https://doi.org/10.17221/19/2026-JFS

Hydrological risks of clear-cuts after bark beetle outbreaks and related forest management decisions in Central Europe

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Citation: Šrámek V., Neudertová Hellebrandová K., Fadrhonsová V. (2026): Hydrological risks of clear-cuts after the bark beetle outbreak and related forest management decisions in Central Europe. J. For. Sci., 72: 161–173.

Abstract: The review synthesises current knowledge on the hydrological and hydrochemical risks associated with large-scale clear-cutting following unprecedented bark beetle outbreaks in Central Europe. By analysing 107 sources published primarily between 2000 and 2026, we evaluate the divergent impacts of natural forest dieback versus intensive salvage logging. The rapid loss of Norway spruce [*Picea abies* (L.) Karst.] canopy has fundamentally altered the microclimate, shifting the energy balance from latent to sensible heat flux, which results in ground temperature increases of up to 5.2 °C. Hydrological consequences include a 16–48% reduction in interception and a cessation of transpiration, leading to an increase in annual water yield by 6–21% and potentially accelerated peak discharges, particularly in headwater catchments where maximum flows can increase by over 50%. The synthesis highlights a critical 'nitrate pulse' exceeding 50 mg·L^{-1} in managed areas, contrasting with higher hydrochemical resilience in unmanaged stands. We emphasise that forest management must ensure sufficient soil protection during the logging and wood transportation, which can reduce hydraulic conductivity by over 40%. The role of logging residues is important because they cover and protect the soil environment. The study concludes that utilising pioneer species and spontaneous succession in combination with timely artificial reforestation represents a superior strategy for stabilising the microclimate and restoring hydrological functions.

Keywords: catchment management; ecohydrology; forest disturbance; *Ips typographus*; microclimate buffering; nitrogen leaching; salvage logging; soil compaction

INTRODUCTION: CLEAR-CUTTING AND BARK BEETLE OUTBREAK

Clear-cutting is a traditional forestry practice that has been used for decades, or even centuries, in even-aged forest stand management, most often in single-species monocultures (Paquette, Messier 2010). Although the system is highly productive and relatively easy to manage, it brings with it certain ecological risks in the form of altered microclimate, which can complicate forest restoration (Hashimoto, Suzuki 2004; Chojnacka-Ożga et al. 2019) reduce biodiversity (Lunde et al. 2025), or, in the long term, even undermine the sustainability of forest ecosystems. Consequently, the size of clear-cuts in individual European countries is lim-

Supported by the National Agency for Agricultural Research, Czech Republic (Project No. QK22010189) and by the Ministry of Agriculture of the Czech Republic (Institutional support MZE-RO0123).

https://doi.org/10.17221/19/2026-JFS

ited by national legislation – in the Czech Republic, it is < 1 ha; in Germany < 1.5 ha, with certain differences in individual federal states; in Austria < 2 ha (with permission required above 0.5 ha); and in Slovakia < 3 ha. Furthermore, the width of a clear-cut is often limited, for example, to one or two heights of the adjacent forest stand. In recent decades, less intensive forestry practises have been favoured in many regions as a response to climate change and declining biodiversity (Puetmann et al. 2015). Conversely, the unprecedented bark beetle outbreak of 2015–2022, which affected to varying degrees Central European Norway spruce forests, led to salvage logging on thousands of hectares, creating clear-cuts with areas far exceeding standard legislative limits. The situation in forestry has changed dramatically in the last decade, presenting numerous challenges for foresters and forest administration including the potential hydrological impacts in affected regions (Das et al. 2025).

Bark beetle outbreaks have historically followed the large-scale windthrow events, endangering Norway spruce [*Picea abies* (L.) Karst.] stands where the damaged trees were not processed in time (Mezei et al. 2014). For example, Schelhaas et al. (2003) reported that the bark beetle caused as much as 8% of all tree mortality due to natural disturbances in Europe between 1850 and 2000. The situation, however, was different during the most recent outbreak, which started in 2015 and accelerated sharply in 2018 due to warm and dry periods during the respective growing seasons (Zahradník, Zahradníková 2019; Hlásny et al. 2021).

In the Czech Republic, registered salvage felling due to bark beetle infestation reached a record volume of 3 million m^3 in 2016 (Figure 1). The total for the years 2018–2020 was 37.74 million m^3, which is significantly more than what was registered for the entire 1990–2015 period (30 million m^3) (Lubojacký et al. 2025). In the 2018–2023 period, the bark beetle outbreak in the Czech Republic led to the formation of more than 200 000 ha of clear-cuts (Křístek et al. 2024).

Similar development has been observed in other Central European countries (Patacca et al. 2023; Hartmann et al. 2025; Hlásny et al. 2025). Although the peaks and progression of the outbreak may vary among individual regions due to climatic differences, forest structure and the implementation of forest protection measures, the overall impact remains severe. Thonfeld et al. (2022) identified a canopy cover loss of 501 000 ha across Germany in 2018–2020, out of which 295 000 ha represent clear-cuts requiring reforestation. In Austria, Hallas et al. (2024) described two independent bark beetle outbreaks – the first began in 2015 and peaked in 2018 in low-altitude Norway spruce stands, while the second started in 2021 in mountainous Alpine forests. The spread of the bark beetle in the Białowieża Forest in Poland is documented by Carr et al. (2025).

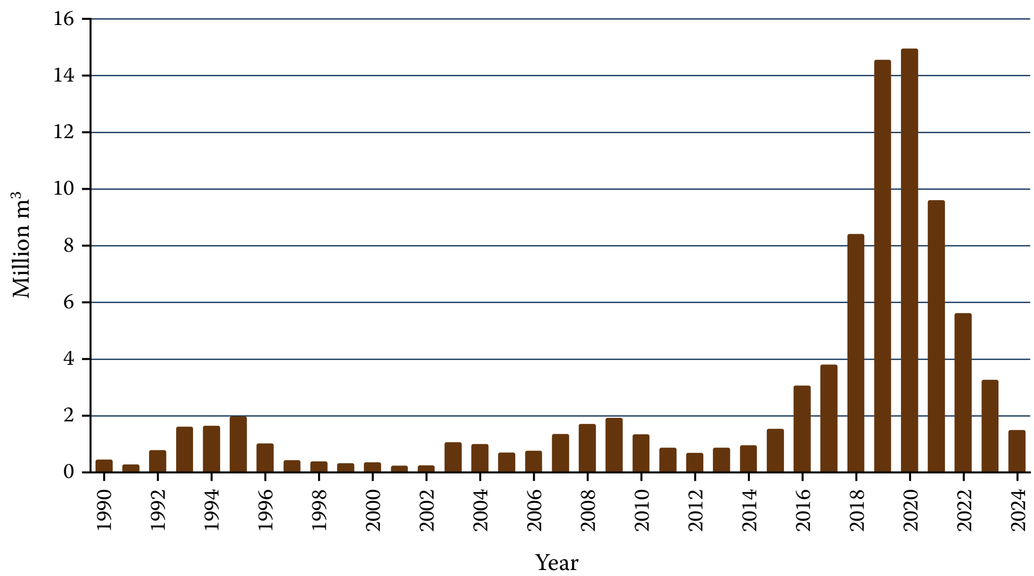

Figure 1. Development of registered salvage felling due to bark beetle infestation in the Czech Republic (adapted from Lubojacký et al. 2025)

https://doi.org/10.17221/19/2026-JFS

METHODS

An extensive literature search was conducted to synthesise current knowledge regarding the environmental consequences of bark beetle outbreaks and subsequent forest management interventions. The primary search was performed using academic databases including Web of Science, Scopus, and Google Scholar. The search strategy utilised combinations of core keywords related to the disturbance agent (e.g. bark beetle, *Ips typographus*), the applied management strategy (e.g. clear-cut, salvage logging, spontaneous succession) and the targeted environmental variables (e.g. microclimate, hydrology, runoff, water quality). While works on the topics of microclimate and water balance in clear-cut areas have been appearing continuously in the last thirty years, the number of works focused on bark beetles has increased significantly in connection with the recent outbreak (Figure 2).

The selection of studies was guided by predefined inclusion criteria to ensure regional and topical relevance. We focused primarily on: (*i*) research conducted in Central European temperate forests, particularly mountain and highland catchments; (*ii*) peer-reviewed original research articles, meta-analyses, and highly relevant review papers; and (*iii*) literature published predominantly between the years 2000 and 2026, a period that adequately captures both recent unprecedented disturbance events and modern mechanised harvesting practices. While the regional focus of the synthesis targets Central European temperate forests, fundamental mechanistic studies from other biomes (e.g. boreal or subtropical catchments) were selectively included to contextualise general ecohydrological principles.

Following the initial screening of titles and abstracts, the full texts of relevant papers were evaluated. A total of 107 sources were ultimately selected for the final review. They mostly include articles in international scientific journals (95), supplemented to a small extent by scientific articles in national languages (7), local studies (3) and books (2). The extracted findings were categorised into thematic clusters corresponding to the structure of this paper: (*i*) microclimatic alterations and energy balance, (*ii*) hydrological processes and runoff generation, (*iii*) hydrochemical responses and water quality, and (*iv*) influence and role of forest management practices.

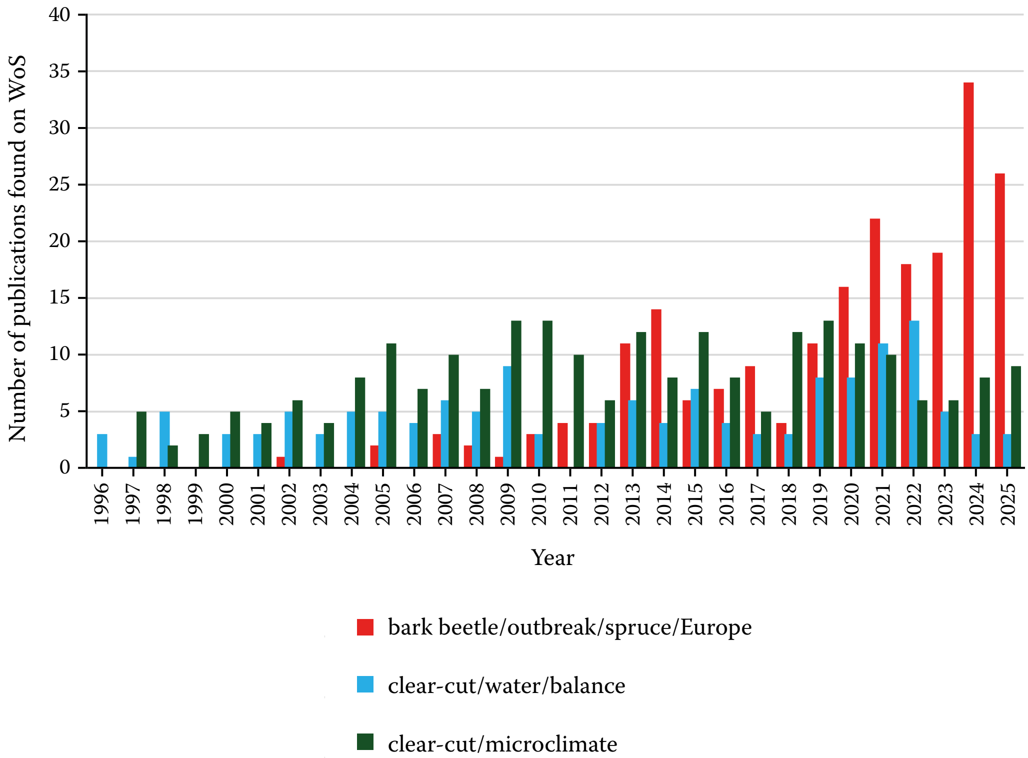

Figure 2: Number of publications found on the Web of Science (WoS) in the last thirty years focused on bark beetle outbreaks, microclimate and water balance on clearcuts (the exact wording used for the search is given in the legend)

https://doi.org/10.17221/19/2026-JFS

LOSS OF TREE CANOPY COVER AS A GAME CHANGER OF (MICRO/MESO)CLIMATE

Forest ecosystems regulate their local microclimate while simultaneously influencing meso-climate and even global climate patterns (Pearce 2020; Ellison et al. 2017). This regulatory function is closely connected to the partitioning of water fluxes within the canopy (Van Stan et al. 2020). Forest canopy interception and evaporation can reach up to 30% of total precipitation (Jančo et al. 2021). However, in evergreen coniferous species such as Norway spruce, it can exceed 50% (Krečmer et al. 1981; Šrámek et al. 2019), the process is partially modulated by forest management practices, such as thinning (Grunicke et al. 2020). Concurrently, tree transpiration extracts water from the entire soil profile, significantly surpassing the evaporative demand of ground vegetation under humid conditions. During drought, however, this flux is tightly constrained by reduced stomatal conductance (Sperry, Love 2015; Frank et al. 2015; Brodribb et al. 2020). For instance, Meusburger et al. (2022) demonstrated that during the extreme droughts of 2015 and 2018, Swiss forests actively down-regulated transpiration by 23% in response to decline of soil water potential in the root zone.

The sudden loss of the forest canopy following bark beetle outbreaks represents a regime shift in the site's energy and water balance. The cessation of interception and transpiration initially increases water availability for surface runoff and ground vegetation (Bearup et al. 2014; Šach et al. 2014; Šrámek et al. 2025). However, this is accompanied by an alteration in energy flux partitioning. In a closed-canopy forest, a substantial portion of incoming net radiation is dissipated via latent heat flux (evapotranspiration). The removal of the canopy cover rapidly redirects energy into sensible heat, triggering ground temperature increase (Gohr et al. 2021).

The magnitude of this microclimatic shift is influenced by the subsequent forest management strategy. The structural legacies of the outbreaks – standing dead trees in unmanaged forests – provide at least partial shading and buffer long-wave radiation exchange even after the canopy is entirely defoliated (Greiser et al. 2025).

In contrast, large-scale salvage logging removes this protective layer, exposing the forest floor to direct solar radiation. This sudden exposure severely alters the soil microclimate (Vichta et al. 2025).

Without the thermal inertia provided by standing or downed biomass, satellite and ground measurements confirm that clear-cut surfaces exhibit temperature increases of 3.5 °C to 5.2 °C compared to intact stands and consistently remain 2–4 °C warmer than adjacent unmanaged snag-forests (Hais, Kučera 2008; Hesslerová et al. 2018, 2022). This thermal extreme is not limited to the surface; Hashimoto and Suzuki (2004) demonstrated that post-harvest warming penetrates deep into the soil profile, increasing annual mean temperatures even at a depth of 3 m (by 1.4 °C).

This thermal instability initiates a feedback loop. The elevated temperatures accelerate the mineralisation of soil organic matter and drive the desiccation of the upper soil horizons, thereby complicating subsequent reforestation efforts (Zhang et al. 2020). Consequently, retaining biomass – whether as standing snags or downed coarse woody debris – operates not merely as a biodiversity conservation measure, but as a functional hydrological tool to maintain stand-level cooling and moisture retention (Přívětivý, Šamonil 2021).

Ultimately, these local microclimatic disruptions scale up to influence regional hydrology. The cooling effect of forests and high evapotranspiration rates are critical for continental moisture transport (Pearce 2020). While globally over 40% of precipitation originates from terrestrial evaporation, regions like China depend on the Eurasian continent for up to 80% of their rainfall (Van der Ent et al. 2010).

However, the role of forests in water cycling is strongly scale-dependent. On a local catchment scale, increased forest cover often correlates with decreased water supply due to high stand-level interception and transpiration (Gallart, Llorens 2003; Bennett, Barton 2018; Buendia et al. 2016). Recognising this inherent trade-off, the widespread conversion of transpiring forests into overheated clear-cuts nevertheless alters the spatial distribution of precipitation and regional climatic stability (Ellison et al. 2017).

CHANGE OF WATER BALANCE AND SOIL DAMAGES IN DEFORESTED CATCHMENTS

The effect of forest cover alterations on water yield in large watersheds (> 1 000 km^2) was syn-

https://doi.org/10.17221/19/2026-JFS

thesised by Li et al. (2017). Based on a sample of 162 catchments, they confirmed that deforestation consistently increases annual water yield, whilst afforestation decreases it. While forest cover and climate variability play co-equal roles in annual water yield variations, hydrological sensitivity to canopy loss is more pronounced in smaller and drier headwater catchments.

Empirical data from Central Europe confirm these models. In a specific regional study, Rajwa-Kuligiewicz et al. (2024) documented increased low (+14%), average (+8%) and maximum monthly outflow (+16%) after a catastrophic windthrow in the Western Tatra Mountains. Similarly, Hlásny et al. (2015) modelled increases in total runoff and surface runoff of 20.4% and 38.8% respectively, after simulated deforestation of the Ulička catchment (97 km^2) in eastern Slovakia.

Furthermore, the temporal distribution of runoff is altered; maximum flow was modelled to be 58% higher and occurred 54 minutes earlier in the deforested catchment compared to the fully forested baseline (Hlásny et al. 2015). Reinhardt-Imjela et al. (2018) reported a comparable impact of large-scale historical deforestation on flood magnitude, with 16.4% to 21.0% increase in peak discharge due to medieval deforestation in the Ore Mountains.

Brown et al. (2013) point out that hydrological responses to canopy loss vary significantly among individual catchments. This variability is largely driven by the subsequent management response to the disturbance. While intact forest cover naturally modulates water budget extremes and maintains minimal outflow during dry periods (Hall et al. 2022; Švihla et al. 2023), post-disturbance interventions determine how much of this regulatory capacity is preserved. For instance, Švihla et al. (2016) demonstrated that large-scale clear-cutting drastically reduces stand-level retention capacity, increasing total runoff by 8–12% while simultaneously increasing the risk of pronounced drought periods. On the other hand, Kopáček et al. (2020) reported only a 6% increase in runoff – without extreme peak flows or erosion – in the Plešné Lake basin following a severe bark beetle outbreak, compared to the intact catchment of Černé Lake. While the loss of the canopy layer alone theoretically increases the threat of erosion (Panagos et al. 2015) the rapid development of ground vegetation on the clear-cuts usually prevents significant soil loss (Matuszkiewicz et al. 2024). The risk of soil loss is increased when bark beetles spread after wind damage to forest stands and the soil is disturbed by uprooted trees (Schroeder, Lindelöw 2003; Lecina-Diaz et al. 2024).

A significant driver of post-disturbance hydrological degradation is the implementation of mechanised operations. Salvage logging, if not applied properly, may fundamentally alter the physical properties of forest soil (Cambi et al. 2015; Haas et al. 2020). Repeated traffic by heavy harvesters and forwarders during clear-cutting leads to severe soil compaction, characterised by increased soil bulk density and a reduction in total porosity, particularly macroporosity (Cambi et al. 2015; Nazari et al. 2021). A meta-analysis demonstrated that logging-associated compaction can reduce saturated hydraulic conductivity by over 40% (Nazari et al. 2021). The reduction in infiltration capacity transforms skid trails and heavily trafficked areas into preferential surface flow paths. Surface runoff generation multiplies several times on compacted skid trails compared to undisturbed forest soils, significantly elevating the risk of localised flash floods and soil erosion during heavy rainfall (Zemke et al. 2019). Consequently, the intensive mechanical disturbance during salvage logging acts synergistically with canopy removal to further accelerate water transport out of the catchment (Zemke et al. 2019).

IMPACTS ON WATER QUALITY

The hydrochemical response to bark beetle outbreaks is a dynamic process characterised by varying recovery trajectories, often influenced by the extent of forest cover loss and the underlying geology (Langhammer et al. 2015; Musolff et al. 2024). The transformation of forest stands into clear-cuts or standing deadwood triggers shifts in stream water chemistry, primarily driven by the decoupling of nutrient cycles and the alteration of hydrological pathways (Mikkelson et al. 2013). However, these effects cannot be easily generalised, as hydrochemical responses are often catchment-specific and may exhibit significant lag times depending on regional conditions (Schmidt et al. 2022).

The most critical immediate response, especially in coniferous and deciduous monocultures, is the 'nitrate pulse', resulting from the sudden cessation of nitrogen uptake by trees (Huber 2005). In the absence of biological demand and under condi-

https://doi.org/10.17221/19/2026-JFS

tions of increased soil temperature and moisture typical of clear-cuts, microbial mineralisation and nitrification are significantly stimulated (Rhoades 2019; Mupepele, Dormann 2016). Long-term monitoring in the Bavarian Forest has demonstrated that nitrate concentrations in seepage water can exceed 50 mg·L^{-1}, with elevated levels persisting for more than five years after the initial dieback (Huber 2005). Statistical modelling suggests that this response is non-linear, with nitrogen export accelerating sharply once a specific threshold of forest loss is exceeded (Jung et al. 2021). Furthermore, large-scale disturbances can trigger a long-term 'regime shift' in catchment biogeochemistry, where the ecosystem's capacity to retain nitrogen remains impaired for decades, regardless of initial forest recovery (Webster et al. 2016).

During this stage, the loss of canopy cover also alters runoff efficiency, leading to increased export of dissolved organic carbon (DOC) as upper organic soil layers are more intensively drained (Mikkelson et al. 2013). Beyond annual averages, the mobilisation of solutes is strongly intensified during episodic events; for instance, rising groundwater tables during snowmelt or heavy rainfall connect previously isolated soil nutrient pools directly to the stream network (Musolff et al. 2024; Gray et al. 2024).

Recent findings from Central European mountain catchments suggest that these hydrochemical impacts may be mitigated by specific local factors. Neudertová Hellebrandová et al. (2026) observed that in catchments with a lower proportion of clear-cut areas and rapid development of ground vegetation, the hypothesised substantial increases in DOC and nitrogen export may not materialise. This 'hydrochemical resilience' is often supported by the rapid expansion of understory species, which quickly replace the nutrient uptake capacity of the lost overstory and facilitate the rapid immobilisation of available nitrates within the developing biomass (Hedwall et al. 2015).

Furthermore, the export of base cations, such as calcium (Ca^{2+}) and magnesium (Mg^{2+}), during this period is driven primarily by lithology rather than by the disturbance event itself. Recent isotope studies (Novak et al. 2024) confirm that these fluxes are controlled by the dissolution of specific minerals, such as biotite for Mg^{2+} and plagioclase for Ca^{2+} and Sr (Novak et al. 2024; Neudertová Hellebrandová et al. 2026). While logging can cause a short-term increase in Ca^{2+}, Mg^{2+} and Na^{+} concentrations due to reduced plant uptake and accelerated decomposition, these levels typically return to pre-disturbance baselines within 4–6 years (Oda et al. 2011; Swank et al. 2014).

The magnitude and duration of this hydrochemical disturbance are highly dependent on the chosen management strategy: salvage logging versus leaving standing deadwood (snags). Mechanised salvage logging accelerates nutrient leaching and sediment transport in the initial years due to physical soil disturbance (Rhoades 2019). Conversely, leaving dead trees in situ may support a more gradual release of nutrients and maintain higher in-stream biodiversity by providing light and temperature shifts without the extreme sediment pulses associated with heavy machinery (McKie, Malmqvist 2009).

Over a decade post-disturbance, most catchments show a return toward hydrochemical baselines (Jung et al. 2021). However, the 'soil memory' of the exchange complex (reflecting decades of historical acidification) can lead to localised re-acidification episodes in sensitive, base-poor regions (Löfgren et al. 2014). Even in cases where annual nutrient budgets remain negative, episodic leaching events driven by hydrological flushes remain highly probable (Novak et al. 2024). In areas critical for human consumption, these processes represent a latent environmental risk, as increased DOC and nitrate can significantly complicate drinking water treatment and lead to the formation of harmful disinfection by-products (Winter et al. 2025).

MANAGEMENT OPTIONS TO MAINTAIN FOREST FUNCTIONS AFTER BARK BEETLE OUTBREAK

The most effective strategy to avoid the risks associated with large-scale clear-cutting is to avoid clear-cuts themselves. This requires not only traditional methods of forest protection – such as early detection, sanitary felling and sanitation of infested trees (Stadelmann et al. 2013), but, above all, the establishment of more resilient forest stands characterised by higher species, age, and structural diversity (Griess et al. 2012; Neuner et al. 2015). Forestry is, of course, a very long-term and therefore conservative discipline, and the current still-high share of even-aged coniferous monocultures with high growing stock sustains a high suscep-

https://doi.org/10.17221/19/2026-JFS

tibility to pest outbreaks, especially under ongoing climatic stress (Netherer et al. 2019; Kędziora et al. 2025).

Once a bark beetle outbreak occurs, microclimatic and hydrological disruptions can be partly mitigated by leaving dead trees *in situ* or by postponing logging for several years. (Valtera et al. 2025; Vichta et al. 2025). Conversely, leaving infested or dead trees without sanitation contributes to the future spread of bark beetles (which is illegal in many jurisdictions), causes economic loss for forest owners, increases fire risk (Beetz et al. 2024), and poses safety hazards to forest workers and visitors. For these reasons, salvage logging remains a common practice in productive forests.

When logging infested forests, management must prioritise the use of appropriate machinery that minimises damage to the soil surface (Cambi et al. 2015) as the intact physical structure of the soil is the main provider of hydrological functions after deforestation. Leaving individual broadleaved trees or viable coniferous trees can partially buffer the microclimate conditions on clear-cuts (Greiser et al. 2025). It is also important to retain logging residues on-site, which help to cover the soil surface, reduce erosion, improve soil hydrological properties, and sustain ecosystem nutrients for the new forest generation (Achat et al. 2015; Dhar et al. 2022). The retention of dead wood is more important for ecosystem biodiversity (Nordén et al. 2004)) than for the hydrological regime, although the amount of water stored in coarse dead wood can be significant (Přívětivý, Šamonil 2021). Furthermore, properly positioned dead wood can reduce soil erosion in hilly terrain (Koyanagi et al. 2025).

The subsequent reforestation of extensive clear-cuts represents a fundamental phase for the recovery of hydrological and biogeochemical ecosystem functions (Belko et al. 2024), while simultaneously offering an opportunity to establish more resilient, mixed-species forests (Griess et al. 2012; Neuner et al. 2015). As the 2018–2022 bark beetle outbreak demonstrated, the extent of the calamity presented a unique challenge for forest owners, combining a drop in wood prices (Toth et al. 2020), the need to manage large areas despite a temporary shortage of logging capacity, and an insufficient supply of reproductive material of the appropriate type and quality. Spontaneous succession of new forests through natural regeneration often appears to be an economically favourable and less capacity-demanding option (Winter et al. 2015; Špulák, Kacálek 2020), although it has certain limitations. The rapid development of ground vegetation may limit forest stand regeneration (Matuszkiewicz et al. 2024), especially on fertile sites. Furthermore, the lack of appropriate seed trees may limit the regeneration of species preferred by forest owners, thereby potentially restricting the transition to more diverse forests (Fischer et al. 2015). Deer browsing may limit both natural and artificial regeneration and reduce species diversity (Rozman et al. 2015; Konôpka et al. 2021). A well-designed combination of natural and artificial regeneration often proves to be the most effective approach (Pommerening, Murphy 2004; Martiník et al. 2014; Souček et al. 2016; Jonczak et al. 2020). Natural succession utilising pioneer species – such as birch, rowan, or aspen – functions effectively as a 'hydrological nurse crop' (Landhäusser et al. 2003), rapidly restoring the vegetative cover which is necessary for the early re-establishment of canopy interception and transpiration fluxes. This rapid green-up effectively reduces excessive surface runoff, mitigates water erosion, and dampens the severe microclimatic and soil temperature extremes associated with large-scale deforestation (Jonášová, Prach 2008; Chojnacka-Ożga et al. 2019; Gohr et al. 2021; Hesslerová et al. 2022).

On extensive disturbance areas, a two-phase regeneration strategy is currently highly recommended (Martiník et al. 2018; Leugner et al. 2023). In this silvicultural system, pioneer species form a temporary preparatory forest that provides a sheltered microclimate (Pommerening, Murphy 2004). Maintaining this continuous vegetative cover mitigates extreme soil moisture fluctuations and provides a functional biogeochemical buffer. As recently demonstrated in Central European mountain catchments, the rapid development of such ground and pioneer vegetation effectively limits the rapid mobilisation and leaching of nitrates and dissolved organic carbon (DOC) into stream networks which typically occur on fully exposed clear-cuts (Neudertová Hellebrandová et al. 2026). Under this protective canopy and stabilised microclimate, more sensitive and shade-tolerant climax species, such as European beech or silver fir, can be subsequently introduced artificially or allowed to regenerate naturally (Martiník et al. 2018; Leugner et al. 2023).

https://doi.org/10.17221/19/2026-JFS

Once the new forest generation is successfully established, early and systematic tending (e.g. pre-commercial thinning) must be viewed as an active management tool (Slodicak, Novak 2006). These silvicultural interventions are essential for regulating interspecific competition for water resources, promoting spatial and structural diversity, and optimising canopy density. Since canopy structure directly governs the balance between precipitation interception and throughfall, appropriate tending ensures the long-term hydrological functionality, water yield stability, and the drought resilience of future forest ecosystems (Aussenac 2000; Slodicak, Novak 2006).

CONCLUSION

This review synthesises the multifaceted environmental consequences of bark beetle outbreaks and subsequent management strategies in Central European forests. The available evidence demonstrates that while the initial canopy loss initiates significant microclimatic and hydrological shifts, the magnitude of these impacts can be at least partly governed by the chosen post-disturbance management.

Improperly executed mechanised salvage logging can amplify the effects of the initial disturbance. The complete removal of biomass induces an insolation shock and widens the diurnal temperature amplitude. Furthermore, soil compaction associated with unproper use of heavy machinery reduces infiltration capacity, transforming clear-cuts into sources of accelerated surface runoff and elevated nutrient leaching, particularly nitrate.

Conversely, integrating structural retention and natural succession into active forest management provides functional mitigation. Strategies such as preserving logging residues, timely reforestation and utilising pioneer species as a biological buffer significantly dampen microclimatic extremes. Furthermore, minimising mechanical soil disturbance and fostering rapid ground cover expansion helps maintain hydrological retention and biogeochemical stability.

To maintain landscape-level resilience, modern commercial forestry in disturbance-prone regions should transition toward these adaptive silvicultural practices, combining natural regeneration with targeted artificial planting. Future research must address existing knowledge gaps, particularly the long-term hydrological trajectories of newly established mixed-species forests, the thresholds of catchment-scale resilience to compound climate extremes (e.g. successive droughts), and the optimisation of predictive ecohydrological models to better capture these complex vegetation-water feedback loops.

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Received: February 23, 2026
Accepted: April 23, 2026