Carbon stocks and their spatial distribution in drained and rewetted peatland forests in a low mountain range area, Germany

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SUMMARY

Drainage and rewetting of peatlands changes their carbon (C) dynamics. We measured C stocks in the soil and biomass of drained and rewetted peatland forests in the region of the National Park Hunsrück-Hochwald, Germany. A detailed soil map was produced, showing the important soil properties for soil C stocks. Based on the horizon-substrate combination as well as LiDAR data, the spatial distribution of soil and forest C stocks was analysed. Our results show that our peatland sites have shallow soils with a heterogeneous spatial distribution. Mean (± SE) soil C stocks in the monitoring sites are 121(± 8) t ha^{-1} whereas the forest stores on average 71(± 0.2) t ha^{-1} of C in the biomass. Tree removal in the drained peatlands reduced the total C stocks by 4,430 t. The quality and longevity of the wood products that arise from tree removal will determine whether or not the harvested portion of the C captured by the trees is sequestered over long timescales. Additionally, the success of rewetting activities and the potential soil carbon sequestration or (non-) soil carbon loss will determine whether these ecosystems are carbon sinks or sources. An extrapolation of our data resulted in estimated C stocks of 171,530 t and 544,282 t for peatland soils and for the spruce forest, respectively, for the whole area of the National Park (about 10,000 ha).

KEY WORDS: drainage, forest carbon stocks, peat, rewetting, soil carbon stocks, tree removal

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INTRODUCTION

Peatlands contain more than 600 Pg of carbon (C) in their soils and are important in the context of the global C cycle (Yu *et al.* 2011, Jungkunst *et al.* 2012, Dargie *et al.* 2017, Nichols & Peteet 2019). Peat formation occurs when plant material does not fully decompose in water-saturated anaerobic conditions. Drainage of peatlands leads to aerobic conditions in the soil resulting in increased decomposition of organic material and a loss of C from the soil to the atmosphere. In central Europe a large proportion of the peatland area is drained and used for agriculture or forestry management (Joosten & Clarke 2002, Christensen & Friborg 2004, Jungkunst *et al.* 2018). Germany has a peatland area equal to about 3.5 % of the country area, but only about 2 % of this peatland area remains in a natural state (Tanneberger *et al.* 2017). Depending on land use and land management, these soils emit various quantities of greenhouse gases (Drösler *et al.* 2013, IPCC 2014, Tiemeyer *et al.* 2016). Drained peatlands are responsible for approximately 5 % of the national greenhouse gas emissions in Germany (Strogies & Gniffke 2014). For several decades, peatland rewetting has become a widespread management tool in formerly utilised peatlands with the aim of restoring their natural function, and thereby also reducing greenhouse gas emissions (Tanneberger & Wichtmann 2011). Carbon sequestration and the avoidance of greenhouse gas emissions via peatland restoration are efficient and relatively low-cost mitigation measures (Leifeld & Menichetti 2018, Humpenöder *et al.* 2020).

Most studies have focussed on the greenhouse gas exchange of peatlands measured by the chamber or eddy covariance method (e.g. Drösler *et al.* 2013, Hommeltenberg *et al.* 2014). Others analysed the C stocks of peatlands including calculations of C losses and gains, respectively, by comparing natural and drained peatland sites (Pitkänen *et al.* 2013, Krüger *et al.* 2016). Another approach is to compare present-day and historical peatland C stocks with the so-called re-sampling method (Simola *et al.* 2012). However, only a few studies have included C stocks of both soils and trees for peatland ecosystems (Minkkinen *et al.* 1999).

In recent years, there has been an increased research effort looking at organic soils and their C balance. In Germany the focus has mainly been on peatlands and their greenhouse gas exchange under grassland or agricultural use (Beetz *et al.* 2013, Drösler *et al.* 2013, Tiemeyer *et al.* 2016). The C dynamics of peatlands under forestry use were mainly studied in the boreal region (Minkkinen *et al.* 2002, Ojanen *et al.* 2017, Minkkinen *et al.* 2018). Only limited work has been carried out on peatlands occurring under temperate forest (Hommeltenberg *et al.* 2014, Sloan *et al.* 2018). In the low mountain range areas of Rhineland-Palatinate, Germany, slope peatlands have been drained since the early 19th century using drainage ditches. These drainage activities were adopted to prepare for the plantation of spruce forests on soils with peat layers. In the last decade, restoration activities including closing drainage ditches and spruce tree removal have started to rewet these slope peatlands (EU-Life Project). Prior to the present study, no data existed on the spatial distribution of slope peatlands and their C stocks in the low mountain range areas of Rhineland-Palatinate.

As such, we identified three main objectives with the aim of obtaining more detailed information on C stocks of slope peatland forests and their spatial distribution: a) Calculate the complete C stock of the peatlands including organic layers, soil and biomass of the spruce forest; b) Compare the C lost by tree removal/thinning with existing C stocks; c) Extrapolate the measured data to the whole National Park region (to estimate the importance of the total C pool of organic layers, soils and spruce forests from slope peatlands in the National Park).

METHODS

Study sites

The National Park Hunsrück-Hochwald is located in Rhineland-Palatinate and Saarland in southwestern Germany (Figure 1) and covers about 10,000 ha. The Hunsrück-Hochwald National Park lies in a transitional zone between oceanic and continental climate. The annual average temperature is between 7.0 and 10.0 °C. Average precipitation is between 600 and 1,200 mm in the year with a weakly developed precipitation maximum in the winter months. The climate type is influenced by altitude and position in the windward or leeward part of the mountain range. From the valley locations with annual precipitation of 800 mm, these rise to over 1200 mm in the mountain ridges of the National Park. The Rhenish Slate Mountains originated between 419 and 299 million years ago. The Hunsrück in the National Park area thus shows rock series of the so-called Rhenoherzynikum, which has unfolded from southwest to northeast in the course of the Variscan mountain formation (Walter 2007).

Soils

Taunus quartzite alternating with Devonian Hunsrück slates are the geological parent material for soil formation in the National Park. Today, podsolic terrestrial brown soils more or less dominate with a tendency to gleyic soils with solifluidal loam layers. Thus, in the case of discontinuity of the soil pore systems, various interflow levels have developed in addition to the interflow pathways in the deeper soil layers. In slopes where interflow or return flow outcrops in sources, the main and middle layers were occasionally eroded down to the base layer. Depending on the severity and duration of water saturation in the soil, hydromorphic substrates within gleyic boggy soils, spring peatlands and slope peatlands have developed. In the National Park these spring peatlands and slope peatlands are very special and unique compared to other European low mountain ranges (Reichert 1975, Schüler 2012). They are fed by spring water and interflow (Ruthsatz 1999). Only when spring water and surface runoff permanently moisten organic layers does peat develop on a small scale with varying thickness.

Hydrogeography/runoff

A direct ecological influence on the near-surface soil water balance, as well as on the water balance of forests and slope peatlands, is exerted by the intensive development of roads built in the past to enable forestry management, and the deep accompanying ditches and culverts for draining the collected water. Deep unnatural erosion phenomena can be observed here. This can only be remedied by closing all culverts. Where it appears necessary to avoid waterlogging and uncontrolled overflow over forest roads, infiltration substructures can replace pipe culverts and thus reduce negative ecological effects (Backes *et al.* 2007).

Forest stands

On wet sites (1,875 ha), coniferous stands account for the largest proportion of the area at 68.8 % (1,291 ha), with 64.8 % (1,216 ha) of dominating spruce (*Picea abies*). The spruce is often mixed with beech (*Fagus sylvatica*) and alder (*Alnus glutinosa*). On medium water-supplied forest sites (8,252 ha), beech stands represent 54.4 % (4,489 ha) of the area. These beech stands are often accompanied by conifers, mainly spruce and more frequently Douglas fir (*Pseudotsuga*

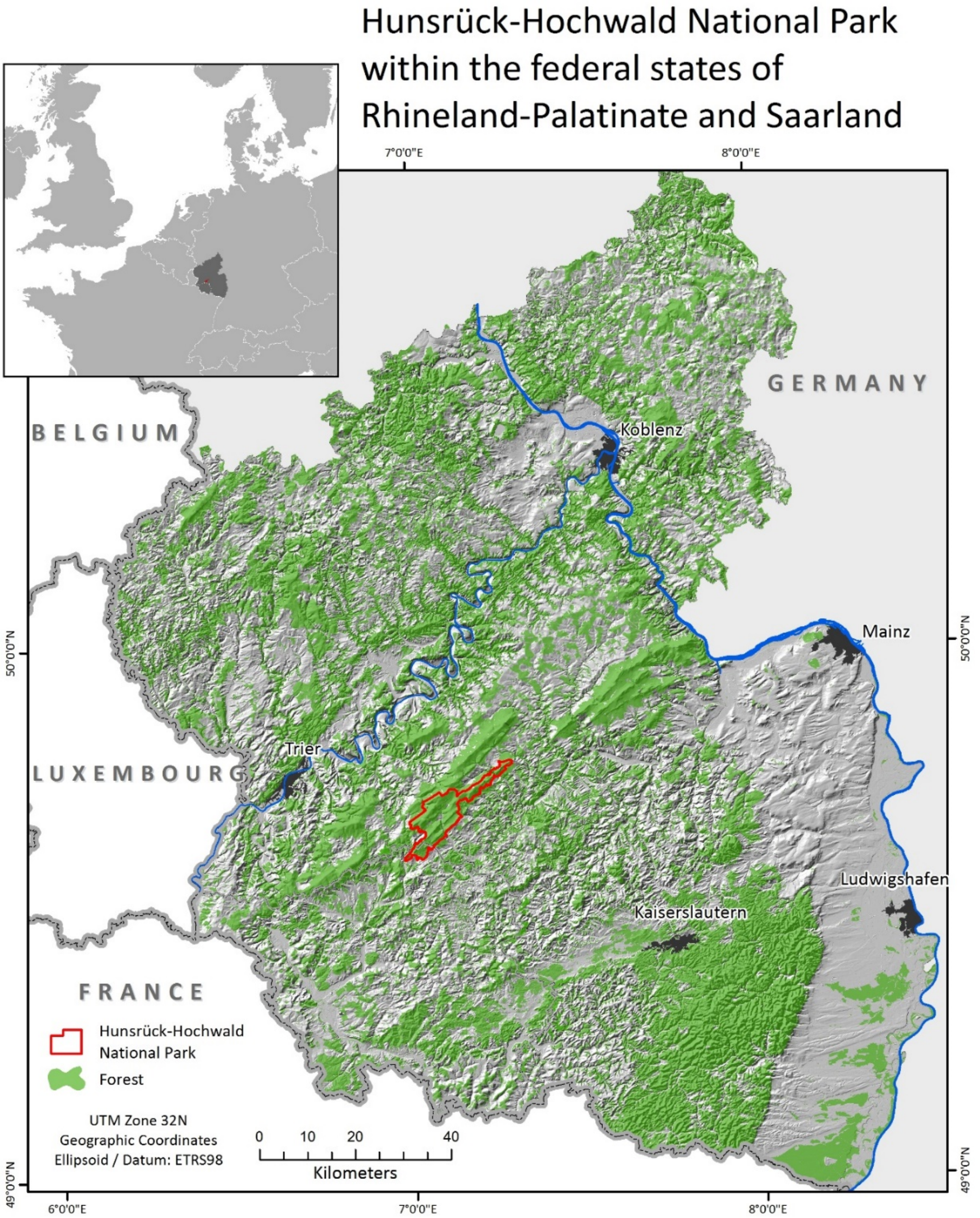

Figure 1. Map of the Hunsrück-Hochwald National Park. (Lamprecht *et al*. 2020).

menziesii), larch (*Larix decidua*) and fir (*Abies* sp.). The group of dry sites cover 44.2 ha and 80.1 % (35.4 ha) of beech stands. The dry beech forests (44.2 ha) are largely accompanied by oak and often by birch, maple and spruce. Potential slope peatlands sites can be found in the wet site group, which occupies 18.4 % (1,875 ha) of the National Park area. In addition to birch fen forests, alder forests and spring forest sites, this group also includes black alder swamp forests, riverbank forests or areas with a very high influence of groundwater and surface water (Wahl & Bushard 2014).

Monitoring sites

Five monitoring sites on peatlands (here slope peatlands) were established in 2016 in the National Park Hunsrück-Hochwald. The five monitoring sites have different characteristics regarding drainage and rewetting as well as tree removal activities (Table 1). Most of these monitoring sites have a close grid of drainage channels which were dug in the 19th century for plantation of spruce forests, with approximately 250 m of drainage channels ha^{-1} in some areas. Since 2015, rewetting activities such as closing drainage channels and felling trees (tree removal) were

Table 1. Characteristics of monitoring sites. Brackets indicate small parts of the peatland for rewetting activities or tree removal/thinning, or a less pronounced drainage ditches density.

Site	Area (ha)	Slope/aspect	Drainage ditches	Rewetting	Tree removal/ thinning
Thranenbruch	81.3	3.6° / south	yes	yes	yes
Riedbruch	33.9	3.8° / south-east	(yes)	(yes)	(yes)
Thierchbruch	14.1	7.5° / south-east	yes	yes	(yes)
Langbruch	19.9	6.1° / south	(no)	no	no
Johannenbruch	50.9	3.5° / south	yes	no	no

undertaken in some peatlands of the National Park Hunsrück-Hochwald.

Soil mapping and soil analyses

Between 2015 and 2018, a comprehensive soil map, according to the German soil classification (KA5), was produced for each monitoring site (AG Boden 2005). The soil colour, structure and texture were analysed in the field for each soil horizon. In total 25 soil profiles, representing the range of peatland soil types in this region, were sampled and analysed in detail. Soil samples were analysed for important soil properties like C content (elemental analysis according to the DIN ISO 10694) and bulk density (sampling ring with drying and weighing) in the laboratory of the State Office for Geology and Mining Rhineland-Palatinate. Additionally the degree of peat humification (H1–H10) was determined according to the von Post scale (von Post 1922). In the von Post scale, a greater number corresponds to a higher degree of decomposition.

For a far-reaching spatial analysis of the C storage of the organic soils, we applied a horizon-substrate combination (Bauriegel 2005, Zauft *et al.* 2010). Based on peat substrates, peat development stages and degree of decomposition of the different horizon-substrate combinations were characterised (www.carbstor.de). The partitioning of the soil data into individual horizon-substrate combinations allowed the creation of new idealised profiles out of the existing chemical and physical soil data. The soil shape files and the idealised soil profiles enable their use at a higher spatial scale for the whole area of the monitoring sites.

Data acquisition and data processing

Data and maps, which we used in the calculations, were compiled from state authorities, the National Park Office and the forestry department. The waterlogging map from the forest location mapping was used for the extrapolation from the monitoring sites to the whole area of the National Park Hunsrück-Hochwald. This map defined the waterlogging stages of the upper soil layers. The stages are defined from s2 to s6. From s4 to s6 the soil is influenced by the backwater or groundwater for 4 to 7 months (s4), 7 to 10 months (s5) and more than 10 months per year (s6). This was the only (soil-) map of this region covering the monitoring sites as well as the whole region of the National Park.

C stock calculation and extrapolation

Carbon stock (t ha^{-1}) calculations were accomplished using the following soil properties: bulk density (g cm^{-3}), C content (%) and thickness of the soil horizon (cm). Based on relative C stocks and peatland area total C stocks of the monitoring sites were calculated.

The extrapolation was done based on the monitoring sites and the waterlogging map. For each waterlogging stage, which is influenced by backwater or groundwater, at the monitoring sites a relative C stock (t ha^{-1}) was calculated (Table 2). These data were used for other parts of the National Park that were covered by the waterlogging map, but not by the monitoring sites. Based on these calculated C stocks an estimate of the total C stock of the peatlands in the National Park Hunsrück-Hochwald could be calculated.

Calculation of forest carbon stocks

Up-to-date spatial information about the type,spatial distribution, and timber volume of forests is an essential element in both sustainable forest management and environmental monitoring. Remote sensing data can provide valuable contributions to these information needs.

Timber volume as a central attribute of forest inventory includes all living tree stems greater than 10 cm diameter at breast height (DBH) (FAO 2010).

Table 2. Weighted mean (± SE) carbon stocks (t ha^{-1}) of waterlogging stages (s4, s5, s6) of the soils at monitoring sites. S4 corresponds to 4 to 7 months of waterlogging conditions in the upper soil, s5 7 to 10 months and s6 more than 10 months.

Peatland	s4 (4–7 months)	s5 (7–10 months)	s6 (> 10 months)
Johannenbruch	1.10±22	70.0±149	n/a
Riedbruch	189±17	n/a	322±16
Thierchbruch	157±17	205±23	411±35
Thranenbruch	68.0±15	220±28	326±44
Langbruch	178±30	204±30	327±32
All monitoring sites	67.0±10	214±15	327±13

Explanation: n/a – not applicable

The main variables for the calculation of single tree stem volume are tree type, tree height (h) and DBH (Zianis *et al.* 2005). However, for the spatially extensive mapping of timber volume using airborne or satellite-based remote sensing data, calculations considering only single-tree stem volume are not viable. Instead, timber volume is usually calculated per unit area in m^3 ha^{-1}. The calculation takes advantage of correlated variables such as forest stand height, derived from LiDAR data or spectral reflectance in certain wavelengths for passive optical information. The latter is not directly correlated to timber volume, but it takes advantage of the forest structure at certain developmental stages and its influence on the reflectance in the near-infrared spectral range (Nink *et al.* 2015). Regarding the availability of LiDAR data, the advantage of a direct correlation between forest stand height and stem-volume can be used, such as that presented in Figure 2.

The LiDAR data was acquired between 24 March and 07 April 2015 using a Riegl Q560 on an airborne platform. The sensor altitude was 600 m above the ground according to GPS data. The full waveform raw data consist of 17 points m^{-2} on average with a total of 10.3×10^9 points. The point-cloud-data has been transformed to rasterised images with a spatial resolution of 1 × 1 metre, providing a digital elevation model (DEM) and a digital surface model (DSM) of the study area. A normalised difference model was calculated from the DSM and DEM, providing the forest stand height. For further processing, the data were resampled to a pixel size of 5 × 5 metres, which roughly corresponds to the crown diameter of full-grown Norway spruce (*Picea abies*) trees. Forest stand heights up to 34 m with a mean value of 16.3 m and a standard deviation of 7.2 m were obtained.

Since focus of the present study was coniferous forests, an up-to-date forest type map was applied on the normalised difference model to mask out deciduous forest and non-forest areas. The forest type map was derived using a supervised classification approach based on boosted decision trees. Utilising a combination of spectral information and texture features of aerial imagery, deciduous and coniferous forest types could be separated with an overall accuracy of 93.2 % ± 0.1 (Haß 2015).

The reference data to which the forest stand height is related to is provided by the forest authorities of Rhineland-Palatinate. It was acquired by expert terrestrial inventory assessments in 2016 (Peerenboom *et al.* 2003). The data are related to forest management units (FMUs) and includes volume information and reference area for each forest stand within the respective FMU. The data allow the derivation of timber volume per hectare for each forest stand. Because some FMUs consist of more than one forest stand, only suitable data where the information can be firmly linked were selected as reference (n = 173).

For the construction of a reference database, the centre points of suitable FMUs were used to extract the corresponding LiDAR derived forest stand height. Although image data have been resampled to a five by five metre ground resolution, single gaps at the sampling points can have a significant influence on the value of the extracted tree height. Thus, a kernel (three by three pixels, median and maximum filter) was applied for the sampling of LiDAR data. For the spatially explicit mapping of timber volume - based only on forest stand height as the explanatory variable - the k-Nearest-Neighbours (k-NN) method

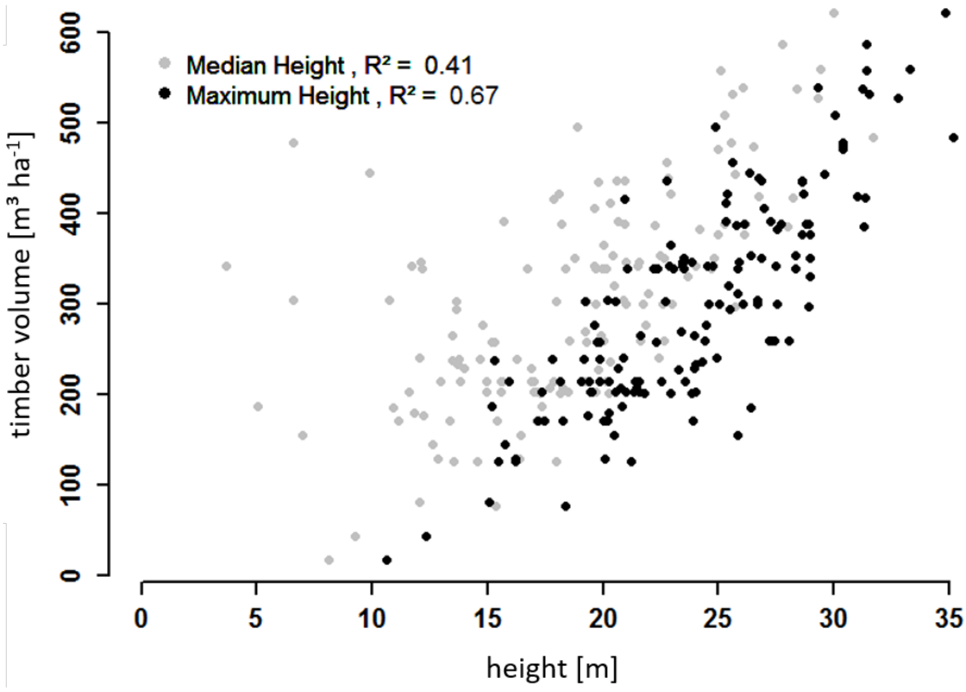

Figure 2. Correlation between LiDAR derived forest stand height and timber volume using the median from a sampling kernel (grey points) and the maximum value from inside a sampling kernel (black points).

is an appropriate method. One main advantage of the non-parametric method is that it does not necessarily depend on a normal distribution in the reference data. The method has been widely used in forestry for the mapping of different attributes such as forest type, biomass or timber volume on local (Latifi *et al.* 2010), regional (Fazakas *et al.* 1999, Nilsson *et al.* 2005) and national scales (Reese *et al.* 2003, McRoberts & Tomppo 2007, Tomppo *et al.* 2012). The reference data, which now include the explanatory and response variables, was first used as a training set for parameterisation (the optimal number of neighbours "*k*" and its weighting factors) using Leave-one-out cross-validation (Gong 1986). Based on that as well as on the reference data, the calculation of the estimated value for each pixel in the image first uses the Euclidean distance from image pixel to reference elements.

$$d_{p,p_i} = \sqrt{\sum_{j=1}^{nc}(x_{p,j} - x_{p_i,j})^2} \qquad [1]$$

Where *nc* is the number of explanatory variables (in our case height information is the only explaining variable). $x_{p_i,j}$ is the image pixel information with unknown response value for the *j*-th explanatory variable and $x_{p,j}$ is the spectral information of the reference element *p* in the *j*-th explanatory variable.

Each element from the reference data is assigned a weighting factor:

$$w_{p,p_i} = \frac{1}{d^t_{p_i,p}} \Big/ \sum_{i=1}^{k} \frac{1}{d^t_{p_i,p}} \qquad [2]$$

where $d^t_{p_i,p}$ is the distance of the *i*-th element in reference data calculated in Equation 1. *t*, *t*={0,1,2}, influences the weighting factor in the effect, that the higher the exponent is, reference elements with a closer distance to the estimation pixel in feature space will get assigned a higher weighting factor. The sum of all *k* weighting factors is one.

The response value ($\widehat{y_p}$) is finally calculated as a linear combination of the weighting factors w_{p,p_i} and the response values y_{p_i} of the *k* nearest elements of the reference dataset.

$$\widehat{y_p} = \sum_{i=1}^{k} w_{p,p_i}\, y_{p_i} \qquad [3]$$

The calculated data for stems were complemented by the data for branches, needles and brushwood as well as for roots. Data of the proportion for different compartments of the trees were used from the literature for spruce forests (see details in Jacobsen *et al.* 2003). Based on these data C stocks for all compartments of the trees were calculated.

Total carbon stocks are presented as sums of the subtotals with means and standard deviation of the subtotals.

RESULTS

Soil properties

The detailed analyses of 25 soil profiles resulted in a large number of different soil horizons according to the German soil classification (AG Boden 2005). Main soil types of the slope peatlands in the National Park are Sapric Histosols, Gleysols, or Histic Gleysols with several different subtypes. Most of the soil horizons were classified as transition peat with organic C contents between 10 % and 45 % (Figure 3).

The majority of the peat horizons are highly decomposed ranging from H6 to H10 according to the von Post scale (von Post 1922) (Figure 3). With increasing degree of decomposition, the organic C content decreases. The bulk density (median) increases from about 0.06 g m^{-3} in slightly decomposed horizons (von Post H1–H2) to 0.23 g m^{-3} for strongly decomposed (von Post H9–H10) organic horizons (Figure 4).

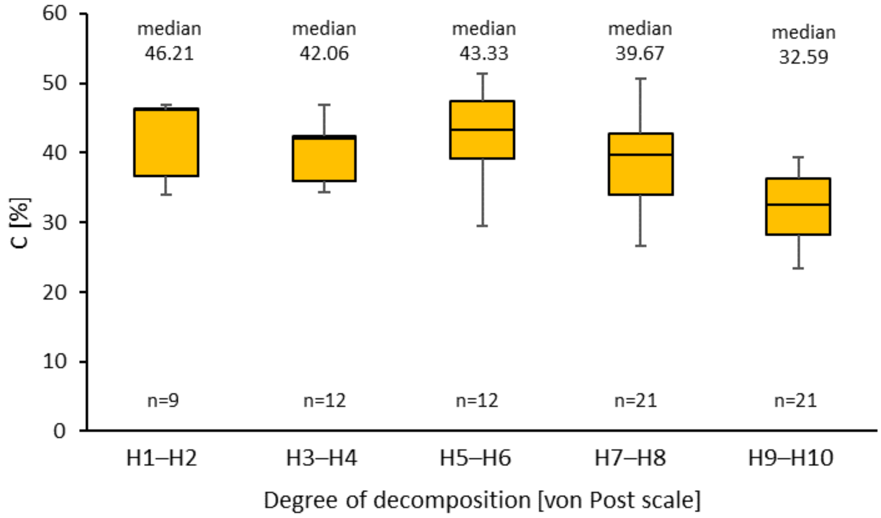

Figure 3. Organic carbon content versus degree of decomposition of the investigated soil profiles. Boxplot showing median, interquartile range, minimum and maximum of organic carbon content versus degree of decomposition.

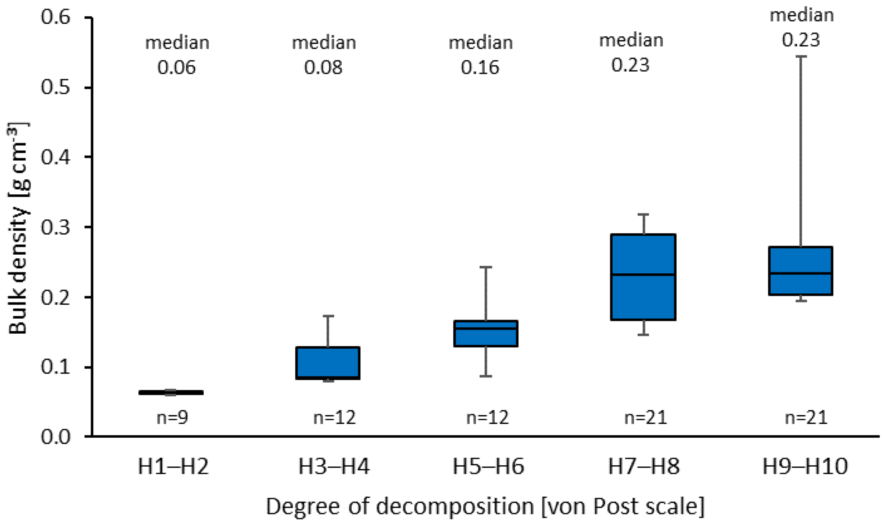

Figure 4. Bulk density versus degree of decomposition of the investigated soil profiles. Boxplot showing median, interquartile range, minimum and maximum of bulk density versus degree of decomposition.

Soil carbon stocks

The detailed soil mapping at the monitoring sites in the National Park Hunsrück-Hochwald showed a heterogenic distribution of organic soils and their C stocks. The organic soils are shallow (typically between 0.4 and 0.6 m) with a maximum thickness of 1.1 m. Large areas of the monitoring sites show C stocks of 0 to 200 t ha^{-1} (Figure 5). However, small areas indicate C stocks up to 800 t ha^{-1}. The highest mean (± SE) C stock of all the monitoring sites was found at Riedbruch with an estimated 234 (± 3) t ha^{-1} and the lowest at Johannenbruch with 2 (± 4) t ha^{-1}. At Johannebruch there are only small areas of peatland soil, and mineral soils predominate. The mean C stock of all five monitoring sites is 121 (± 8) t ha^{-1}.

Timber volume

Because the forest is not a homogeneous area, reference data sampling comprised image data resampling (1–5 m ground resolution) as well as kernel-based sampling. More appropriate reference data were obtained using the maximum filter. The coefficient of determination between forest stand height and timber volume increased from 0.41 to 0.67. The reference data values ranged from 3.70 m to 31.7 m in the median mask derived reference dataset and 10.6 m to 35.2 m in the maximum filter derived set, with mean values of 18.6 m (median filter sampling) and 23.9 m (maximum filter sampling) and standard deviations of 5.4 m (median filter sampling) and 4.6 m (maximum filter sampling). The data are normally distributed (Shapiro-Wilk's p = 0.89). Timber volume in the reference dataset ranged from 18 to 622 m^3 ha^{-1}, but it is not normally distributed (Shapiro-Wilk's p = 0.03).

The timber volume map presents a detailed overview of the volume distribution of Norway spruce areas (Figure 6). A number of three nearest neighbours with inverse weighting of the distance was sufficient to provide the best results with a RMSE of 25 %.

Forest carbon stocks

The spatial distribution of spruce forest C stocks show values between 0 and 160 t ha^{-1} with highest values in the peatland Thranenbruch and lowest in the peatland Langbruch (Figure 7). Mean (± SE) C stocks of spruce forests are 82 (± 0.4) t ha^{-1} for Thranenbruch and 51 (± 0.6) t ha^{-1} for Langbruch. On average the C stocks of spruce forest at monitoring sites are 71 (± 0.2) t ha^{-1}. Detailed total carbon stocks are presented in Table 3.

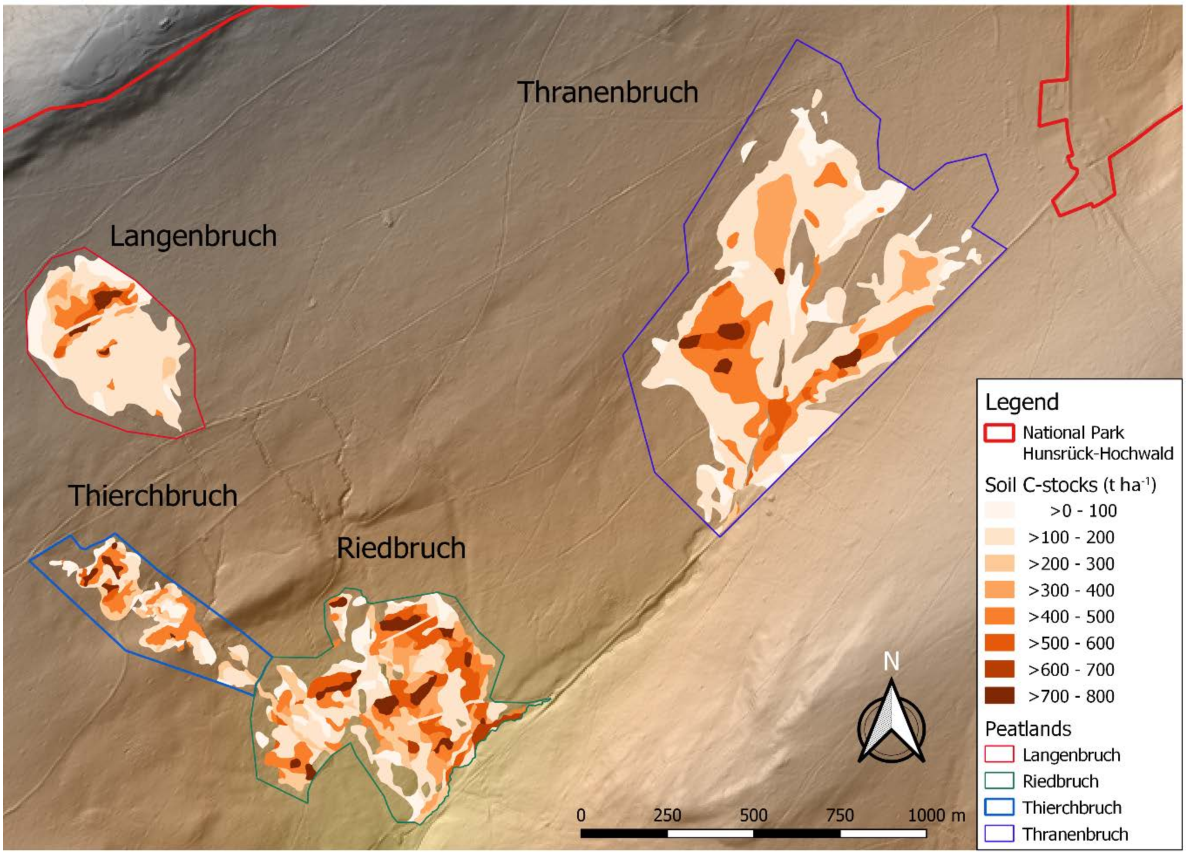

Figure 5. Distribution of soil carbon stocks at monitoring sites.

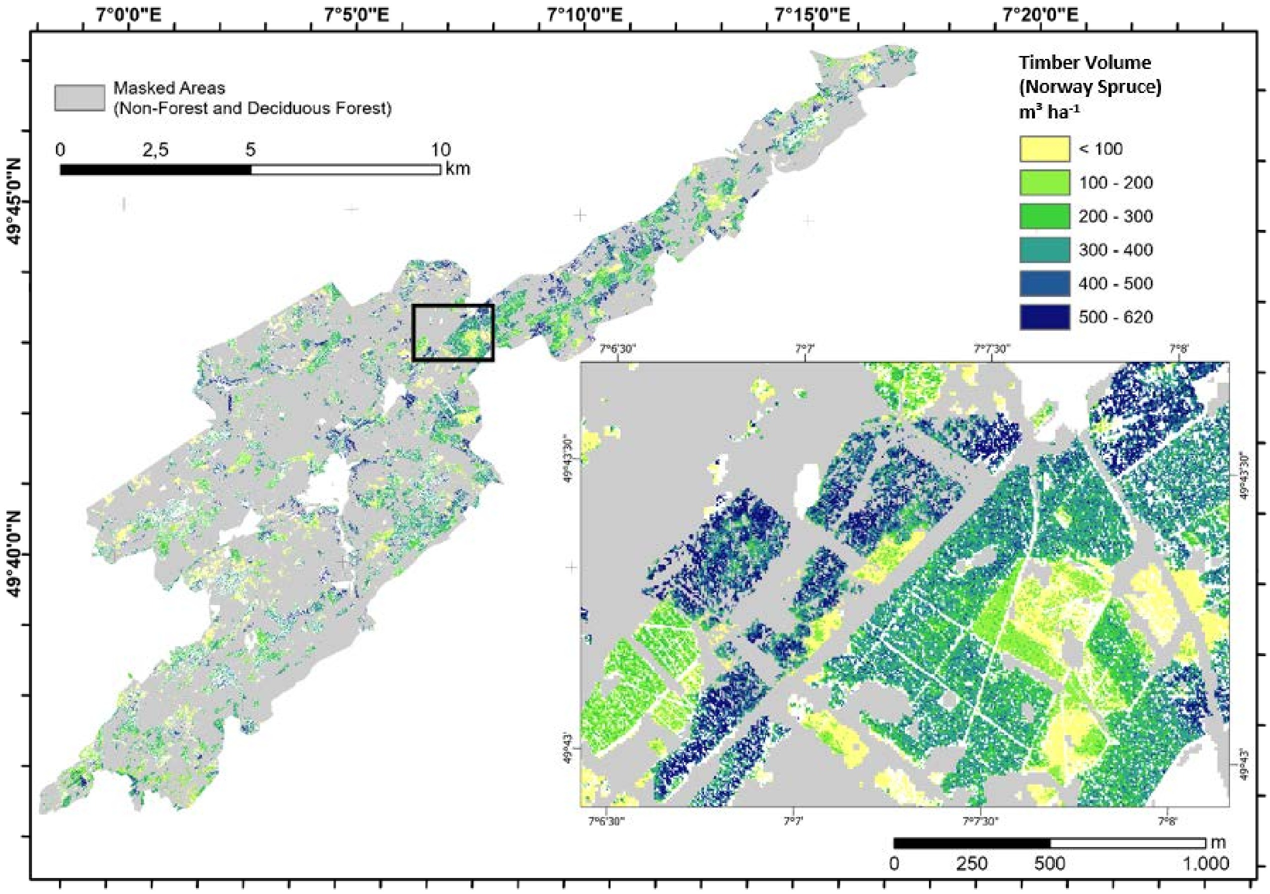

Figure 6. Distribution of k-NN derived Norway spruce volume in the National Park Hunsrück-Hochwald. The inlay shows the now deforested area near Thranenweier (49° 72’ N, 7° 11’ E).

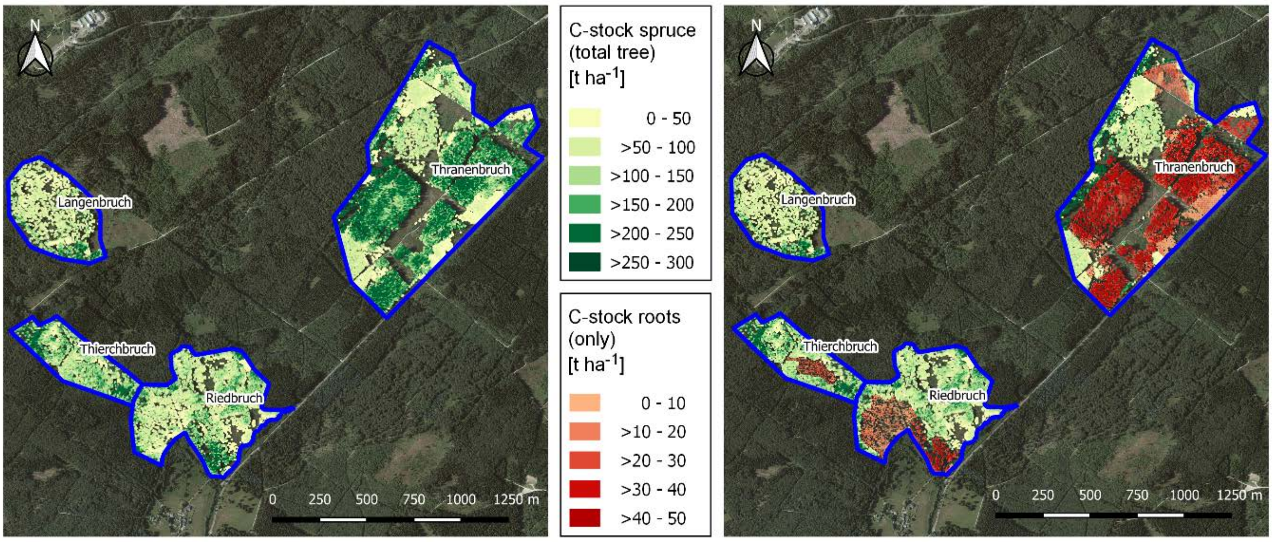

Figure 7. Distribution of spruce forest carbon stocks at monitoring sites before and after tree removal. Red areas indicate tree removal with loss of biomass carbon and leaving roots (C-stocks of roots) on the sites.

Table 3. Total carbon stocks (mean (± SD) of subtotals) of soils, roots, stems and branches before and after tree removal at the monitoring sites. The soil and root C stock were assumed not to have altered substantially.

Peatland	Soil C stock (t)		Root C stock (t)		Before 2015				After 2018			
					Stem C stock (t)		Branches, needles, brushwood C stock (t)		Stem C stock (t)		Branches, needles, brushwood C stock [t]	
Thranenbruch	11,286 (155±414)	n=73	884 (0.06±0.03)	n=15,354	3,143 (0.20±0.11)	n=15,354	1,486 (0.10±0.05)	n=15,354	473 (0.14±0.09)	n=3,815	223 (0.06±0.04)	n=3,815
Riedbruch	7958 (38±42)	n=211	281 (0.04±0.02)	n=6,656	998 (0.15±0.08)	n=6,656	472 (0.07±0.04)	n=6,656	725 (0.15±0.08)	n=4,782	343 (0.07±0.04)	n=4,782
Thierchbruch	1,762 (13±16)	n=135	147 (0.05±0.02)	n=2,734	523 (0.19±0.08)	n=2,734	247 (0.09±0.04)	n=2,734	458 (0.19±0.08)	n=2,371	217 (0.08±0.04)	n=2,371
Langbruch	3,218 (51±157)	n=63	90 (0.04±0.02)	n=2,512	319 (0.13±0.08)	n=2,512	151 (0.06±0.04)	n=2,512	319 (0.13±0.08)	n=2,512	151 (0.06±0.04)	n=2,512
Johannenbruch	77 (11±11)	n=7	342 (0.04±0.02)	n=7,824	1,216 (0.16±0.08)	n=7,824	575 (0.07±0.04)	n=7,824	1,216 (0.16±0.08)	n=7,824	575 (0.07±0.04)	n=7,824
Total	24,300 (50±177)	n=489	1.744 (0.05±0.03)	n=35,080	6,200 (0.18±0.10)	n=35,080	2,931 (0.08±0.05)	n=35,080	3,192 (0.15±0.08)	n=21,250	1509 (0.07±0.04)	n=21,250

During the restoration programme, most of the spruce forests were felled. All parts of the trees except roots and stumps were taken away from the monitoring sites, leaving the roots C pool on the sites (Figure 8).

Total carbon stocks

The total soil C stock of the five monitoring sites is about 24,300 t (mean ± SD of subtotals 50 ± 177) with almost half of the soil C stock stored in the Thranenbruch peatland (Table 3). The spruce forest stored about 10,875 t (mean of subtotals 0.16 ± 0.15) in the vegetation (including roots and branches, and other above ground biomass) prior to thinning and tree removal. After tree removal, this was reduced to about 6,445 t of C (mean of subtotals 0.23 ± 0.13) in the spruce forest.

At three monitoring sites (Thranenbruch, Riedbruch and Thierchbruch) removal of spruce forest was done as part of peatland restoration activities. At these three monitoring sites about 54 ha were thinned (corresponding to about 41 % of the total area at these sites). The tree removal process reduces the aboveground C stocks in the spruce forests by about 50 %, and as a result approximately 4,430 t (mean of subtotals 0.32 ± 0.15) were exported from the monitoring sites (Figure 8). As the roots were left on the sites and we expected no changes of soil C stocks due to tree removal activities, these pools were assumed to have remained stable between the years 2015 and 2018. Prior to tree removal at the monitoring sites, about one third of the total C stock was stored in the forest and two thirds in the soil. After the tree removal, proportionally more C was held in the soil pool (Figure 8).

Extrapolation of the soil C stocks from the monitoring sites to the area of the whole National Park leads to an estimate of 171,530 t of C in the peatland soils including peaty mineral soils (Figure 9). The spruce forest of the National Park contains an estimated 544,282 t of C as biomass.

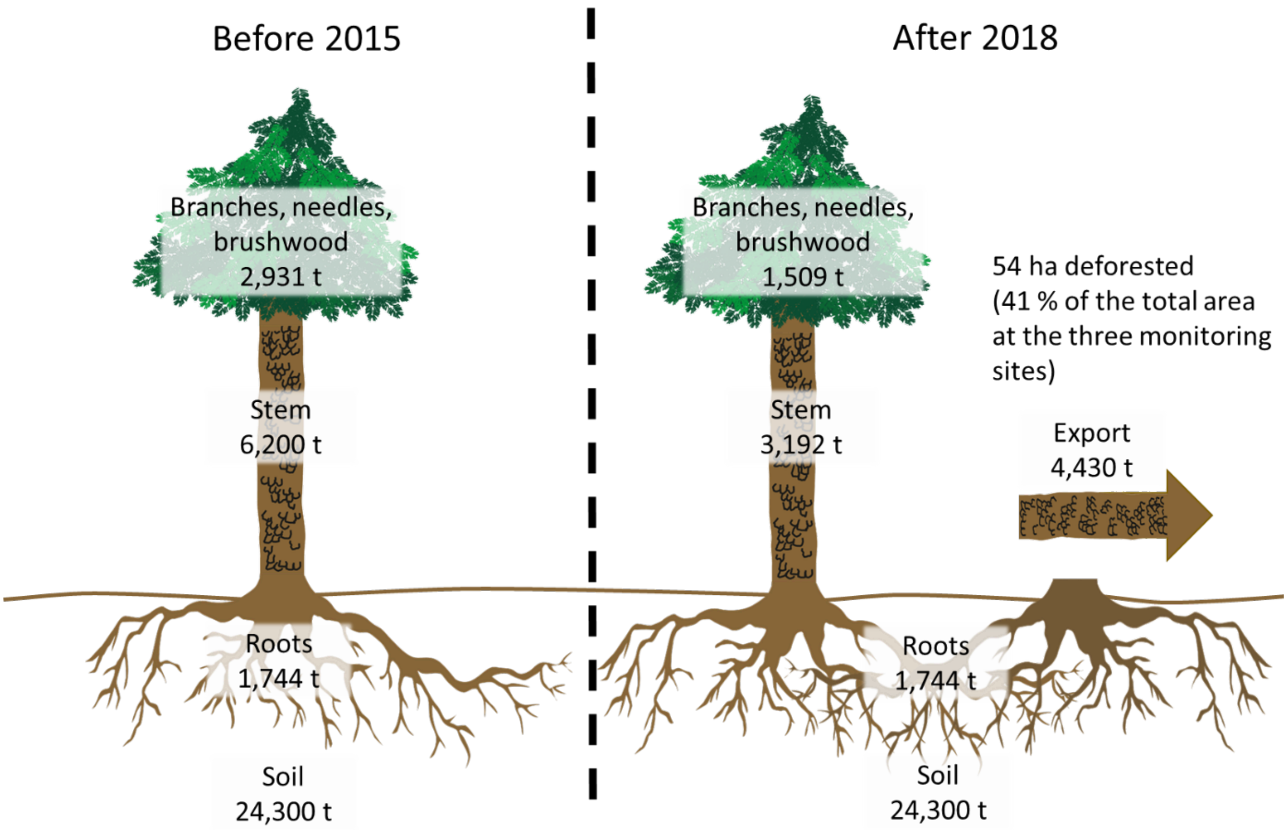

Figure 8. Total carbon stocks from monitoring sites of peatland forests before (left) and after the tree removal (right).

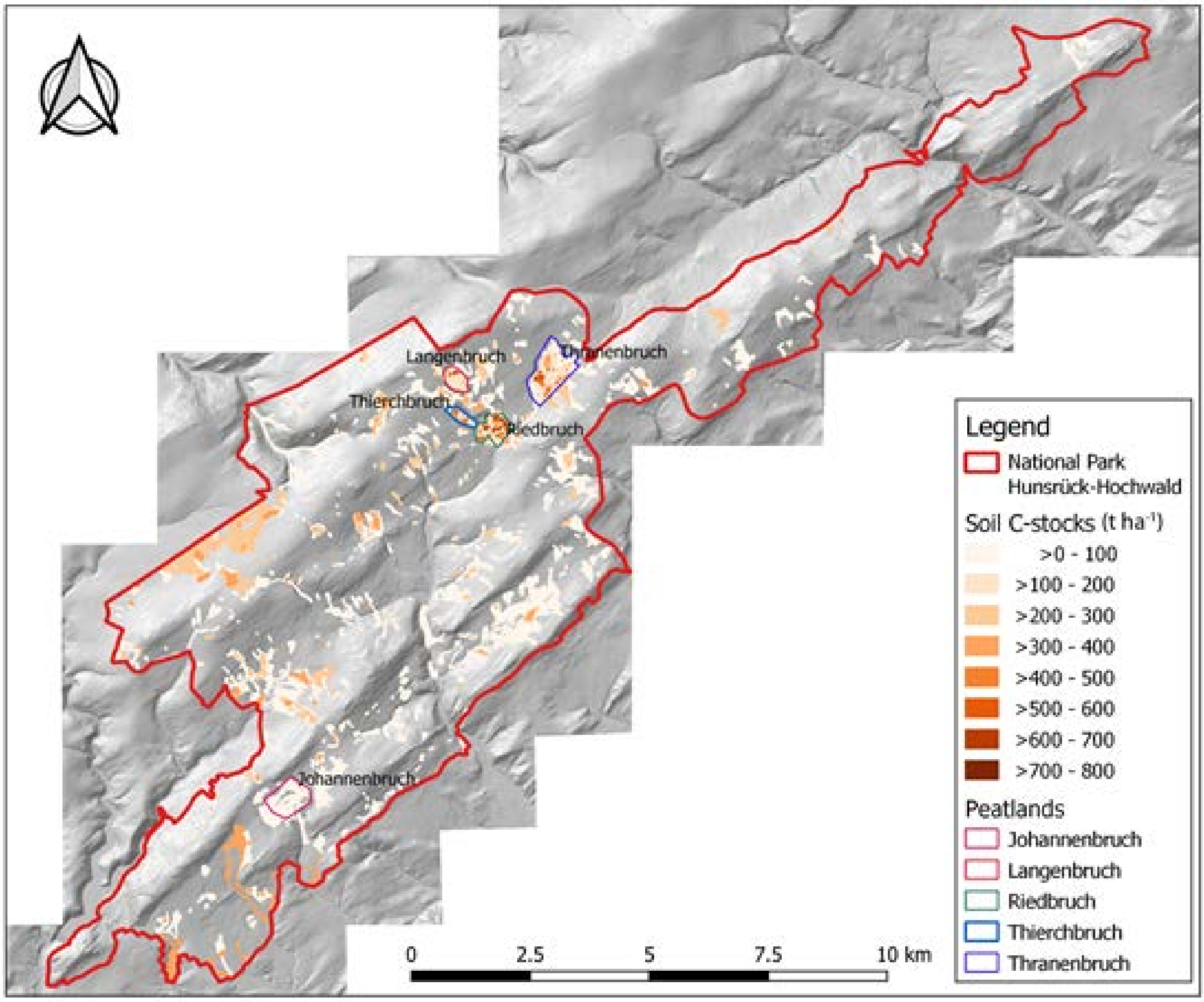

Figure 9. Extrapolation map of soil carbon stocks at the National Park Hunsrück-Hochwald.

DISCUSSION

Soil properties

Soil properties of the investigated soil profiles are in the range of other natural and drained peatlands from temperate regions (Loisel *et al.* 2014). However most of the peat is strongly decomposed with the degree of humification ranging from H6–H10 (von Post 1922). This likely reflects the influence of drainage activities on the rate of decomposition of the peat organic matter; there is an inferred loss of organic material due to oxidation and mineralisation of peat substrates. This is suggested by the increasing degree of decomposition with decreasing organic matter contents (Figure 4). Organic C contents from 40 to 45 % in slightly decomposed and 30 to 40 % in strongly decomposed peat material are low compared to other peatlands under forestry use (Wüst-Galley *et al.* 2016). A comparison of organic C content and degree of decomposition from the study by Roßkopf *et al.* (2015) showed similar values to our results.

Bulk density values for undrained peats are usually below 0.10 g cm^{-3} (Minkkinen & Laine 1998, Leifeld *et al.* 2011, Krüger *et al.* 2015). Previous studies have shown that drainage for forestry can lead to an increase in bulk density, particularly in the upper horizons of the peat profile with typical values of more than 0.15 g cm^{-3} (Leifeld *et al.* 2011, Krüger *et al.* 2016). A nationwide determination of peat bulk densities of drained and undrained peatlands in Finland found a significant increase in bulk density down to 60 cm depth which was attributed to the drainage of peatlands for forestry (Minkkinen & Laine 1998). In Switzerland, peatlands with different forest types have mean bulk density values of 0.09 to 0.13 g cm^{-3} (Wüst-Galley *et al.* 2016). Our results (Figure 4) are comparable to these findings as less decomposed peat showed lower bulk density values of about 0.10 g cm^{-3}, whereas more decomposed peats had higher values between 0.20 and 0.30 g cm^{-3}. This is comparable to the findings from Roßkopf *et al.* (2015) who found increasing bulk densities with increasing degree of decomposition. The data of Roßkopf *et al.* (2015) show a high degree of variability, but the general correlation applies to both fens and bogs.

Soil carbon stocks

The soil C stocks of the monitoring sites show a heterogeneous distribution (Figure 5). Some smaller parts of the monitoring sites have high C stocks, comparable to soil C stocks of forest peatlands in Switzerland investigated by Wüst-Galley *et al.* (2016). They found mean soil C stocks of 495 t ha^{-1} (ranging from around 200 to 900 t ha^{-1}) down to 1 m depth (Wüst-Galley *et al.* 2016). This can rise to a C stock of over 1,000 t ha^{-1} in deeper soils of peatland forests for example in Finland (Minkkinen *et al.* 1999).

C stock calculations are mainly affected by the values obtained for C concentrations, bulk density and thickness of the peat layer. Our results accord with other studies, in that soil C stock calculations are more influenced by bulk density (and thickness of the peat layer) than C concentrations (Krüger *et al.* 2015, Wüst-Galley *et al.* 2016, Glina *et al.* 2019). However, the thickness of organic soils does not correlate with greenhouse gas emissions, as shallow organic soils can emit a quantity of greenhouse gases equal to that of deep peat soils (Leiber-Sauheitl *et al.* 2014). The water table of a peatland is generally the main driving influence on greenhouse gas emissions (Moore & Knowles 1989). Flooded conditions during rewetting might cause high CH_4 emissions, while fluctuating water tables might enhance N_2O emissions (Osterloh *et al.* 2018). These organic soils can be hot spots of greenhouse gas emissions and can dominate the regional greenhouse gas budget (Jungkunst *et al.* 2004, Tiemeyer *et al.* 2016). However, greenhouse gases have not been measured at these sites. This first detailed distribution map of soil C stocks could be used to return to the sites in the future, applying the re-sampling method (Simola *et al.* 2012) to enable a comparison of present soil C stocks and future soil C stocks. This allows an estimate of C losses or gains to be produced for the peatland soils.

The greenhouse gas exchange of a peatland is crucial for determining if the peatland is a C sink or source. CO_2 from mineralisation of the soil organic matter is, in most cases, the largest component of greenhouse gas emissions from peatland soils. Clearcutting and rewetting of peatlands formerly managed for forestry strongly affects the C dynamics (Mäkiranta *et al.* 2010, Rigney *et al.* 2018). The short-term effect of clearcutting is a strong climate warming effect with accelerated emissions of greenhouse gases turning the peatland into a large C source (Korkiakoski *et al.* 2019). Alongside the drastic changes in micrometeorological conditions and missing input by vegetation, the retention of logging residue increases the release of C from the soil organic matter store (Mäkiranta *et al.* 2012). Logging residues will decompose relatively fast, and may enhance the decomposition rate of the underlying peat soil (Mäkiranta *et al.*, 2012). Rewetting of formerly used peatland forests does not necessary re-establish the C sink function in the short term (Rigney *et al.* 2018). Removal of all fresh organic matter (e.g. branches) is recommended to limit both CO_2 emissions as a result of priming effects and the introduction of non-peatland species (Rigney *et al.* 2018). The greenhouse gas balance of these peatlands, especially of clear-cutting or thinned peatland forests, is still an open question.

Forest carbon stocks

Our calculated forest C stocks are substantially higher (mean value of 71 t ha^{-1} at monitoring sites before tree removal) compared to other drained peatland forest in the boreal region (Minkkinen *et al.* 1999). However, compared to mineral soils, where spruce forests store an estimated 87 t ha^{-1} of C (Wördehoff *et al.* 2011), the C storage of the peatland forests in the present study is substantially lower.

Other studies have shown that most boreal and temperate drained peatland forests act as contemporary C sinks (Meyer *et al.* 2013, Ojanen *et al.* 2013, Hommeltenberg *et al.* 2014), because the tree stand C sequestration exceeds the loss of C from soil. On the other hand, harvesting typically leaves tree stumps and roots at the site, increasing the soil C stock. The portion of the C captured by the trees that is left below ground when they are felled consists of roots, litter and soil organic matter derived from these. In addition, the stumps, branches and top parts of the stems are normally left on the ground after harvesting.

The decomposition of this coarse woody debris in peat soil is slow and so leaving it at the site will compensate for soil C losses for several years (Minkkinen *et al.* 2018). Further, the water table will rise because of the removal of the transpiring tree stand, likely reducing peat decomposition. However, this reduction is probably small and the site is likely to be a strong C source at least for the first few years, after which the growing vegetation again starts to bind C to the ecosystem (Mäkiranta *et al.* 2010). Nevertheless, in peatlands used for forestry the soil C storage is important in the long term, because the tree stock will eventually be harvested and the C in wood products will gradually be lost back to the atmosphere (Minkkinen *et al.* 2018). Thus, the most relevant question is whether the sites remain C sinks, especially the soil, in the long term if they are managed for forestry.

The rewetting of peatland forests in order to re-establish the C sink function of these ecosystems is a long-term approach. It requires both raising the water table to natural conditions and re-establishing typical peatland vegetation. This will increase the likelihood of returning the C sink function to the peatland. However, raising the water table might be a difficult task taking into account the small-scale heterogeneity of the subsurface at the investigated sites (cf. Trappe & Kneisel 2019). It is difficult to achieve a uniformly high water table for the whole peatland area, especially for peatlands with a steep slope. The non-native biomass should be exported from the rewetting sites in order to reduce the volume of fresh organic matter on the site and thereby limit CO_2 emissions from the decomposition of remaining litter, the priming effect and possibly the introduction of non-peatland species (Rigney *et al.* 2018).

Total carbon stocks

The extrapolation of the C stocks produced a C storage estimate which was three times higher for the spruce forest compared to the soil C stocks in the peatlands. However, spruce forests are distributed all over the National Park whereas potential peatlands only cover about 13 % of the National Park area. This indicates the high C density of the peatland areas, especially the peatland soils.

Any loss of C from peat soils may be offset by gains of C stored in tree biomass, litter and new soil organic matter. The true C balance then depends partly on the fate of the wood produced (Minkkinen *et al.* 2002). The quality and longevity of the wood products that arise from forestry will determine whether or not the harvested portion of the C captured by the trees is sequestered over long timescales (Laine *et al.* 1992, Ojanen *et al.* 2013). In areas with high-quality wood this timber may be used for long-lifespan uses purposes like construction, effectively storing the C for many decades or even centuries (Sloan *et al.* 2018).

In situations where rewetting activities will not establish high water tables and the rewetted peatland will remain a C source, it is possible that the most favourable C balance for the study site may in fact be reached by leaving the trees growing on the peatland (Rigney *et al.* 2018).

Implications

Peatlands, here slope peatlands, are typical landscape features in the National Park Hunsrück-Hochwald. Despite their relatively small areas and their specific site conditions, these peatlands store substantially more C unit area than mineral soils. Even the shallow peatlands at the monitoring sites in the present study store almost twice as much C in the soil as in the vegetation. Tree removal from these peatlands reduced the C stocks of the spruce forest by 4,430 t across the monitoring sites, however this accounts for less than 1 % of the spruce forest C stocks in the National Park Hunsrück-Hochwald.

Small peatland areas can contribute a relatively large proportion of emissions to the regional greenhouse gas budget. Therefore, measurements of greenhouse gases at the rewetted sites as well as on the peaty mineral soils are necessary to evaluate if these peatlands are C sinks or sources, as their greenhouse gas emissions can be equal to those of deep peatland soils. Peatland rewetting projects should not only be attended by vegetation studies, but also by monitoring studies examining water table dynamics, soil C balance and biomass C, in order to determine changes in ecosystem-relevant factors. Geobotanical research with age-dating methods has showed that these peatlands have an age of a few hundred years (Kopf *et al.* 2019), and the (past/present) C accumulation (rates) of these peatlands should be investigated in detail. Furthermore, in the future a re-measurement of C stocks could be done applying the re-sampling method (Simola *et al.* 2012), enabling a comparison between our C stocks and future C stock measurements. Peatland forests, with their small area, high C density and potentially low–quality wood, should be managed for C storage rather than for timber production (Wüst-Galley *et al.* 2016).

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AUTHOR CONTRIBUTIONS

GS and MD conceived the original idea and supervised the project. CK carried out soil sampling. ASS, SH and JPK did the GIS-analyses and C stock calculations. SD, SN and JS worked on LiDAR data and contribute to the data of forest C stocks. JPK wrote the paper with contributions of all co-authors.

REFERENCES

AG-Boden (2005) *Bodenkundliche Kartieranleitung* (*Manual of Soil Mapping*). Version 5, Schweizerbart, Hannover, 438 pp. (in German).

Backes, C., Gallus, M., Schubert, D., Schüler, G. Vasel, R. (2007) Entschärfung von linearen Abflüssen durch vorsorgende Wegebautechnik (Mitigation of linear outflows by preventive track structural engineering). In: Schüler, G., Gellweiler, I., Seeling, S. (eds.) *Dezentraler Wasserrückhalt in der Landschaft durch vorbeugende Maßnahmen der Waldwirtschaft, der Landwirtschaft und im Siedlungswesen* (*Decentralised Water Retention in the Landscape due to Preventive Measures in Forestry Management, Agriculture and Settlement*), Mitteilungen FAWF 64/07, Struktur- und Genehmigungsdirektion Süd, Forschungsanstalt für Waldökologie und Forstwirtschaft Rheinland-Pfalz, Trippstadt, 51–60 (in German).

Bauriegel, A. (2005) *Methoden zur Ableitung und Parametrisierung von flächenbezogenen Profil- und Horizontdaten* (*Methods for the Derivation and Parameterisation of Areal Profile and Horizon Data*). PhD thesis, Humboldt-Universität zu Berlin, 156 pp. (in German).

Beetz, S., Liebersbach, H., Glatzel, S., Jurasinski, G., Buczko, U., Höper, H. (2013) Effects of land use intensity on the full greenhouse gas balance in an Atlantic peat bog. *Biogeosciences*, 10, 1067–1082.

Christensen, T.R., Friborg, T. (eds.) (2004) *EU Peatlands: Current Carbon Stocks and Trace Gas Fluxes*. Discussion paper from a workshop in Lund Sweden (October 2003), contribution to the project 'Concerted Action CarboEurope-GHG', University of Lund and GeoBiosphere Science Centre, Lund, Sweden, 58 pp.

Dargie, G.C., Lewis, S.L., Lawson, I.T., Mitchard, E.T., Page, S.E., Bocko, Y.E., Ifo, S.A. (2017) Age, extent and carbon storage of the central Congo Basin peatland complex. *Nature*, 542, 86–90, https://doi.org/10.1038/nature21048.

DIN ISO 10694 1996-08. Soil quality - Determination of organic and total carbon after dry combustion (elementary analysis) (ISO 10694:1995).

Drösler, M., Adelmann, W., Augustin, J., Bergman, L., Beyer, C., Chojnicki, B., Förster, C., Freibauer, A., Giebels, M., Görlitz, S., Höper, H., Kantelhardt, J., Liebersbach, H., Hahn-Schöfl, M., Minke, M., Petschow, U., Pfadenhauer, J., Schaller, L., Schägner, P., Sommer, M., Thuille, A., Werhan, M. (2013) *Klimaschutz durch Moorschutz* (*Climate Protection by Peatland Protection*). Final Report of the Project "Climate Protection - Peatland Usage Strategies 2006–2010", Technische Informationsbibliothek und Universitätsbibliothek, Hannover, 190 pp. (in German). Online at: http://edok01.tib.uni-hannover.de/edoks/e01fb13/735500762.pdf, accessed 19 Feb 2021.

FAO (2010) *Global Forest Resources Assessment*. Main report, Food and Agriculture Organization of the United Nations (FAO), Rome, 163 pp.

Fazakas, Z., Nilsson, M., Olsson, H. (1999) Regional forest biomass and wood volume estimation using satellite data and ancillary data. *Agricultural and Forest Meteorology*, 98–99, 417–425.

Glina, B., Gajewski, P., Mendyk, Ł., Zawieja, B., Kaczmarek, Z. (2019) Recent changes in soil properties and carbon stock in fen peatlands adjacent to open-pit lignite mines. *Land Degradation and Development*, 30(18), 2371–2380.

Gong, G. (1986) Cross-validation, the jackknife, and the bootstrap: Excess error estimation in forward logistic regression. *Journal of the American Statistical Association*, 81(393), 108–113.

Haß, E. (2015) Texture-based classification of forest types using high resolution aerial photographs. Master thesis, Trier University, 120 pp.

Hommeltenberg, J., Schmid, H.P., Drösler, M., Werle, P. (2014) Can a bog drained for forestry be a stronger carbon sink than a natural bog forest? *Biogeosciences*, 11(13), 3477–3493.

Humpenöder, F., Karstens, K., Lotze-Campen, H., Leifeld, J., Menichetti, L., Barthelmes, A., Popp, A. (2020) Peatland protection and restoration are key for climate change mitigation. *Environmental Research Letters*, 15, 104093, 12 pp.

IPCC (2014) *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands*. Hiraishi, T., Krug, T., Tanabe, K., Srivastava, N., Baasansuren, J., Fukuda, M., Troxler, T.G. (eds.), IPCC, Switzerland, 354 pp.

Jacobsen, C., Rademacher, P., Meesenburg, H. Meiwes, K.J. (2003) *Gehalt chemischer Elemente in Baumkompartimenten - Literaturstudie und*

Datensammlung (*Content of Chemical Elements in Tree Compartments - Literature Study and Data Collection*). Berichte des Forschungszentrums Waldökosysteme B69, Göttingen, Germany, 79 pp. (in German).

Joosten, H., Clarke, D. (2002) *Wise Use of Mires and Peatlands: Background and Principles Including a Framework for Decision-Making.* International Mire Conservation Group and International Peat Society, Saarijärvi, Finland, 307 pp.

Jungkunst, H.F., Fiedler, S., Stahr, K. (2004) N_2O emissions of a mature Norway spruce (*Picea abies*) stand in the Black Forest (southwest Germany) as differentiated by the soil pattern. *Journal of Geophysical Research: Atmospheres*, 109, D07302, 11 pp.

Jungkunst, H.F., Krüger, J.P., Heitkamp, F., Erasmi, S., Fiedler, S., Glatzel, S., Lal, R. (2012) Accounting more precisely for peat and other soil carbon resources. In: Lal, R., Lorenz, K., Hüttl, R., Schneider, B., von Braun, J. (eds.) *Recarbonization of the Biosphere*, Springer, Dordrecht, Netherlands, 127–157.

Jungkunst, H.F., Horvath, T., Erasmi, S., Krüger, J.P., Meurer, K.H., Schützenmeister, K., Guillaume, T., Scholten, T., Baumann, F., Schleuss, P.M., He, J.S., Kühn, P., Henkner, J., Boy, J., Katterer, T., Schneider, J. (2018) Regionally diverse land-use driven feedbacks from soils to the climate system. In: Lal, R., Stewart, B.A. (eds.) *Soil and Climate*, CRC Press, Boca Raton, USA, 61–130.

Kopf, C., Segatz, E., Kneisel, C., Stoffels, J., Krüger, J.P., Dotterweich, M., Schüler, G. (2019) Hypothese der Moorgenese südwestdeutscher Mittelgebirgsmoore anhand bodenkundlicher, hydrologischer und geobotanischer Aspekte (Hypothesis of the peatland genesis of south-west German low mountain bogs on the basis of pedological, hydrological and geobotanical aspects). *BGS Bulletin,* 40, 53–60 (in German with English abstract).

Korkiakoski, M., Tuovinen, J.P., Penttilä, T., Sarkkola, S., Ojanen, P., Minkkinen, K., Rainne, J., Laurila, T., Lohila, A. (2019) Greenhouse gas and energy fluxes in a boreal peatland forest after clearcutting. *Biogeosciences*, 16, 3703–3723.

Krüger, J.P., Leifeld, J., Glatzel, S., Szidat, S., Alewell, C. (2015) Biogeochemical indicators of peatland degradation - a case study of a temperate bog in northern Germany. *Biogeosciences*, 12(10), 2861–2871.

Krüger, J.P., Alewell, C., Minkkinen, K., Szidat, S., Leifeld, J. (2016) Calculating carbon changes in peat soils drained for forestry with four different profile-based methods. *Forest Ecology and Management*, 381, 29–36.

Laine, J., Vasander, H., Puhalainen, A. (1992) A method to estimate the effect of forest drainage on the carbon store of a mire. *Suo*, 43(4–5), 227–230.

Lamprecht, S., Stoffels, J., Udelhoven, T. (2020) ALS as tool to study preferred stem inclination directions. *Remote Sensing*, 12(22), 3744, 29 pp.

Latifi, H., Nothdurft, A., Koch, B. (2010) Non-parametric prediction and mapping of standing timber volume and biomass in a temperate forest: application of multiple optical/LiDAR-derived predictors. *Forestry*, 83(4), 395–407.

Leiber-Sauheitl, K., Fuß, R., Voigt, C., Freibauer, A. (2014) High CO_2 fluxes from grassland on histic Gleysol along soil carbon and drainage gradients. *Biogeosciences*, 11(3), 749–761.

Leifeld, J., Menichetti, L. (2018) The underappreciated potential of peatlands in global climate change mitigation strategies. *Nature Communications*, 9, 1071, 7 pp.

Leifeld, J., Gubler, L., Grünig, A. (2011) Organic matter losses from temperate ombrotrophic peatlands: an evaluation of the ash residue method. *Plant and Soil*, 341(1), 349–361.

Loisel, J., Yu, Z., Beilman, D.W., Camill, P. and 56 others (2014) A database and synthesis of northern peatland soil properties and Holocene carbon and nitrogen accumulation. *The Holocene*, 24(9), 1028–1042.

Mäkiranta, P., Riutta, T., Penttilä, T., Minkkinen, K. (2010) Dynamics of net ecosystem CO_2 exchange and heterotrophic soil respiration following clearfelling in a drained peatland forest. *Agricultural and Forest Meteorology*, 150(12), 1585–1596.

Mäkiranta, P., Laiho, R., Penttilä, T., Minkkinen, K. (2012) The impact of logging residue on soil GHG fluxes in a drained peatland forest. *Soil Biology and Biochemistry*, 48, 1–9.

McRoberts, R., Tomppo, E. (2007) Remote sensing support for national forest inventories. *Remote Sensing of Environment*, 110(4), 412–419.

Meyer, A., Tarvainen, L., Nousratpour, A., Björk, R. and 9 others (2013) A fertile peatland forest does not constitute a major greenhouse gas sink. *Biogeosciences*, 10(11), 7739–7758.

Minkkinen, K., Laine, J. (1998) Effect of forest drainage on the peat bulk density of pine mires in Finland. *Canadian Journal of Forest Research*, 28(2), 178–186.

Minkkinen, K., Vasander, H., Jauhiainen, S., Karsisto, M., Laine, J. (1999) Post-drainage changes in vegetation composition and carbon balance in Lakkasuo mire, Central Finland. *Plant* *and Soil*, 207(1), 107–120.

Minkkinen, K., Korhonen, R., Savolainen, I., Laine, J. (2002) Carbon balance and radiative forcing of Finnish peatlands 1900–2100 - the impact of forestry drainage. *Global Change Biology*, 8(8), 785–799.

Minkkinen, K., Ojanen, P., Penttilä, T., Aurela, M., Laurila, T., Tuovinen, J.P., Lohila, A. (2018) Persistent carbon sink at a boreal drained bog forest. *Biogeosciences*, 15, 3603–3624.

Moore, T.R., Knowles, R. (1989). The influence of water table levels on methane and carbon dioxide emissions from peatland soils. *Canadian Journal of Soil Science*, 69(1), 33–38.

Nichols, J.E., Peteet, D.M. (2019) Rapid expansion of northern peatlands and doubled estimate of carbon storage. *Nature Geoscience*, 12(11), 917–921.

Nilsson, M., Bohlin, J., Olsson, H., Svensson, S.A., Haapaniemi, M. (2005) Operational use of remote sensing for regional level assessment of forest estate values. In: Oluić, M. (ed.) *New Strategies for European Remote Sensing*: *Proceedings of the 24th Symposium of the European Association of Remote Sensing Laboratories*, *Dubrovnik, Croatia, 25–27 May 2004*, IOC Press (Millpress), Rotterdam, 263–268.

Nink, S., Hill, J., Buddenbaum, H., Stoffels, J., Sachtleber, T., Langshausen, J. (2015) Assessing the suitability of future multi- and hyperspectral satellite systems for mapping the spatial distribution of Norway spruce timber volume. *Remote Sensing*, 7(9), 12009–12040.

Ojanen, P., Minkkinen, K., Penttilä, T. (2013) The current greenhouse gas impact of forestry-drained boreal peatlands. *Forest Ecology and Management*, 289, 201–208.

Ojanen, P., Mäkiranta, P., Penttilä, T., Minkkinen, K. (2017) Do logging residue piles trigger extra decomposition of soil organic matter? *Forest Ecology and Management*, 405, 367–380.

Osterloh, K., Tauchnitz, N., Spott, O., Hepp, J., Bernsdorf, S., Meissner, R. (2018) Changes of methane and nitrous oxide emissions in a transition bog in central Germany (German National Park Harz Mountains) after rewetting. *Wetlands Ecology and Management*, 26(1), 87–102.

Peerenboom, H.G., Ontrup, G., Böhmer, O. (2003) Weiterentwicklung der forsteinrichtung in Rheinland-Pfalz (Further development in the forest institution in Rhineland-Palatinate). *Forst und Holz*, 58(23–24), 728–730 (in German).

Pitkänen, A., Turunen, J., Tahvanainen, T., Simola, H. (2013) Carbon storage change in a partially forestry-drained boreal mire determined through peat column inventories. *Boreal Environment Research*, 18, 223–234.

Reese, H., Nilsson, M., Granqvist Pahlén, T., Hagner, O., Tingelöf, U., Egberth, M., Olsson, H. (2003) Countrywide estimates of forest variables using satellite data and field data from the national forest inventory. *AMBIO: A Journal of the Human Environment*, 32(8), 542–548.

Reichert, H. (1975) *Die Quellmoore (Brücher) des südwestlichen Hunsrücks* (*The Spring Mires (Brücher) of the Southwestern Hunsrück*). Landesamt für Umwelt Rheinland-Pfalz, Mainz, Germany, 3, 101–164 (in German).

Rigney, C., Wilson, D., Renou-Wilson, F., Müller, C., Moser, G., Byrne, K.A. (2018) Greenhouse gas emissions from two rewetted peatlands previously managed for forestry. *Mires and Peat*, 21, 24, 23 pp.

Roßkopf, N., Fell, H., Zeitz, J. (2015) Organic soils in Germany, their distribution and carbon stocks. *Catena*, 133, 157–170.

Ruthsatz, B. (1999) Die Quellwässer von hangmooren im Hunsrück (Rheinland-Pfalz). Chemismus und einfluss auf vegetation und flora (Spring waters of slope mires in the Hunsrück (Rhineland-Palatinate). Chemism and influence of vegetation and flora). *Archiv für Naturschutz und Landschaftsforschung*, 38, 1–41 (in German).

Schüler, G. (2012) *Waldmoore - im Spannungsfeld zwischen Naturschutz und Forstwirtschaft* (*Forest Peatlands - in the Conflict of Nature Protection and Forest Management*). Forschungsanstalt für Waldökologie und Forstwirtschaft Rheinland-Pfalz, 12 pp. Online at: https://docplayer.org/41363406-Zusammenfassung-moore-waldmoore-und-bruchwaelder-und-ihre-gefaehrdung. html, accessed 28 Oct 2019.

Simola, H., Pitkänen, A., Turunen, J. (2012) Carbon loss in drained forestry peatlands in Finland, estimated by re-sampling peatlands surveyed in the 1980s. *European Journal of Soil Science*, 63(6), 798–807.

Sloan, T.J., Payne, R.J., Anderson, A.R., Bain, C., Chapman, S., Cowie, N., Gilbert, P., Lindsay, R., Mauquoy, D., Newton, A.J. Andersen, R. (2018) Peatland afforestation in the UK and consequences for carbon storage. *Mires and Peat*, 23, 01, 17 pp.

Strogies, M., Gniffke, P. (2014) *Submission Under the United Nations Framework Convention on Climate Change and the Kyoto Protocol 2014. National Inventory Report for the German Greenhouse Gas Inventory 1990–2012*. Climate Change 28, Umweltbundesamt, Dessau-Roßlau, Germany, 956 pp.

Tanneberger, F., Wichtmann, W. (2011) *Carbon Credits from Peatland Rewetting: Climate - Biodiversity - Land Use*. Schweizerbart Science Publishers, Stuttgart, Germany, 223 pp.

Tanneberger, F., Tegetmeyer, C., Busse, S., Barthelmes, A. and 55 others (2017) The peatland map of Europe. *Mires and Peat*, 19, 22, 17 pp.

Tiemeyer, B., Albiac Borraz, E., Augustin, J., Bechtold, M. and 19 others (2016) High emissions of greenhouse gases from grasslands on peat and other organic soils. *Global Change Biology*, 22(12), 4134–4149.

Tomppo, E., Katila, M., Mäkisara, K., Peräsaari, J. (2014) *The Multi-source National Forest Inventory of Finland - Methods and Results 2011*. Working Papers of the Finnish Forest Research Institute 319, Finnish Forest Research Institute, Vantaa, Finland, 224 pp. Online at: http://www.metla.fi/julkaisut/workingpapers/2014/mwp319.htm, accessed 28 Oct 2019.

Trappe, J., Kneisel, C. (2019) Geophysical and sedimentological investigations of peatlands for the assessment of lithology and subsurface water pathways. *Geosciences*, 9(3), 118 pp.

von Post, L. (1922) Sveriges geologiska undersöknings torvinventering och några av dess hitills vunna resultat (The Swedish Geological Survey's peat inventory and some of the results so far). *Svenska Mosskulturföreningens Tidskrift*, 36, 1–27 (in Swedish).

Wahl, P., Bushard, M. (2014) *Vegetationskundliche Standortkarte Rheinland-Pfalz* (*Vegetation Science Site Map Rhineland-Palatinate*). Landesamt für Umwelt Rheinland-Pfalz, Mainz, Germany, 212 pp. (in German). Online at: https://lfu.rlp.de/fileadmin/lfu/Naturschutz/Dokumente/HpnV_Erlaeuterungen.pdf, accessed 28 Oct 2019.

Walter, R. (2007) *Geologie von Mitteleuropa* (*The Geology of Central Europe*). Schweizerbart Science Publishers, Stuttgart, Germany, 511 pp. (in German).

Wördehoff, R., Spellmann, H., Evers, J., Nagel, J. (2011) *Kohlenstoffstudie forst und holz Niedersachsen* (*Carbon study on Forestry and Wood in Lower Saxony*). Universitätsverlag Göttingen, Germany, 104 pp. (in German).

Wüst-Galley, C., Mössinger, E., Leifeld, J. (2016) Loss of the soil carbon storage function of drained forested peatlands. *Mires and Peat*, 18, 07, 22 pp.

Yu, Z., Beilman, D.W., Frolking, S., MacDonald, G.M., Roulet, N.T., Camill, P., Charman, D.J. (2011) Peatlands and their role in the global carbon cycle. *Eos, Transactions, American Geophysical Union*, 92(12), 97–98.

Zauft, M., Fell, H., Glaßer, F., Rosskopf, N., Zeitz, J. (2010) Carbon storage in the peatlands of Mecklenburg-Western Pomerania, north-east Germany. *Mires and Peat*, 6, 04, 12 pp.

Zianis, D., Muukkonen, P., Mäkipää, R., Mencuccini, M. (2005) *Biomass and Stem Volume Equations for Tree Species in Europe*. Silva Fennica Monographs 4, Finnish Society of Forest Science/ Finnish Forest Research Institute, Helsinki, 63 pp.

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