Additionally, they found that hydrological partitioning was most sensitive to vegetation changes in catchments with a drier climate and lower soil water holding capacity (Luo et al., 2020).

Similarly, Gomes et al. (2021) used the SWAT model to assess the contribution of changes in weather patterns, land use, and land cover on the water cycle components in a Brazilian catchment between 1990 and 2015. Their results highlighted the major role played by changes in climate pattern on historical water dynamics on the study catchment, resulting in increases in surface runoff and streamflow, attributable to marked decreases in evapotranspiration. Additionally, they investigated the future effect of two contrasting land use and land cover scenarios on the hydrology of the catchment, finding that the increase in forest cover of one scenario will produce a decrease in surface runoff and in water yield, favouring water infiltration and soil erosion control, and buffering against extreme precipitation events (Gomes et al., 2021).

A similar modelling approach was adopted by Hu et al. (2021) to identify the spatial variability of the hydrological response to land use and land cover changes over the 1980–2010 period in different regions of the largest subcatchment of the Yellow River basin, in China. They quantified the decline of cropland and the corresponding increase in forest and grassland areas as well as the dramatic expansion of urban areas. Their simulations revealed that land use and land cover changes lead to a marked decrease in streamflow and an increase in soil water content, but to negligible alteration of evapotranspiration rates. These authors also showed that land use conversions of cropland to grassland or forest resulted in negative effects on soil water content and streamflow, and that the change in evapotranspiration was only visible in areas where cropland on steep slopes (>15°) was converted to grassland or forest (Hu et al., 2021).

The SWAT model was also used by Galleguillos et al. (2021) to assess whether adaptive plantation strategies could mitigate the impacts of climate change and increase streamflow in a catchment in central Chile. They analysed five different scenarios of land use and land cover changes based on current climate conditions and various climate projections showing variations in mean annual streamflow up to −46%. They concluded that afforestation with exotic pines has the potential to intensify the reduction in streamflow, whereas conservative scenarios focused on native forests protection and restoration could partially mitigate the effect of climate change (Galleguillos et al., 2021).

Zhao et al. (2021) investigated the effects of long-term land cover change on hydrological processes in an experimental catchment in Idaho (USA) from 1991 to 2013 through a modelling approach. Their results revealed the strong impacts of timber harvest on increasing streamflow and peak flow, with an average increase of 20% in soil saturation degree after timber harvest making the area prone to high flooding risk during large rainfall events. The authors also simulated three logging scenarios, showing that logging areas had a positive relationship with water yield, and that clearcutting on south-facing slopes strongly augmented the average melt rate leading to potential flooding when temperatures increased. Moreover, their simulations also showed that partial cutting in areas with low probability of runoff generation would reduce peak flow amount by 40% (Zhao et al., 2021).

Birch et al. (2021) used end-member mixing analysis based on stream chemistry to assess possible differences in water pathways related to land cover and land use in humid tropical catchments in Panama. They analysed several storm events in a mature tropical forest, a young secondary tropical forest, and a cattle pasture. Their results revealed that lateral preferential flow within the top 30 cm of the soil profile was a dominant process for runoff generation in the two forested catchments, whereas runoff was a combination of infiltration-excess overland flow (with runoff contributions up to 62%) and lateral subsurface flow in the grazed pastoral catchment (Birch et al., 2021).

Analogously, Bukoski et al. (2021) used stream chemistry (including dissolved organic carbon), performed hydrograph separation, and analysed concentration-runoff relationships to investigate the major runoff generation processes and address the relationship between land use and water flow pathways in low-elevation foothills and montane catchments in Colorado (USA). They inferred transition from shallow subsurface flowpaths to deeper subsurface flowpaths as seasonal runoff decreased in the three foothill catchments. Moreover, they observed large concentration in certain ions in two catchments during baseflow periods and related them to the impact of past and/or current anthropogenic activities, such as mining, application of road salt, and/or near-stream septic systems. These activities also affected runoff generation, as revealed by faster runoff responses and surficial flowpaths in a catchment with anthropogenic and geologic impervious surfaces compared to a less disturbed neighbouring catchment (Bukoski et al., 2021).

Safeeq et al. (2020) aimed at better understanding the relation between sediment yield and streamflow following forest timber adopting the paired catchment approach in the well-studied H.J. Andrews Experimental Forest (Oregon, USA) to reconstruct a prior harvesting streamflow time series for the treated watershed. These authors used the streamflow-sediment yield relation to evaluate the effect of changes in hydrology and sediment supply. Their findings showed that increases in streamflow accounted for small increases in sediment transport, but that the increased supply of sediment that accompanies timber harvest minimized this effect (Safeeq et al., 2020).

To understand whether the hydrological functioning of heterogeneous mountainous catchments in tectonically active regions can be simulated by simple runoff models with a runoff-storage power-law relationships, Tani et al. (2020) conducted numerical experiments using soils of different hydraulic properties. They found the outflow rate was dependent on the total storage only in the unsaturated zone. This might result in a low sensitivity of discharge to the heterogeneities of soil hydraulic properties, while storm-runoff responses would be more sensitive to vertical unsaturated flow processes.

Regarding the link between forests and flood generation and prediction, McEachran et al. (2021) designed new non-stationary flood-frequency analysis methods with Bayesian parameter estimation to examine the effect of harvesting and forest regrowth on discharge peaks. For their analysis, they could rely on data from two long-term, paired catchment experiments in the boreal-temperate transition zone in Minnesota (USA). Their results indicate that clearcutting led to increases in the maximum peak flow for almost all return intervals of peak flows. Harvesting also resulted in a pronounced decoupling of events, i.e., the control catchment showed its annual peak discharge in response to a different event as compared to the harvested catchment. This points to a fundamental change of hydrologic response as a consequence of removing the forest vegetation. Upon forest regrowth, the degree of event decoupling between control and treatment catchment decreased again, suggesting a rebound to pre-harvest conditions.

Nainar et al. (2021) investigated the effects of forest type on runoff characteristics in two steep headwater catchments, in the context of water supply and flood generation. The study area was characterized by a warm temperate climate with high year-round rainfall and a typhoon season. The aim was to identify if there were differences in hydrologic response between the managed coniferous forest catchment and the unmanaged secondary mixed-broadleaf forest catchment. In contrast to common perceptions, the managed plantation forest did not show substantially different hydrologic response with respect to runoff coefficients or peak discharges. The authors concluded that managed forested headwater catchments do not necessarily have negative impacts on water supply and flood generation and can provide hydrological functions similar to unmanaged forests.

The final paper in this topic explored the hydrological response of invisible subsurface displacement in a natural forested headwater in Taiwan (Liang, 2020). Using field observations over two years after subsurface displacement, the author found an increased maximum pore water pressure but reduced increasing rate of pore water pressure. Both the level and increasing rate in peak runoff were also reduced. Liang (2020) also found that subsurface displacement modified the response time such that the maximum responses in pore water pressure and runoff tended to occur earlier than maximum rainfall during the period after displacement.

2.3. Disturbance effects, feedbacks, and management implications

Eight papers addressed disturbance events specifically, most considering the impacts of wildfire on catchment hydrological behaviours. Loiselle et al. (2020) incorporated an in-stream Organic Carbon Simulation Module into the Soil and Water Assessment Tool (SWAT-OCSM). Based on model simulations, they examined the effects of climate change and wildfire on water budget, sediment, and organic carbon under different climate change and wildfire scenarios in a Canadian catchment. They found that surface runoff, sediment load, and total organic carbon export all increased when wildfire and climate change were imposed. The burn severity invoked a stronger catchment response than burnt area.

Based on seven-year post-fire measurements of soil water infiltration, Ebel (2020) examined the temporal recovery of infiltration and soil-hydraulic properties following fire disturbance in the Colorado Front Range (USA). He found that infiltration increased monotonically with increasing time since fire, suggesting a reduced vulnerability to infiltration-excess runoff generation (and floods) as time passed. His findings highlight the need to consider dynamic hillslope properties during the post-fire recovery period when modelling catchment hydrological behaviors following fire events.

Ma et al. (2020) examined the impacts of wildfires on vegetation water use across the California's Sierra Nevada (USA) using satellite-based evapotranspiration estimates. Their results show that evapotranspiration was reduced by an average of 36% in the first year after fire. Evapotranspiration was suppressed for at least 15 years post-fire, and its reduction was most dependent on pre-fire canopy density and burn severity.

Also in the Sierra Nevada (USA), Rakhmatulina et al. (2021) assessed the effects of future climate change and fire use strategies that restored natural fire regimes on hydrology using an ecohydrological model forced with downscaled climate projections. They found that the hydrological outcomes of fire use strategies under future climate scenarios were similar to those under the current climate. Specifically, they found that restoring wildfire would decrease catchment-scale evapotranspiration and increase streamflow in a warmer future climate, similar to inferred actual changes in the late 20th century.

Tsinnajinnie et al. (2021) examined whether the presence of springs mitigated the impacts of wildfires in semiarid, mountainous catchments. Their results demonstrate that (i) springs buffered the impact of wildfires by providing soil moisture that protects buds, roots, and seed banks, and (ii) springs promoted revegetation after fire disturbances. These findings highlight that springs offer particular benefits to postfire restoration.

Two papers examined the ecohydrological effects of partial vegetation removal due to human activities in arid/semi-arid ecosystems. With respect to other types of disturbances and implication for water and forest management, Souza et al. (2020) developed a coupled soil water balance, vegetation, and cattle biomass model to explore an optimal cattle grazing management strategy in a Brazilian dry tropical forest under rainfall fluctuations. Cattle grazing considerably reduced vegetation biomass. The maximum animal weight gain increased with total rainfall volume, and under scenarios rainfall events were more evenly distributed during the year. Forecasting dry spells could help farmers to planning grazing management strategies in these dry forest environments.

Similarly, focusing on interdunal woodlands in the Monte Desert in Argentina, Meglioli et al. (2021) evaluated the consequences of livestock grazing on shallow groundwater dynamics and vertical solute transport, based on six-year in situ observations. Seasonal water table fluctuations were reduced in the presence of livestock, which also were associated with increased salinity, chloride, and nitrate concentrations. Livestock seemed to increase recharge rates and nitrate leaching to the aquifer.

Understanding flow processes not only improves the accuracy of flood prediction, but also improves the prediction of expansion of pathogens that affect the composition and function of forests. Plant pathogens can affect forest composition, structure, and function but the dynamics of these disturbances are not well understood. Wilkening et al. (2021) used a numerical model of pathogen growth and dispersal to investigate the importance of pathogen transport in intermittent surface runoff compared to more continuous rhizosphere pathogen spread via diffusion-like hyphal growth. By comparing two well-studied sites with deep sandy soil and shallow soil on steep terrain, they showed the importance of saturation excess overland flow for the spread of plant pathogens.

3. Future research directions

Land and water managers in the coming decades face difficult choices regarding the management of forests. Climate changes will impose stresses upon trees and on water supplies, and these changes will produce and interact with more extreme forms of disturbance, whether wildfires, pathogens, or mortality events. In response, managers have an array of tools to deploy within forests - clearing, thinning, selective removal or planting of species, fire use, afforestation, and conservation. They also have access to a series of water management strategies including the storage and allocation of water resources, as well as increasingly engineered water systems incorporating water recycling, water harvesting, or managed aquifer recharge/replenishment. In the context of rapid change, predicting the effects and interactions of these management strategies, and understanding how they differ from a status quo treatment, is essential. Even if a management action is taken for non-hydrological purposes – e.g., selective forest thinning to reduce wildfire risks – knowing the hydrological implications is often essential for building the economic and social argument for the intervention. For example, thinning may be more economically viable if both fire hazard mitigation and additional surface water supply/recharge are factored in.

Thus, the knowledge imparted by the studies in this VSI has both operational and scientific merit. Yet some issues remain difficult to understand. A general theory of how plant mediated water fluxes respond to different disturbance remains elusive. While reducing leaf area can confidently be predicted to increase throughfall, decrease transpiration, and increase bare soil evaporation, the magnitude of the net resulting change in water storage and flow production is highly dependent on the relative sizes of each of these changes. The role of multiple plants in facilitation and competition for water is highly dynamic and also remains difficult to predict. Thus, the papers in this VSI illustrate contrasting effects of afforestation and deforestation in different contexts, and show that interactions between species can change before and after the imposition of disturbance. Some of these issues are likely to be illuminated by emerging collaborative efforts between hydrologists, ecophysiologists, and micrometeorologists. Other issues, however, will require new efforts to bridge disciplinary divides – in particular to embrace and engage with community ecology and frameworks for understanding responses to disturbance that emerge across multiple interacting individual organisms and species. This connection is likely to become increasingly important as hydrologists confront more frequent and extreme disturbance. The importance of plant cover type in mediating climatic variations and their influence of hydrological outcomes is evident in the VSI. The more frequent and extreme disturbance events are, the more likely that forest ecosystems will change in ways both subtle and extreme. How will the hydrology change in a fire-disturbed catchment that converts from a forest to a shrubland at the same time as the climate dries? What if the fire selectively eliminates deep rooted tree species while shallow rooted species remain? While the answers to these questions may be knowable, forecasts and predictions need to factor in the timing and probability of such changes occurring. This kind of task has so far been confronted by community ecologists, but a dialogue between water management and these predictions needs to be established.

Forest disturbance is multidimensional, ubiquitous, and increasing. Forests are an indispensable component of the global biosphere and hydrosphere. Confronting the physical, biotic, and ecological consequences of disturbance and pathways of recovery is essential for weighing up the human actions that will best mitigate the effects of disturbance and adapt to their consequences.

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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