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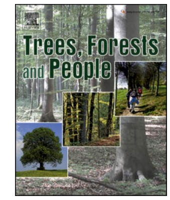

Effects of salvage logging after forest fire on Siberian larch regeneration and ecosystem carbon stocks at the drought limit of the boreal forest in Mongolia

Choimaa Dulamsuren [a,*], Avirmed Buyanbaatar [b], Ganbaatar Batsaikhan [a,c], Dovdondemberel Batdorj [c], Mookhor Khishigjargal [b], Chimidnyam Dorjsuren [d], Zandraabal Tsogt [d], Tumurbaatar Ariunbaatar [d], Batmunkh Munkhtuya [c], Daramragchaa Tuya [e]

[a] *Applied Vegetation Ecology, University of Freiburg, Stefan-Meier-Str. 76, 79104 Freiburg, Germany*
[b] *School of Agroecology, Mongolian University of Life Sciences, Ulan Bator, Mongolia*
[c] *Forest Resources and Forest Protection, Institute of Geography and Geoecology, Mongolian Academy of Sciences, Ulan Bator, Mongolia*
[d] *Botanic Garden and Research Institute, Mongolian Academy of Sciences, Ulan Bator, Mongolia*
[e] *Tarvagatai Nuruu National Park, Mongolia*

A R T I C L E I N F O

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A B S T R A C T

Post-fire salvage logging is widely applied in Mongolia's boreal forests with the intent to prevent intact forests from logging. The rationale behind this approach is the assumption that the additional disturbance caused by the removal of standing deadwood after stand-replacing fire is of no further significance for the already heavily disturbed ecosystem. However, while there is a global debate on effects of salvage logging for regeneration success, biodiversity, and soil health, little evidence has been collected from strongly drought-limited southern boreal forests of Central Asia. Comparing sites with and without salvage logging, we investigated forests of Siberian larch (*Larix sibirica*) ca. 20 years after stand-replacing fire and asked whether postfire salvage logging affected regeneration density, terminal shoot length and radial stem increment, ecosystem carbon stock densities, and reduced organic layer depth and compacted the soil. The biomass of the larch regeneration was significantly reduced by salvage logging, while tree growth was not affected. The ecosystem carbon stock density of burnt forest without salvage logging was 202 Mg C ha^{-1} and thus even in the lower range of intact larch forests from Mongolia, whereas burnt forests with salvage logging had organic carbon stock densities (104 Mg C ha^{-1}) that were lower than those of unburned grasslands in the forest-steppe. These results show that removing deadwood from burnt forest is not insignificant, but has the potential to delay forest recovery and strongly reduces organic carbon storage. However, we did not find significant reductions in soil organic carbon stocks or soil compaction. Nonetheless, our findings raise the question of whether careful management of intact forests (especially by selective felling under a continuous-cover forestry regime) would be a more ecologically sustainable alternative than post-fire salvage logging.

Introduction

Boreal forest dynamics are significantly controlled by fire, insect calamities, and windbreak by storms (Thom and Seidl, 2016). Drought, which has always been a relevant disturbance factor in southern boreal forests near Eurasian and North American temperate grasslands (Dulamsuren et al., 2010), has recently spread to larger boreal forest areas as a result of climate change (Buermann et al., 2014; Babst et al., 2019). In addition, direct human intervention through logging influences the disturbance regime (Senf and Seidl, 2021). Fire as well as forest canopy age and density interact with permafrost depth and active layer thickness, which in turn influence vegetation vigor and productivity (Erasmi et al., 2021; Stuenzi et al., 2021). Forest gaps promote soil warming and thus permafrost thaw (Chang et al., 2015; Klinge et al., 2021b). Under a closing canopy, which shades the soil surface, permafrost can regenerate if not prevented by climate warming (Fedorov et al.,

* Corresponding author.
E-mail address: choimaa.dulamsuren@ecology.uni-freiburg.de (C. Dulamsuren).

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2019; Holloway et al., 2020; Li et al., 2021). Forest fires cause significant combustion losses of C and N from soil organic matter to the atmosphere (Boby et al., 2010; Kasischke and Hoy, 2012). Post-fire C loss occurs due to increased respiration on sun-exposed and blackened soil surfaces (Isaev et al., 2002), whereas accelerated mineralization releases plant-available N and other nutrients (DeLuca et al., 2002).

Though disturbances are part of the natural forest dynamics, they also annihilate significant economical values in commercial forests. Therefore, salvage logging of remaining wood is widely and increasingly applied to obtain at least some financial return from the disturbed stand (Greene et al., 2006; Schmiegelow et al., 2006; Prestemon and Holmes, 2008). Moreover, salvage logging is also considered as preventing measure against the spread of insect outbreaks and pathogenic fungi (Thorn et al., 2014; Leverkus et al., 2021). Whether these incentives justify salvage logging is under debate, because disturbed forest sites with large deadwood volumes increase structural diversity and are home to various species of different groups of organisms, which are dependent on deadwood as a microhabitat or benefit from the shelter and forage supply in the light-open habitat (Foster and Orwig, 2006; Lindenmayer et al., 2012). Salvage logging decreases species richness and alter species composition for various taxonomic groups and those organisms in particular that directly depend on wood as a microhabitat (Thorn et al., 2018, 2020). In this context, deadwood legacies are critical functions as a bridge for many species to the next forest generation (Dittrich et al., 2013).

Salvage logging also promotes soil erosion (Greene et al., 2006; Malvar et al., 2017) and soil warming and can thus foster alterations in the N cycle and the loss of C and other nutrients from the soil (Lindenmayer et al., 2004; Foster and Orwig, 2006; Martineau et al., 2020). In addition, the forest operations during wood extraction result in soil compaction (Ginzburg and Steinberger, 2012; García-Orenes et al., 2017). Exposing the soil surface to the sun, reduces soil moisture that is needed to support tree regeneration and simultaneously increases soil temperatures (Dulamsuren et al., 2008, 2013; Castro et al., 2011; Griffin et al., 2013). Studies to the effect of salvage logging on tree regeneration exhibited different effects: Deadwood can facilitate the establishment of tree regeneration by providing shade and reducing soil moisture loss, especially in dry areas (Ginzburg and Steinberger, 2012; Marzano et al., 2013; Marcolin et al., 2019). However, locally, deadwood can also generate soil patches with reduced soil moisture by sheltering the soil from precipitation (Woodall et al., 2020; Perreault et al., 2021). On the other hand, large deadwood forms shelter for browsing animals that are attracted by the increased forage availability in forest gaps and contribute to the suppression of regeneration (Leverkus et al., 2021).

Since salvage logging is not necessarily applied before the first tree regeneration has emerged, it can also destroy already established seedlings and saplings (Greene et al., 2006; Castro et al., 2011). This can be problematic, because salvage logging is the second major disturbance in a row, which encounters a not yet replenished seed bank due to the preceding fire and subsequent seedling emergence (van Nieuwstadt et al., 2001). Greene et al. (2006) considered the loss of seeds and seedlings due to mechanical damage during salvage logging operations to be more significant than the shift towards drier site conditions. Moreover, salvage logging reduces regeneration if potential seed trees are also cut (Keyser et al., 2009). Reduced or delayed stand recovery after post-fire salvage logging, in turn, lowers C sequestration by the lower tree biomass and thus impedes the compensation of disturbance-induced C losses by the upgrowing stand of the next tree generation (Serrano-Ortiz et al., 2011).

Salvage logging after fire is widely applied in Mongolia. It refers to the removal of standing deadwood with the intention of an environmental-friendly alternative to cutting living trees from healthy forest stands (Battuvshin et al., 2022; Ikeda et al., 2022). However, the ecological consequences of this practice have hardly been investigated (Sakamoto et al., 2021). Hauck et al. (2012) pointed out the high value of coarse deadwood for the conservation of organisms specialized to this microhabitat. Yet, Mongolia's forests are not only important for biodiversity (Dulamsuren, 2004; Dulamsuren et al., 2005; Hauck et al., 2014), but also for C sequestration from the atmosphere and organic C storage (Dulamsuren et al., 2016, 2019). Since fire is a key feature controlling forest dynamics in boreal forests under continental climate (Liu and Ding, 2024) and sustainable forest use is an important issue in a region, which heavily relies on wood for fuel and construction material in rural areas (Lkhagvadorj et al., 2013; Enkhjargal et al., 2018), the ecological impact of post-fire salvage logging is of great importance, but hardly studied in the Inner Asian boreal forest region. Therefore, we studied the effect of salvage logging on burnt forests at the drought-limited southern edge of the boreal forest in the Mongolian forest-steppe. We analyzed effects of salvage logging on regeneration density, tree biomass, annual radial stem increment, organic carbon stock, and soil bulk density in post-fire stands of Mongolia's most common tree species, Siberian larch (*Larix sibirica*) that were or were not subjected to salvage logging.

Because boreal forests in Mongolia are frequently drought-exposed and therefore a positive influence of deadwood on soil moisture was to be assumed and also because of potential mechanical damage during salvage logging, we tested the hypotheses (1) that tree regeneration density and thus also tree biomass was higher at sites without deadwood removal, and (2) that annual shoot length and radial stem increment were higher in stands without deadwood removal. Since salvage logging has the potential to cause soil erosion and promotes soil warming, we tested the hypothesis (3) that organic carbon stocks in the organic layer and the mineral soil were reduced after deadwood removal. Furthermore, we tested the hypothesis (4) that post-fire salvage logging resulted in increased soil bulk density due to soil compaction.

Materials and methods

Study area

The study was carried out in and close to the Tarvagatai Nuruu National Park in the western Khangai Mountains in the Zavkhan Province of northwestern Mongolia. The study area represents one of the southernmost occurrences of boreal forest in Inner Asia (Klinge et al., 2018). The study area was subjected to severe forest fires in 1996 and 2002; stand-replacing fires were widespread (Klinge et al., 2021a).

Climate data and climate trends

Climate data were obtained from the CRU TS 4.04 data set of the Climate Research Unit, University of East Anglia (Norwich, UK) and the Met Office (Exeter, UK) and downloaded from the website of the World Meteorological Organization (WMO) at https://climaexp.knmi.nl at a resolution of 0.5° × 0.5° for the grid field of 48.0 – 48.5 °N and 98.5 – 99.0 °E. The Standardized Precipitation-Evapotranspiration Index (SPEI) was calculated with the R package SPEI 1.7 (Vicente-Serrano et al., 2010) for one-monthly (SPEI1) and three-monthly (SPEI3) values following Thornthwaite (1948) for the calculation of potential evapotranspiration and using a latitude of 48.33 °N to assess monthly sunshine duration.

The climate in the Tarvagatai Nuruu National Park is characterized by a subzero mean annual temperature (−7.7 °C, 1901 – 2019), cold dry winters (mean January temperature: −29.8 °C) and short warm summers (July: 11.3 °C). The mean annual precipitation of 275 mm (1937 – 2019) is received to two-thirds (67.9 ± 0.8 %) during summer (June to August) after the collapse of the Siberian Anticyclone. Mean annual temperature has increased by 2.5 K (or 0.21 K decade^{-1}) since 1901 (linear trend, $r = 0.71$, $P < 0.001$). Consistent with the global average, warming has accelerated since the 1970s (Fig. S1a in the Supplementary Information). This non-linear warming trend is found for the complete growing season (May to September; Fig. S1b), but the winter remains cold lacking a significant warming trend (Fig. S1c). Precipitation has not changed at any season (Fig. S1d–f), whereas meteorological drought

(SPEI1) has increased as a consequence of the increasing temperatures (Fig. S2 in the Supplementary Information).

Sample plot design

A landscape section of ca. 150 km^2, where stand-replacing forest fire had widely occurred, was overlaid by a 1 km × 1 km grid and grid fields were randomly selected to find burnt Siberian larch forest with no salvage logging (N) and with coarse deadwood removal (i.e. the removal of standing deadwood trunks) by salvage logging (D) in the field (Fig. S3). During the selection procedure slope aspect (NE) and inclination (ca. 20 – 25°) were kept constant, thus excluding many grid fields. Moreover, we excluded all grid fields lacking gaps from stand-replacing fire. This way 5 N plots (N1 to N5) and 5 D plots (D1 to D5) were selected at an elevation between ca. 2100 and 2300 m a.s.l. (Table S1). This selection procedure resulted in three clusters of sample plots (Fig. 1) with clusters A (plots N1, N2, D1 – D3), B (N3, N3, D4), and C (N5, D5). This spatial arrangement of sample plots was addressed by using “cluster” as a random factor in statistical analysis. All studied burnt forest plots were monospecific stands of Siberian larch (*Larix sibirica* Ledeb.) lacking mature tree individuals after fire.

Field work

Field work was done in fall 2021 at a point in time when stem increment of that year was already complete. The entire tree regeneration and deadwood were surveyed on plots of 10 m × 10 m. This concerned 225 trees on plots with post-fire deadwood removal (45 ± 9 trees per plot) and 337 trees on plots without deadwood removal (67 ± 10 trees per plot). We measured root collar diameter, tree height and shoot length increment of the last 2 years (2021 and 2020) of the terminal shoot. The dimensions of all coarse deadwood with a minimum diameter of 7 cm were gauged, including height and diameter of standing deadwood and tree stumps as well as length and diameter of downed deadwood. Seven soil profiles (1 m depth) were dug on a bigger sample plot of 20 m × 20 m adhering to a minimum distance of 10 m between profiles. Samples of the organic layer and each horizon of the mineral soil were collected using a steel cylinder of a volume of 190 cm^3.

Annual radial stem increment was analyzed in two individuals of the larger tree regeneration of an age of ca. 10–20 years from each sample plot to analyze potential differences in stem increment between plots with and without salvage logging. Samples were collected with an increment borer of 5 mm inner diameter (Haglöf, Långsele, Sweden) at 1.3 m stem height in parallel to the contour lines of the mountain slope to avoid compression wood.

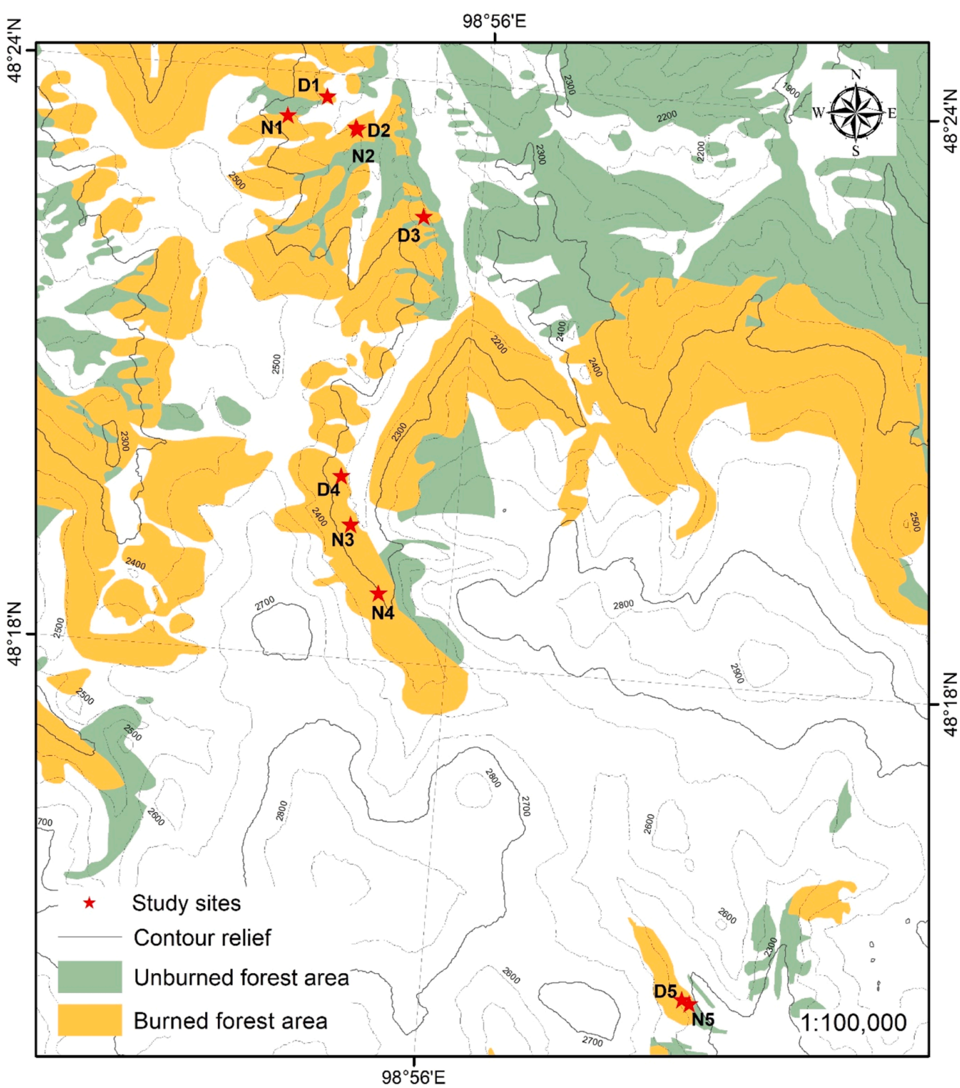

Fig. 1. Studied forest stands of *Larix sibirica* after stand-replacing fire in and near the Tarvagatai Nuruu National Park with (D) and without (N) deadwood removal during salvage logging.

Tree biomass and carbon stock estimates

Tree biomass was estimated using allometric regression functions for *L. sibirica* that were established from forests in western Mongolia based on stem diameter and tree height measurements (Battulga et al., 2013; Dulamsuren et al., 2016). Following Dulamsuren et al. (2016), we measured stem diameter at breast height (dbh) for all trees >4 m height and root collar diameter for smaller seedlings and saplings. Estimates for dry weight-related stem, branch, needle, and root biomass were added per tree and the results from the alternative equations of Battulga et al. (2013) and Dulamsuren et al. (2016) were averaged. Dulamsuren et al. (2016) showed that the equations from these two studies lead to comparable results in the same magnitude. Deadwood biomass was assessed from diameter and length/height data assuming a cylindrical shape. To compensate for conical shapes of long deadwood, we used a low wood density estimate of only 0.2 g cm^{-3} (Dulamsuren et al., 2016). Biomass was converted into organic C stock estimates assuming a total C content of 47 % (Dulamsuren et al., 2016). Biomass and C stock estimates were related to 1 ha

Chemical soil analysis

Material of the organic layer and mineral soil was dried at 40 °C, sieved at 2 mm mash size, and homogenized in a swing mill. Chemical analysis for C and N was conducted with a Vario MAX Cube (Elementar, Langenselbold, Germany) based on the analysis of thermal conductivity after combustion of the sample at high temperature. Soil organic C (SOC) density was calculated by adding the C stock densities of all mineral soil horizons.

Analysis of annual shoot length and radial increment

Shoot length increment in 2020 and 2021 was expressed as relative growth rate based on tree height in 2019 and 2020, respectively. For the analysis of radial stem increment, wood cores were mounted on wooden strips and cut lengthwise with a wood core microtome (Gärtner, WSL, Birmensdorf, Switzerland), before annual ring width was measured with a precision of 10 µm on a movable object table (Lintab 6, Rinntech, Heidelberg, Germany) that was connected to a computer equipped with TSAP (Time Series Analysis and Presentation)-Win software (Rinntech). TSAP-Win and visual control were used for cross-dating. We did not standardize the data, because they were only used to compare absolute

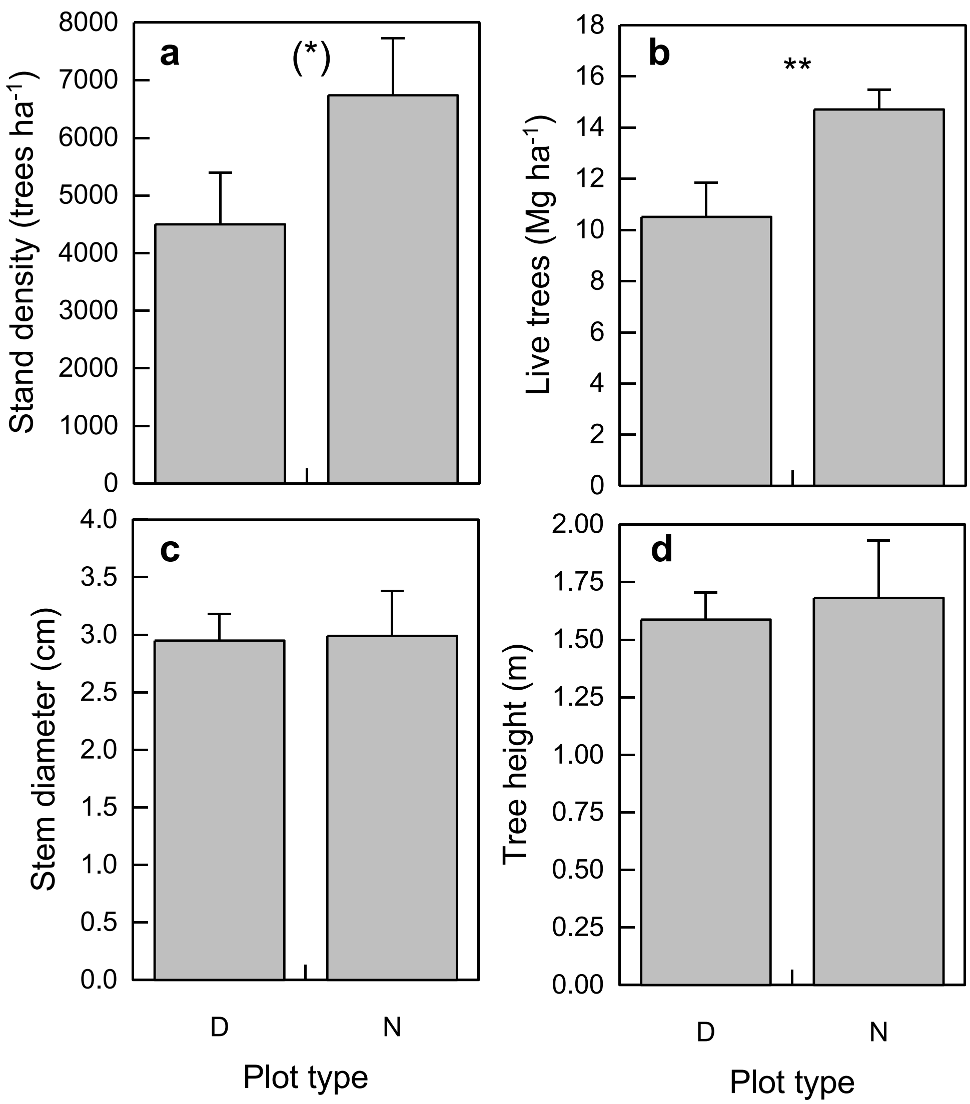

Fig. 2. (a) Stand density, (b) living tree aboveground and belowground biomass, (c) stem diameter, and (d) tree height of post-fire regeneration of *Larix sibirica* in stands with (D) and without (N) deadwood removal ca. 20 years after stand-replacing fire. Living mature trees were absent. Asterisks indicate significant difference between D and N: (*) $P \leq 0.10$, ** $P \leq 0.01$; linear mixed-effect modeling.

values of annual radial stem increment between the variants with and without deadwood removal. Mean curves were smoothed with cubic spline keeping 90 % of the original variance.

Statistical analysis

Arithmetic means ± standard errors (SE) are presented throughout the paper. Statistical analyses were computed in R 4.2.2 software. The effect of salvage logging on stand and soil traits was analyzed with linear mixed-effect modeling using the R package ‘lme4’ 1.1–31 and considering the plot cluster as a random factor. Normal distribution of the residuals was checked positively with the R package ‘DHARMa’ 0.4.6 using quantile-quantile plots.

Results

Regeneration density and tree biomass

All living trees on our sample plots represented tree regeneration that had established after stand-replacing fire ca. 20 years ago. While regeneration of *L. sibirica* occurred in both stands with and without post-fire salvage logging, living tree biomass was significantly higher in stands without salvage logging (Fig. 2). Because salvage logging had no effect on tree size as assessed by stem diameter and tree height, the higher biomass in stands without deadwood removal was attributable to higher stand density, though this difference was only marginally significant ($P = 0.08$; Fig. 2; Table 1). The higher tree biomass in stands without salvage logging was primarily due to higher branch biomass, whereas stem and root biomasses did not differ significantly between plot types (Table 1).

Deadwood

Since salvage logging meant the removal of dead trees, total deadwood mass was highly significantly larger in stands without post-fire wood extraction (Table 1). Standing deadwood played no significant role ca. 20 year after fire, but there were great amounts of downed deadwood logs and tree stumps in the stands without deadwood removal (Fig. 3). More than 10-times higher biomass and organic C stock densities of downed deadwood (D: 1.0 ± 0.9 Mg C ha^{-1}; N: 12.9 ± 2.9 Mg C ha^{-1}) and more than 100-times higher stock densities of tree stumps (D: 0.1 ± 0.1 Mg C ha^{-1}; N: 12.9 ± 6.1 Mg C ha^{-1}) in stands without salvage logging, prove that tree stumps were remnants of the time-delayed breakdown of standing deadwood after the fire and not the result of logging.

Organic layer and soil carbon stocks

Organic C stock densities in the organic layer and the mineral soil were not significantly influenced by salvage logging. Tendencies for higher organic C stock densities in the mineral soil of stands without deadwood removal were not significant and only marginally significant ($P = 0.06$) in the organic layer (Table 1). The mean C stock densities in the organic layer of stands with salvage logging was 8.2 ± 2.6 Mg C ha^{-1} compared to 16.6 ± 6.8 Mg C ha^{-1} without salvage logging. Bulk densities of the organic layer and the mineral soil were not significantly higher, and C concentrations not significantly lower in stands with deadwood removal (Fig. 4). The organic layer was 2.9 ± 0.5 cm deep in

Table 1
Linear mixed-effect models for the effect of post-fire deadwood removal in *Larix sibirica* forest on regeneration density, organic C stock densities and related stand and soil parameters.

Parameter	Intercept[a]	Estimate[b]	P[b]	Cluster[c]	Residual[c]	R^2_{cond}	R^2_{marg}
Regeneration density (trees ha^{-1})	4500±944	2240±1336	0.08(*)	0	2112	0.24	0.24
Basal area (m^2 ha^{-1})	5.30±0.97	1.31±0.76	0.08(*)	1.87	1.18	0.63	0.13
Stem diameter (cm)	3.00±0.37	−0.04±0.42	1.00	0.14	0.65	0.24	0.00
Tree height (m)	1.60±0.21	0.07±0.27	0.70	0.02	0.42	0.09	0.01
Total ecosystem C (Mg C ha^{-1})	105.57±25.61	97.61±33.92	0.008**	208.90	53.32	0.50	0.46
Total live trees (Mg C ha^{-1})[d]	5.23±0.62	1.70±0.56	0.007**	0.64	0.87	0.66	0.36
Aboveground live tree biomass C (Mg C ha^{-1})	3.48±5.81	0.51±2.83	0.008**	0.48	0.84	0.62	0.37
Stem live tree biomass C (Mg C ha^{-1})	1.78±0.26	0.44±0.31	0.13	0.05	0.49	0.31	0.16
Branch live tree biomass C (Mg C ha^{-1})	10.61±1.73	3.09±1.53	0.05*	5.26	2.37	0.58	0.20
Needle live tree biomass C (Mg C ha^{-1})	1.64±0.36	0.90±0.51	0.07(*)	0.00	0.81	0.26	0.26
Root live tree biomass C (Mg C ha^{-1})	0.61±0.09	0.16±0.11	0.11	0.01	0.17	0.30	0.18
Total deadwood (Mg C ha^{-1})	1.66±4.33	25.78±5.78	<0.001***	5.42	9.09	0.70	0.68
Standing deadwood (Mg C ha^{-1})	−0.10±0.98	1.65±1.17	0.20	0.75	1.83	0.31	0.16
Downed deadwood (Mg C ha^{-1})	1.90±2.46	11.14±2.62	<0.001***	7.32	4.07	0.72	0.59
Tree stumps (Mg C ha^{-1})	0.13±4.32	12.78±6.11	0.04*	0.00	9.67	0.33	0.33
Live and dead tree biomass C (Mg C ha^{-1})	9.03±8.96	52.78±11.23	<0.001***	45.69	17.58	0.73	0.69
Organic layer depth (cm)	2.90±0.99	2.10±0.95	0.07(*)	1.50	1.47	0.56	0.25
Organic layer C (Mg C ha^{-1})	10.05±7.69	9.14±4.45	0.06(*)	145.27	6.86	0.78	0.11
SOC (Mg C ha^{-1})	87.85±19.30	35.65±27.30	0.17	0.00	43.16	0.16	0.16
Belowground C (MgC)[e]	98.51±23.64	44.61±31.16	0.14	190.10	49.0	0.24	0.18
A horizon (Mg C ha^{-1})	29.40±6.56	0.97±9.28	0.91	0.00	14.67	0.00	0.00
B horizon (Mg C ha^{-1})	22.71±6.68	14.67±9.45	0.11	0.00	14.94	0.21	0.21
Organic C, organic layer (%)	9.50±3.23	4.37±2.57	0.11	20.64	3.97	0.62	0.13
Organic C, A horizon (%)	4.15±1.17	2.19±1.53	0.15	0.51	2.41	0.24	0.18
Organic C, B horizon (%)	1.33±0.82	1.82±1.15	0.10(*)	0.00	1.82	0.22	0.22
Organic C, C horizon (%)	0.75±0.25	0.42±0.35	0.20	0.00	0.55	0.14	0.14
Total N, organic layer (%)	0.66±0.12	0.10±0.09	0.27	0.03	0.17	0.62	0.05
Bulk density, organic layer (g cm^{-3})	0.35±0.03	−0.05±0.04	0.14	0.00	0.01	0.18	0.18
Bulk density, A horizon (g cm^{-3})	0.79±0.05	−0.11±0.07	0.10(*)	0.00	0.11	0.22	0.22
Bulk density, B horizon (g cm^{-3})	1.02±0.07	−0.14±0.10	0.15	0.00	0.16	0.17	0.17
Bulk density, C horizon (g cm^{-3})	1.03±0.08	−0.13±0.11	0.23	0.00	0.17	0.24	0.14

[a] Intercept (±SE) for stand with post-fire deadwood removal (salvage logging).
[b] Estimate (±SE) for no deadwood removal with *P* value: (*) $P \leq 0.10$, * $P \leq 0.05$, ** $P \leq 0.01$, *** $P \leq 0.001$.
[c] Estimates of random effects represent standard deviations (SD) and are given with conditional (R^2_{cond}) and marginal (R^2_{marg}) model R^2.
[d] Only tree regeneration; mature trees absent.
[e] Belowground defined as roots, organic layer, and mineral soil.

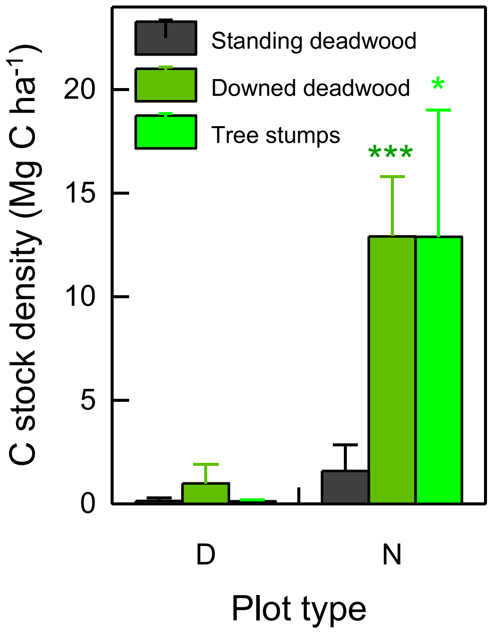

Fig. 3. Organic C stock density in standing deadwood, downed deadwood, and tree stumps of *Larix sibirica* in stands with (D) and without (N) deadwood removal ca. 20 years after stand-replacing fire. Asterisks indicate significant difference between D and N: * $P \leq 0.05$, *** $P \leq 0.001$; linear mixed-effect modeling.

stands with salvage logging, but 4.8 ± 1.0 cm deep in the other stands ($P = 0.07$).

Ecosystem carbon stock density

The ecosystem C stock density was approximately twice as high in stands without (202 ± 34 Mg C ha^{-1}) than with (104 ± 8 Mg C ha^{-1}) post-fire salvage logging (Fig. 5). This significant difference was primarily due to significantly greater stocks of live and dead biomass and supplemented by the only marginally significant trend for higher C stock density in the organic layer in stands without salvage logging (Fig. 5). The sum of C stock density in live trees and deadwood amounted to 61.8 ± 11.6 Mg C ha^{-1} in forests without post-fire salvage logging and 7.5 ± 2.0 Mg C ha^{-1} ($P \leq 0.001$) in stands where dead trees were harvested.

Tree growth

Based on a large sample size of trees where shoot length increment was measured (Fig. 6) and on a smaller sample size where annual stem increment was analyzed (Fig. 7), growth did not differ between *L. sibirica* individuals from stands with or without salvage logging. For shoot length increment, this applied to relative growth rates, where the increment is related to the existing biomass (Fig. 7; Table S2), and absolute growth (data not shown).

Discussion

Reforestation after fire was clearly impacted by salvage logging in the studied stands of Siberian larch at the southern edge of the boreal forest in Mongolia confirming our first hypothesis. The lower biomass of the tree regeneration in post-fire stands with salvage logging can be a combined effect of reduced soil moisture after deadwood removal (Castro et al., 2011) and of mechanical damage of already established seedlings and saplings during the forest operations (Greene et al., 2006). The effect of deadwood on microclimate is due to reducing extremes of high soil temperature and evaporation by shading and covering parts of the soil surface, which is especially important in dry forests (Ginzburg and Steinberger, 2012). Thus, deadwood appears to be increasingly relevant under the rapid climate change in Central Asia (IPCC, 2021), including our study area (Figs. S1, S2). Differences in water supply have been shown to have a great impact on mature trees (Dulamsuren et al., 2010, 2023) and regeneration (Dulamsuren et al., 2008) of *L. sibirica* in the southern boreal forests of Asia. Reduced regeneration density of *L. sibirica* after post-fire salvage logging compared to burned forest without salvage logging is in line with published results from Mongolia obtained in a case study 7 years after fire (Sakamoto et al., 2021). Our findings of the positive effect of deadwood on tree regeneration add to the known value of coarse deadwood for forest biodiversity (Hauck et al., 2012). The reduced regeneration densities might be less critical

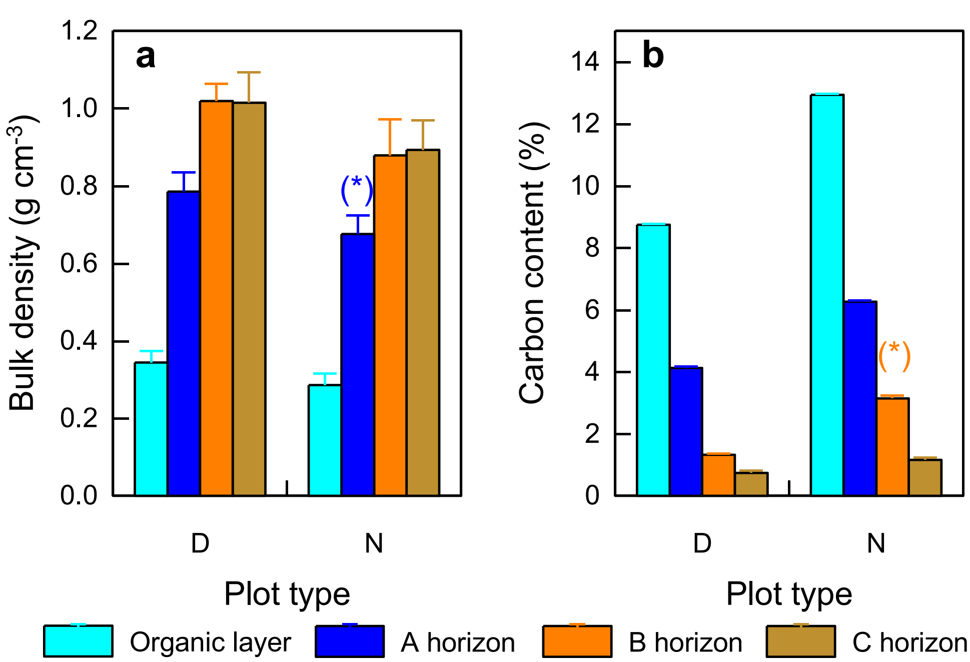

Fig. 4. (a) Bulk density and (b) C content in organic layer and mineral soil (A, B, and C horizons) of *Larix sibirica* in stands with (D) and without (N) deadwood removal ca. 20 years after stand-replacing fire. Asterisks indicate significant difference between D and N: (*) $P \leq 0.10$; linear mixed-effect modeling.

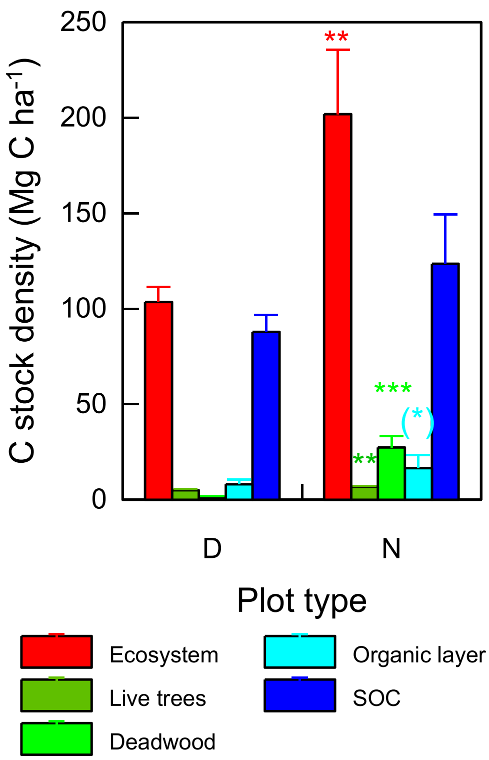

Fig. 5. Organic C stock density (total ecosystem with individual components) in *Larix sibirica* in stands with (D) and without (N) deadwood removal ca. 20 years after stand-replacing fire. Asterisks indicate significant difference between D and N: (*) $P \leq 0.10$, ** $P \leq 0.01$, *** $P \leq 0.001$; linear mixed-effect modeling. Living mature trees were absent.

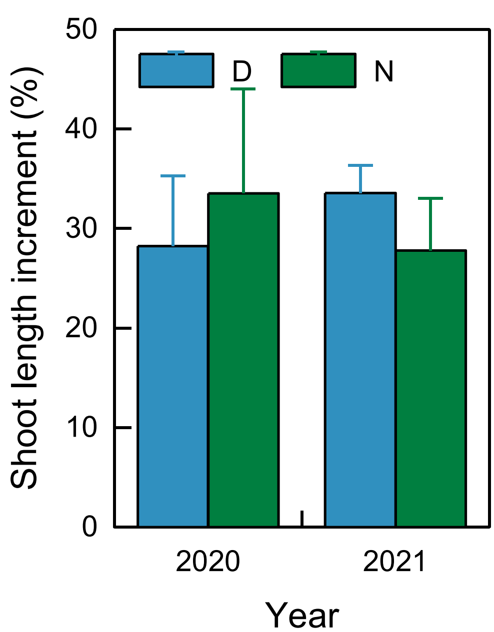

Fig. 6. Terminal shoot length increment relative to tree height at the start of the year in 2020 and 2021 in *Larix sibirica* in stands with (D; $N = 225$ trees) and without (N; $N = 337$ trees) deadwood removal ca. 20 years after stand-replacing fire. No significant differences ($P \leq 0.05$; linear mixed-effect modeling).

under conditions of ample water supply, but should be viewed with concern in the specific case of Mongolia, where tree regeneration is already strongly reduced by the combined impact of rapid climate change (Dulamsuren et al., 2010) and increasing populations of cashmere goats that preferentially feed larch seedlings (Khishigjargal et al., 2013; Lkhagvadorj et al., 2013).

The rationale to harvest dead trees after fire rather than to log undisturbed forest (Battuvshin et al., 2022) is comprehensible in an environment that provides marginal habitats for forests for climatic reasons (Gunin et al., 1999) and where forests are additionally exposed to multiple anthropogenic stressors from land use and climate change (Dulamsuren et al., 2010; Khishigjargal et al., 2013; Juřička et al., 2020). However, economic and ecological benefits from salvage logging by capitalizing the remaining wood after fire and by saving intact forest, must be traded off against potential constraints to forest regeneration. Mongolia has been subjected to forest cover losses from climate change-induced tree mortality and land use in the recent past (Hansen et al., 2013) and substantial efforts are made to support afforestation (Borodyna et al., 2023). Therefore, reducing regeneration by salvage logging and preventing forest land after stand-placing fire from reforestation can become even economically unsustainable if the profit from salvage logging after fire delays or inhibits the establishment of new forest. Constant shoot length growth and radial stem increment irrespective of salvage logging (rejecting our second hypothesis) suggest that the effect of post-fire deadwood removal concerns the most sensitive early stages of establishment, including seed germination and seedling survival (Padilla et al., 2011). An influence of the different stand densities on competition for water was apparently not significant at the investigated stage 20 years after fire, as otherwise different growth rates should have been found for trees at sites with and without salvage logging. However, it is conceivable that the lower stand density of the new forest generation at logged sites might increase growth rates on the long run, when trees get taller and consume more water (Bennett et al., 2015). For mature *L. sibirica* forests from Mongolia lower competition for water and higher rates of annual stem increment have been shown for forest edges compared to forest interiors with higher stand density (Dulamsuren et al., 2009, 2010; Chenlemuge et al., 2015).

In our study, there were no significant effects of salvage logging on soil organic C stocks or soil compaction, which did not support our third and fourth hypotheses. Sporadic marginally significant differences and insignificant trends towards lower C stock densities and higher bulk densities suggest that the impact was negligible. However, it is conceivable that effects on soil organic C (SOC) stocks and soil compaction vary depending on soil and relief, so that more detailed studies including higher variability of site conditions could possibly yield deviating results, especially as there was already an insignificant trend for higher SOC stock density on plots without deadwood removal in our plots (Fig. 5). Soil compaction, which is often found as a result of salvage logging (Leverkus et al., 2021) might play a minor role in Mongolia's forests, because logging is not completely mechanized, except for heavy vehicles that are used for transportation.

Total ecosystem C stock densities in *L. sibirica* forests of Mongolia assessed with the same methodology vary between 180 and 260 Mg C ha^{-1} (Dulamsuren et al., 2016, 2019; Dulamsuren, 2021), which is of course in the upper range much higher than in the regenerating *L. sibirica* stands ca. 20 years after stand-replacing fire in our study. However, the ecosystem C stock density in the forest stands without salvage logging was 202 Mg C ha^{-1} and thus within the lower range of intact *L. sibirica* forest. This result highlights the importance of keeping coarse deadwood in the forest after fire for ecosystem C stocks. Removing deadwood after fire from the forest might be economically profitable, though the quality of the salvaged wood might be questionable, but it strongly affects the capability of the ecosystem to recover and thus contribute to climate change mitigation. This reduced mitigation potential is twofold: first, by removing C from the forest and inducting it into uncertain supply-use chains (Enkhjargal et al., 2018; Battuvshin and Aruga, 2022), and second, by reducing tree regeneration with its strong potential for C sequestration from the atmosphere in young forests (Khansaritoreh et al., 2017).

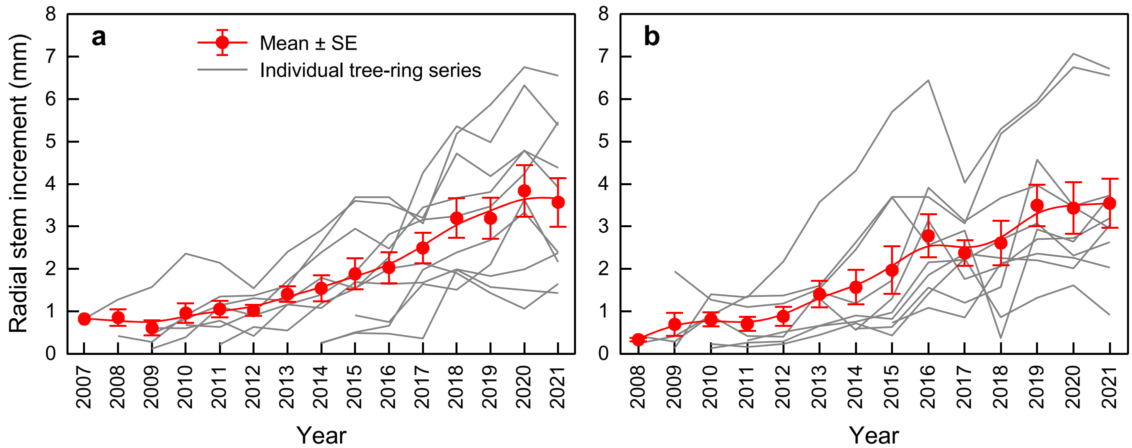

Fig. 7. Annual radial stem increment in tree regeneration of *Larix sibirica* in stands with (D; $N = 10$ trees) and without (N; $N = 10$ trees) deadwood removal ca. 20 years after stand-replacing fire.

The large difference in the ecosystem C stocks between forests with and without salvage logging is primarily carried by the large-diameter deadwood in the forests without salvage logging. Under the dry and cold climate of Mongolia with subzero mean annual temperatures, deadwood decomposition is slow and can last several decades (Chagnon et al., 2022), which is enough time to keep the ecosystem C stocks stable, before the new forest generation can accumulate new C in the ecosystem. On the long run, of course, much of the deadwood C stock will be transferred as CO_2 to the atmosphere by decomposition, whereas some of it will be kept in the ecosystem as SOC (Kurz et al., 2013; Wambsganss et al., 2017; Błońska et al., 2019). The trend to a thicker soil organic layer in forests without salvage logging (though the difference was only marginally significant) adds to the significant difference caused by live and dead biomass. Shading and covering of the soil surface by coarse deadwood also cool the permafrost and can therefore be expected to support its stabilization after fire (Klinge et al., 2021b). The ecosystem C stock density in burned forests with salvage logging (104 Mg C ha^{-1}) was even below the stock reported from grasslands of the Mongolian forest-steppe (ca. 125 – 165 Mg C ha^{-1}), which can be explained with C losses from the organic layer and the upper mineral soil due to combustion during the fire, soil abrasion during forest operations, and increased soil respiration of the sun-exposed, blackened soil surfaces before the recolonization by vegetation (Isaev et al., 2002). In terms of ecosystem C stocks, salvage logging in burnt forests is thus neither negligible nor insignificant, but decides on whether C stock density remains in the lower range of intact forest and can therefore easily recover to higher values or whether C stock density falls far below the range of intact forests and even below values reported from intact steppe grasslands. It would be a rewarding task to analyze chronosequences of forests burnt at different points in time with and without post-fire salvage logging to scrutinize whether our findings prove true even at longer intervals after fire. Our time span of ca. 20 years after fire is already in the range of what other studies refer to as long-term effects (e.g. 13–28 yr in Povak et al., 2020, 17–35 yr in Monsanto and Agee, 2008).

Conclusions

Post-fire salvage logging, which is widely applied in Mongolia had negative effects on forest regeneration and on ecosystem C stocks in *L. sibirica* forests that burnt ca. 20 years ago. Even though the aim of salvage logging in Mongolia is to prevent logging from intact forests, it seems questionable whether limitations on post-fire forest recovery and the organic C release to the atmosphere is actually the better and more sustainable alternative than cutting trees from intact forest, as long as this logging at undisturbed sites is done in the scope of close-to-nature management.

CRediT authorship contribution statement

Choimaa Dulamsuren: Writing – review & editing, Writing – original draft, Visualization, Methodology, Funding acquisition, Formal analysis, Conceptualization. **Avirmed Buyanbaatar:** Writing – review & editing, Investigation. **Ganbaatar Batsaikhan:** Writing – review & editing, Investigation. **Dovdondemberel Batdorj:** Investigation. **Mookhor Khishigjargal:** Investigation. **Chimidnyam Dorjsuren:** Investigation. **Zandraabal Tsogt:** Investigation. **Tumurbaatar Ariunbaatar:** Investigation. **Batmunkh Munkhtuya:** Visualization. **Daramragchaa Tuya:** Investigation.

Declaration of competing interest

The authors have no relevant financial or non-financial interests to disclose.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.tfp.2024.100720.

Data availability

Data will be made available on request.

References

Babst, F., Bouriaud, O., Poulter, B., Trouet, V., Girardin, M.P., Frank, D.C., 2019. Twentieth century redistribution in climatic drivers of global tree growth. Sci. Adv. 5, eaat4313. https://doi.org/10.1126/sciadv.aat4313.

Battulga, P., Tsogtbaatar, J., Dulamsuren, C., Hauck, M., 2013. Equations for estimating the above-ground biomass of *Larix sibirica* in the forest-steppe of Mongolia. J. Forestry Res. 24, 431–437.
Battuvshin, B., Aruga, K., 2022. Forest, forestry and energy in Mongolia toward cleaner production. Environ. Sci. Proc. 13, 22.
Battuvshin, B., Ikeda, Y., Shirasawa, H., Chultem, G., Ishiguri, F., Aruga, K., 2022. Estimating available unused dead wood materials for heat generation in Mongolia: how much coal can unused dead wood materials substitute? Environ. Monit. Assess. 194, 291.
Bennett, A.C., McDowell, N.G., Allen, C.D., Anderson-Teixeira, K.J., 2015. Larger trees suffer most during drought in forests worldwide. Nat. Plants. 1, 15139.
Błońska, E., Lasota, J., Tullus, A., Lutter, R., Ostonen, I., 2019. Impact of deadwood decomposition on soil organic carbon sequestration in Estonian and Polish forests. Ann. For. Sci. 76, 102.
Borodyna O., Mami E., Nijhar I. (2023) Mongolia: towards sustainable economic recovery. ODI Emerging Analysis. ODI, London.
Boby, L.A., Schuur, E.A.G., Mack, M.C., Verbyla, D., Johnstone, J.F., 2010. Quantifying fire severity, carbon, and nitrogen emissions in Alaska's boreal forest. Ecol. Appl. 20, 1633–1647.
Buermann, W., Parida, B.R., Jung, M., MacDonald, G.M., Tucker, C.J., Reichstein, M., 2014. Recent shift in Eurasian boreal forest greening response may be associated with warmer and drier summers. Geophys. Res. Lett. 41, 1995–2002.
Castro, J., Allen, C.D., Molina-Morales, M., Marañón-Jiménez, S., Sánchez-Miranda, Á., Zamora, R., 2011. Salvage logging versus the use of burnt wood as a nurse object to promote post-fire tree seedling establishment. Restor. Ecol. 19, 537–544.
Chagnon, C., Moreau, G., Bombardier-Cauffopé, C., Barrette, J., Havreljuk, F., Achim, A., 2022. Broad-scale wood degradation dynamics in the face of climate change: a meta-analysis. Glob. Change Biol. Bioenergy 14, 941–958.
Chang, X., Jin, H., Zhang, Y., He, R., Luo, D., Wang, Y., Lü, L., Zhang, Q., 2015. Thermal impacts of boreal forest vegetation on active layer and permafrost soils in northern Da Xing'anling (Hinggan) Mountains, Northeast China. Arct. Antarct. Alp. Res. 47, 267–279.
Chenlemuge, T., Dulamsuren, C., Hertel, D., Schuldt, B., Leuschner, C., Hauck, M., 2015a. Hydraulic properties and fine root mass of *Larix sibirica* along forest edge-interior gradients. Acta Oecol. 63, 28–35.
DeLuca, T.H., Nilsson, M.-C., Zackrisson, O., 2002. Nitrogen mineralization and phenol accumulation along a fire chronosequence in northern Sweden. Oecologia 133, 206–214.
Dittrich, S., Hauck, M., Jacob, M., Rommerskirchen, A., Leuschner, C., 2013. Response of ground vegetation and epiphyte diversity to natural age dynamics in a Central European mountain spruce forest. J. Veg. Sci. 24, 675–687.
Dulamsuren, C., 2004. Floristische Diversität, Vegetation und Standortbedingungen in der Gebirgstaiga des Westkhentej. Nordmongolei. Ber Forschungszentr Waldökosyst A 191, 1–290.
Dulamsuren, C., 2021. Organic carbon stock losses by disturbance: comparing broadleaved pioneer and late-successional conifer forests in Mongolia's boreal forest. For. Ecol. Manag. 499, 119636.
Dulamsuren, C., Hauck, M., Mühlenberg, M., 2005. Ground vegetation in the Mongolian taiga forest-steppe ecotone does not offer evidence for the human origin of grasslands. Appl. Veg. Sci. 8, 149–154.
Dulamsuren, C., Hauck, M., Mühlenberg, M., 2008. Insect and small mammal herbivores limit tree establishment in northern Mongolian steppe. Plant Ecol. 195, 143–156.
Dulamsuren, C., Hauck, M., Bader, M., Osokhjargal, D., Oyungerel, Sh, Nyambayar, S., Runge, M., Leuschner, C., 2009. Water relations and photosynthetic performance in *Larix sibirica* growing in the forest-steppe ecotone of northern Mongolia. Tree Physiol. 29, 99–110.
Dulamsuren, C., Hauck, M., Leuschner, C., 2010. Recent drought stress leads to growth reductions in *Larix sibirica* in the western Khentey, Mongolia. Glob. Change Biol. 16, 3024–3035.
Dulamsuren, C., Hauck, M., Leuschner, C., 2013. Seedling emergence and establishment of *Pinus sylvestris* in the Mongolian forest-steppe ecotone. Plant Ecol. 214, 139–152.
Dulamsuren, C., Klinge, M., Degener, J., Khishigjargal, M., Chenlemuge, T., Bat-Enerel, B., Yeruult, Y., Saindovdon, D., Ganbaatar, K., Tsogtbaatar, J., Leuschner, C., Hauck, M., 2016. Carbon pool densities and a first estimate of the total carbon pool in the Mongolian forest-steppe. Glob. Change Biol. 22, 830–844.
Dulamsuren, Ch, Klinge, M., Bat-Enerel, B., Ariunbaatar, T., Tuya, D., 2019. Effects of forest fragmentation on organic carbon pool densities in the Mongolian forest-steppe. For. Ecol. Manag. 433, 780–788.
Dulamsuren, C., Coners, H., Leuschner, C., Hauck, M., 2023. Climatic control of high-resolution stem radius changes in a drought-limited southern boreal forest. Trees 37, 797–810.
Enkhjargal, D., Banzragch, T., Annandale, D., Hicks, C., 2018. Background Report: Policies, Laws, and Regulations Relevant to the Cancun Safeguards in Mongolia. Mongolia UN-REDD Program, Ulan Bator.
Erasmi, S., Klinge, M., Dulamsuren, C., Schneider, F., Hauck, M., 2021. Modelling the productivity of Siberian larch forests from Landsat NDVI time series in fragmented forest stands of the Mongolian forest-steppe. Environ. Monit. Assess. 193, 200.
Fedorov, A.N., Konstantinov, P.Y., Vasilyev, N.F., Shestakova, A.A., 2019. The influence of boreal forest dynamics on the current state of permafrost in Central Yakutia. Polar Sci. 22, 100483.
Foster, D.R., Orwig, D.A., 2006. Preemptive and salvage harvesting of New England forests: when doing nothing is a viable alternative. Conserv. Biol. 20, 959–970.
García-Orenes, F., Arcenegui, V., Chrenková, K., Mataix-Solera, J., Moltó, J., Jara-Navarro, A.B., Torres, M.P., 2017. Effects of salvage logging on soil properties and vegetation recovery in a fire-affected Mediterranean forest: a two year monitoring research. Sci. Total. Environ. 586, 1057–1065.
Ginzburg, O., Steinberger, Y., 2012. Salvage logging versus natural regeneration post-fire practices in a forest: soil chemical and microbial aspects. Open J. Ecol. 2, 29–37.
Greene, D.F., Gauthier, S., Noël, J., Rousseau, M., Bergeron, Y., 2006. A field experiment to determine the effect of post-fire salvage on seedbeds and tree regeneration. Front. Ecol. Environ. 4, 69–74.
Griffin, J.M., Simard, M., Turner, M.G., 2013. Salvage harvest effects on advance tree regeneration, soil nitrogen, and fuels following mountain pine beetle outbreak in lodgepole pine. For. Ecol. Manag. 291, 228–239.
Gunin, P.D., Vostokova, E.A., Dorofeyuk, N.I., Tarasov, P.E., Black, C.C., 1999. Vegetation Dynamics of Mongolia. Kluwer, Dordrecht.
Hansen, M.C., Potapov, P.V., Moore, R., Hancher, M., Turubanova, S.A., Tyukavina, A., Thau, D., Stehmann, S.V., Goetz, S.J., Loveland, T.R., Kommareddy, A., Egorov, A., Chini, L., Justice, C.O., Townshend, J.R.G., 2013. High-resolution global maps of 21st-century forest cover change. Science 342, 850–853.
Hauck, M., Javkhlan, S., Lkhagvadorj, D., Bayartogtokh, B., Dulamsuren, Ch, Leuschner, C., 2012. Edge and land-use effects on epiphytic lichen diversity in the forest-steppe ecotone of the Mongolian Altai. Flora 207, 450–458.
Hauck, M., Dulamsuren, Ch, Bayartogtokh, B., Ulykpan, K., Burkitbaeva, U.D., Otgonjargal, E., Titov, S.V., Enkhbayar, T., Sundetpaev, A.K., Beket, U., Leuschner, C., 2014. Relationships between the diversity patterns of vascular plants, lichens and invertebrates in the Central Asian forest-steppe ecotone. Biodiv. Conserv. 23, 1105–1117.
Holloway, J.E., Lewkowicz, A.G., Douglas, T.A., Li, X., Turetsky, M.R., Baltzer, J.L., Jin, H., 2020. Impact of wildfire on permafrost landscapes: a review of recent advances and future prospects. Permafrost Periglac Process 31, 371–382.
Ikeda, Y., Shirasawa, H., Battuvshin, B., Chultem, G., Ishiguri, F., Aruga, K., 2022. Effects of site conditions on costs and profitability in the extraction and use of dead trees in Mongolia. Eur. J. For. Eng. 8, 11–25.
IPCC, 2021. Climate Change 2021: the Physical Science Basis. Cambridge University Press, Cambridge.
Isaev, A.S., Korovin, G.N., Bartalev, S.A., Ershov, D.V., Janetos, A., Kasischke, E.S., Shugart, H.H., French, N.H.F., Orlick, B.E., Murphy, T.L., 2002. Using remote sensing to assess Russian forest fire carbon emissions. Clim. Change 55, 235–249.
Juřička, D., Novotná, J., Houška, J., Pařílková, J., Hladký, J., Pecina, V., Cihlářová, H., Burnog, M., Ebl, J., Rosická, Z., Brtnický, M., Kynický, J., 2020. Large-scale permafrost degradation as a primary factor in *Larix sibirica* forest dieback in the Khentii massif, northern Mongolia. J. For. Res. 31, 197–208.
Kasischke, E.S., Hoy, E.E., 2012. Controls on carbon consumption during Alaskan wildland fires. Glob. Change Biol. 18, 685–699.
Keyser, T.L., Smith, F.W., Shepperd, W.D., 2009. Short-term impact of post-fire salvage logging on regeneration, hazardous fuel accumulation, and understorey development in ponderosa pine forests of the Black Hills, SD, USA. Int. J. Wildland. Fire 18, 451–458.
Khansaritoreh, E., Eldarov, M., Ganbaatar, K., Saindovdon, D., Leuschner, C., Hauck, M., Dulamsuren, C., 2017. Age structure and trends in annual stem increment of *Larix sibirica* in two neighboring Mongolian forest-steppe regions differing in land use history. Trees 31, 1973–1986.
Khishigjargal, M., Dulamsuren, Ch, Lkhagvadorj, D., Leuschner, C., Hauck, M., 2013. Contrasting responses of seedling and sapling densities to livestock density in the Mongolian forest-steppe. Plant Ecol. 214, 1391–1403.
Klinge, M., Dulamsuren, C., Erasmi, S., Karger, D.N., Hauck, M., 2018. Climate effects on vegetation vitality at the treeline of boreal forests of Mongolia. Biogeosciences. 15, 1319–1333.
Klinge, M., Dulamsuren, Ch, Schneider, F., Erasmi, S., Bayarsaikhan, U., Sauer, D., Hauck, M., 2021a. Geoecological parameters indicate discrepancies between potential and actual forest area in the forest-steppe of Central Mongolia. For. Ecosyst. 8, 55.
Klinge, M., Schneider, F., Dulamsuren, Ch, Arndt, K., Bayarsaikhan, U., Sauer, D., 2021b. Interrelations between relief, vegetation, disturbances, and permafrost in the forest-steppe of central Mongolia. Earth Surf. Process Landform 46, 1766–1782.
Kurz, W.A., Shaw, C.H., Boisvenue, C., Stinson, G., Metsaranta, J., Leckie, D., Dyk, A., Smyth, C., Neilson, E.T., 2013. Carbon in Canada's boreal forest – a synthesis. Environ. Rev. 21, 260–292.
Leverkus, A.B., Buma, B., Wagenbrenner, J., Burton, P.J., Lingua, E., Marzano, R., Thorn, S., 2021. Tamm review: does salvage logging mitigate subsequent forest disturbances? For. Ecol. Manag. 481, 118721.
Li, X.Y., Jin, H.J., Wang, H.W., Marchenko, S.S., Shan, W., Luo, D.L., He, R.X., Spektor, V., Huang, Y.D., Li, X.Y., Ning, J., 2021. Influences of forest fires on permafrost environment: a review. Adv. Clim. Change Res. 12, 48–65.
Lindenmayer, D.B., Foster, D.R., Franklin, J.F., Hunter, M.L., Noss, R.F., Schmiegelow, F. A., Perry, D., 2004. Salvage harvesting policies after natural disturbance. Science 303, 1303.
Lindenmayer, D.B., Burton, P.J., Franklin, J.F., 2012. Salvage Logging and Its Ecological Consequences. Island Press, Washington DC.
Liu, Y., Ding, A., 2024. Contrasting trends of carbon emission from savanna and boreal forest fires during 1999 –2022. Meteorol. Appl. 31, e2177.
Lkhagvadorj, D., Hauck, M., Dulamsuren, C., Tsogtbaatar, J., 2013. Twenty years after decollectivization: mobile livestock husbandry and its ecological impact in the Mongolian forest-steppe. Hum. Ecol. 41, 725–735.
Malvar, M.C., Silva, F.C., Prats, S.A., Vieira, D.C.S., Coelho, C.O.A., Keizer, J.J., 2017. Short-term effects of post-fire salvage logging on runoff and soil erosion. For. Ecol. Manag. 400, 555–567.
Marcolin, E., Marzano, R., Vitali, A., Garbarino, M., Lingua, E., 2019. Post-fire management impact on natural forest regeneration through altered microsite conditions. Forests. 10, 1014.

Martineau, C., Beguin, J., Séguin, A., Paré, D., 2020. Cumulative effects of disturbances on soil nutrients: predominance of antagonistic short-term responses to the salvage logging of insect-killed stands. Ecosystems. 23, 812–827.

Marzano, R., Garbarino, M., Marcolin, E., Pividori, M., Lingua, E., 2013. Deadwood anisotropic facilitation on seedling establishment after a stand-replacing wildfire in Aosta Valley (NW Italy. Ecol. Eng. 51, 117–122.

Monsanto, P.G., Agee, J.K., 2008. Long-term post-wildfire dynamics of coarse woody debris after salvage logging and implications for soil heating in dry forests of the eastern Cascades, Washington. For. Ecol. Manag. 255, 3952–3961.

Padilla, F.M., de, Dios, Miranda, J., Ortega, R., Hervás, M., Sánchez, J., Pugnaire, F.I., 2011. Does shelter enhance early seedling survival in dry environments? A test with eight Mediterranean species. Appl. Veg. Sci. 14, 31–39.

Perreault, L., Forrester, J.A., Mladenoff, D.J., Lewandowski, T.E., 2021. Deadwood reduces the variation in soil microbial communities caused by experimental forest gaps. Ecosystems. 24, 1928–1943.

Povak, N.A., Churchill, D.J., Cansler, C.A., Hessburg, P.F., Kane, V.R., Kane, J.T., Lutz, J. A., Larson, A.J., 2020. Wildfire severity and postfire salvage harvest effects on long-term forest regeneration. Ecosphere 11, e03199.

Prestemon, J.P., Holmes, T.P., 2008. Timber salvage economics. In: Holmes, T.P., Prestemon, J.P., Abt, K.L. (Eds.), The Economics of Forest Disturbances. Springer, Dordrecht, pp. 167–190.

Sakamoto, K., Tomonari, M., Ariya, U., Nakagiri, E., Matsumoto, T.K., Akaji, Y., Otoda, T., Hirobe, M., Nachin, B., 2021. Effects of large-scale forest fire followed by illegal logging on the regeneration of boreal forests in Mongolia. Landsc. Ecol. Eng. 17, 267–279.

Schmiegelow, F.K.A., Stepnisky, D.P., Stambaugh, C.A., Koivula, M., 2006. Reconcilling salvage logging of boreal forests with a natural-disturbance management model. Conserv. Lett. 20, 971–983.

Senf, C., Seidl, R., 2021. Mapping the forest disturbance regimes of Europe. Nat. Sustain. 4, 60–63.

Serrano-Ortiz, P., Marañón-Jiménez, S., Reverter, B.R., Sánchez-Cañete, E.P., Castro, J., Zamora, R., Kowalski, A.S., 2011. Post-fire salvage logging reduces carbon sequestration in Mediterranean coniferous forest. For. Ecol. Manag. 262, 2287–2296.

Stuenzi, S.M., Boike, J., Cable, W., Herzschuh, U., Kruse, S., Pestryakova, L.A., Schneider von Deimling, T., Westermann, S., Zakharov, E.S., Langer, M., 2021. Variability of the surface energy balance in permafrost-underlain boreal forest. Biogeosciences. 18, 343–365.

Thom, D., Seidl, R., 2016. Natural disturbance impacts on ecosystem services and biodiversity in temperate and boreal forests. Biol. Rev. 91, 760–781.

Thorn, S., Bässler, C., Gottschalk, T., Hothorn, T., Bussler, H., Raffa, K., Müller, J., 2014. New insights into the consequences of post-windthrow salvage logging revealed by functional structure of saproxylic beetle assemblages. PLoS. One 9, e101757.

Thorn, S., Bässler, C., Brandl, R., et al., 2018. Impacts of salvage on biodiversity: a meta-analysis. J. Appl. Ecol. 55, 279–289.

Thorn, S., Chao, A., Georgiev, K.B., et al., 2020. Estimating retention benchmarks for salvage logging to protect biodiversity. Nat. Commun. 11, 4762.

Thornthwaite, C.W., 1948. An approach toward a rational classification of climate. Geogr. Rev. 38, 55–94.

van Nieuwstadt, M.G.L., Sheil, D., Kartawinata, K., 2001. The ecological consequences of logging in the burned forests of East Kalimantan, Indonesia. Conserv. Biol. 15, 1183–1186.

Vicente-Serrano, S.M., Beguería, S., López-Moreno, J.I., 2010. A multiscalar drought index sensitive to global warming: the Standardized Precipitation Evapotranspiration Index. J. Clim. 23, 1696–1718.

Wambsganss, J., Stutz, K.P., Lang, F., 2017. European beech deadwood can increase soil organic carbon sequestration in forest topsoils. For. Ecol. Manag. 405, 200–209.

Woodall, C.W., Evans, D.M., Fraver, S., Freen, M.B., Lutz, D.A., D`Amato, A.W., 2020. Real-time monitoring of deadwood moisture in forests: lessons learned from an intensive case study. Can. J. For. Res. 50, 1244–1252.