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The economy of selective cutting in recent mixed stands during restoration of temperate deciduous forest

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ABSTRACT

Forest cover is increasing in many regions due to spontaneous reforestation on abandoned pastures and fields. The resulting recent forests may need management to improve ecosystem quality, and this could possibly be combined with timber production in specific cases. Temperate deciduous (TD) trees have declined steeply during the past millennium, but some now increase in the recent forests, often mixed with Norway spruce. Removing spruce may benefit these trees and for example oak regeneration, flowering plants and pollination. The total area of forest suitable for restoration in Norway and Sweden is >100,000 ha. We evaluate the cost of selective cutting based on 26 field trials, 13 in each country, and sales from the initial cutting on average just barely compensate for the costs. By resurveying plots from a parallel project in Sweden, we found that about half of the cut volume had regrown after 16 years, and a second thinning may be needed in the near future. Coarse woody debris (CWD) had increased by 78%, indicating increasingly natural conditions. We conclude that selective cutting in recent forests may be part of a strategy to reach restoration and sustainability goals, but that long-term incentives for landowners need to be developed.

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Introduction

Temperate deciduous forest (TDF) is one of the most degraded biomes in Europe and the world (Hannah et al. 1995; Venter et al. 2016), and has declined historically due to the expansion of agriculture (Lindbladh et al. 2007; Spiecker et al. 2004; Löf et al. 2012). However, the standing volume of the constituting tree species, such as oaks (Petersson et al. 2019), during the last decades increased in many regions due to re-establishment on abandoned agricultural land, often developed in mixed stands (Chazdon 2008; Lunt et al. 2010; Sitzia et al. 2010; Kolk et al. 2017). In Scandinavia, for example, overgrowing of arable land is nowadays an ongoing process due to abandonment of marginal lands and intensification in animal husbandry, and the area of such sites with high probability for future reforestation is considerable (Bryn et al. 2013).

Norway and Sweden are dominated by conifer forest, constituting more than 75% of the forested area in each country (Nibio 2016; Swedish Forest Agency 2016). It consists mainly of *Picea abies* (Norway spruce) and *Pinus sylvestris* (Scots pine), while *Betula pubescens* and *B. pendula* (referred to as birch below) are the most common deciduous trees (Moen 1998). In southern Sweden, and further to the north along the west coast of Norway, TDF with "noble deciduous trees" becomes more important (Raab and Vedin 1995; Moen 1998). While the largest volume of noble deciduous trees is found in the southernmost part of Scandinavia, our sites are mainly situated in the boreonemoral zone, a transition zone from the taiga to the temperate forest. The dominant noble tree species in the boreonemoral region are *Ulmus glabra* (elm), *Fraxinus excelsior* (ash), *Tilia cordata* (lime), *Quercus robur* and *Q. petraea* (referred to as oak below), *Acer platanoides* (maple), and to a lesser extent *Fagus sylvatica* (beech). For detailed data on the Swedish TDF, see Götmark (2010). For distribution of TDF in Norway, see Sverdrup-Thygeson et al. (2011) and Nordén et al. (2015).

The resulting recent mixed forests on such sites often yield little income to the landowners, but a combined strategy with emphasis on both timber production and biodiversity may be a way to increase their value (Löf et al. 2016). By testing and designing proper management, it may be possible to restore TDF at low costs. One promising approach is to manage these dense mixed forest through removing (cutting) of the many times dominant Norway spruce (*Picea abies*) while retaining tree species with conservation values. This type of restoration by selective cutting, sometimes called restoration cutting, release cutting, rehabilitation or conservation-oriented thinning, would improve the ecosystem functions of these sites (Zerbe 2002; Götmark 2013; Stanturf et al. 2014). Selective cutting has previously been applied to ecological restoration problems in various contexts (see Götmark 2013; Dwyer and Mason 2018 and references therein), and in near-natural forestry, but there is a need to study the restoration potential of TDF in recent mixed forests containing coniferous and TD tree

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species. Further, the long-term effects on the volume of living and dead trees should be studied in order to draw conclusions on the production potential as well as nature conservation value of the treated forests.

One main factor limiting such activities is the lack of economic incentive, and there is a need to study ways to improve and supplement the economy for forest owners. The cost-effectiveness of restoration is dependent on, e.g. the costs and revenues from any management (e.g. selective cuttings), their area and location, and policies and any subsidies (Armsworth 2014; Blignaut et al. 2014; Kim et al. 2014; BenDor et al. 2015; Iftekhar et al. 2017). The cost of restoration often increases with the degree of degradation (Stanturf and Madsen 2005; Chazdon 2008), while the possibility to utilize natural regeneration on these types of sites greatly improves possibilities for cost-effectiveness (Birch et al. 2010; Meli et al. 2017).

We here focus on some of these factors relevant to abandoned pastures, hay meadows and fields that have been re-colonized with temperate deciduous (TD) and other tree species in mixtures. We utilize data from a field experiment established at 26 sites in southern Norway and Sweden. In addition, we draw conclusions about stand development from a similar but long-term experiment where we study effects 16 years after removal of spruce and other trees (see also Götmark 2013; Leonardsson 2015). Our aim is to study the potential for an increased TDF area in Norway and Sweden through selective cutting, and we ask the following specific research questions:

1. What are the net economic results of selective cutting in abandoned pastures, hay meadows and fields that has been re-colonized with a mixture of trees?
2. How large is the area of forest types relevant for this kind of restoration in the region?
3. How does the standing volume of living trees, and volume standing and lying coarse woody debris (CWD) develop after such cutting?

Except for restoration, these questions relate also to near-natural forestry and conservation management. We use our results to discuss the challenges and feasibility of this type of management. In addition, we discuss potential subsidy systems for favouring such forest restoration.

Methods

Field sites and selective cutting

In 2016, we established 26 field trials, 13 in southern Norway and 13 in southern Sweden (Figure 1).

The sites of the trials were identified with the help of stakeholder organizations and landowners, aerial photographs and field visits. All forests had dry to mesic soil types and consisted of a mixture of TD and other tree species such as spruce and birch. They were 40–80 years old and had closed canopies. The forest had been natural regenerated on abandoned pastures, hay meadows and to a lesser degree on old fields, but showed few recent signs of management for wood production or grazing (e.g. stumps or fences). Out of all sites, 12 had private, 5 had state, 8 municipal and 1 mixed private/state ownership. In addition, 13 of the sites had one or two kinds of protection (see Table 1 for site characteristics and Table S1 for supporting information on forest structures).

At each site, we established two treatment plots, one selective cutting plot and one reference plot (the latter was similar to the treatment plot but used for measurements and left without selective cutting/thinning), each with an area of 1 ha (100×100 m). Trees to be cut were marked by us, and the thinning operation and transportation of felled trees was done by entrepreneurs hired by the project or by the landowners. The main aim of the thinning was restoration, and not optimization of wood production. Therefore, TD trees of all size classes and trees with structures (e.g. cavities, injuries and dead wood) valuable for biodiversity were kept whereas mainly Norway spruce, birch and woody shrubs were cut and removed. The selective cutting and transportation of felled trees was carried out during the winter 2016/2017 and about one-fourth the basal area was removed at each plot.

Evaluation of economic revenue and costs of selective cutting

Information about the harvested volumes and the equipment used for selective cutting was collected from the entrepreneurs/owners who performed the operations. For the Norwegian sites, the harvesting costs were paid by the project. For the Swedish sites, the owners paid the harvesting themselves.

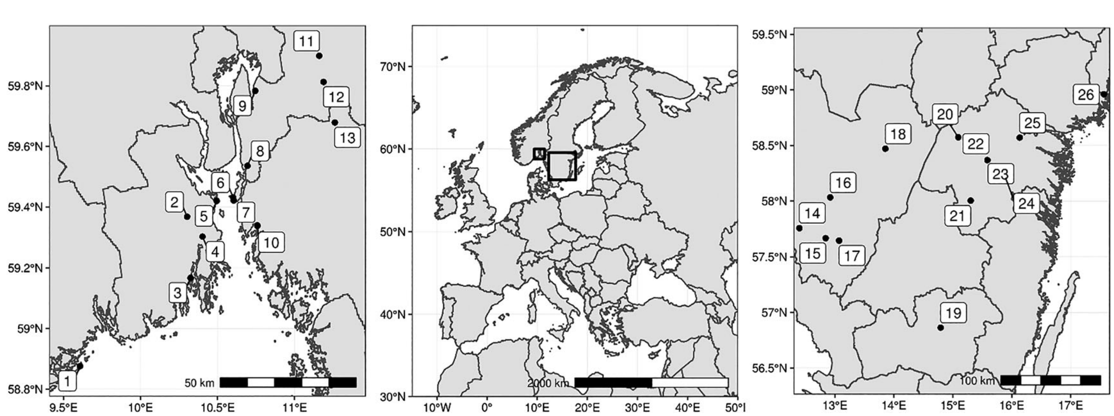

Figure 1. Map of Europe (middle) showing the locations of the 26 sites in Scandinavia. Southern Norway (left) and Sweden (right). Numbers refer to site names in Table 1.

Table 1. Name, county location, protection form if any, and former land use at the 26 sites in the study.

No	Site	County	Owner type	Protection form[a]	Former land use[b]	Vegetation type[c]
	Norway					
1	Jomfruland	Telemark	Private, state	NP	Pasture	Low herb
2	Kåpe	Vestfold	Private	–	Pasture	Low herb
3	Sand	Vestfold	Private	–	Field, pasture, meadow	Low herb, tall herb
4	Berg	Vestfold	State	–	Wooded pasture	Low herb, tall herb
5	Karljohans-vern	Vestfold	State	PWPA	Military training ground with some trees	Low herb
6	Grønli-parken	Østfold	Private	LPA, NR	Field, wooded pasture	Low herb
7	Alby	Østfold	State	LPA	Wooded pasture, meadow	Low herb
8	Kolås	Akershus	Private	NR	Pasture	Low herb, bilberry
9	Svartskog	Akershus	Private	LPA	Field, pasture, meadow	Low herb, tall herb
10	Tasken	Østfold	Private	Partly NR	Pasture, meadow, field	Low herb, tall herb
11	Bjanes	Akershus	Municipality	–	Pasture, meadow	Low herb
12	Omberg	Akershus	Private	–	Pasture, meadow	Low herb, tall herb
13	Håkås	Østfold	Private	–	Pasture	Low herb, tall herb
	Sweden					
14	Tvärsjönäs	Västra Götaland	Private	Partly WKH	Pasture	Low herb
15	Bosnäs	Västra Götaland	Municipality	–	Pasture, meadow	Low herb, tall herb
16	Remmene	Västra Götaland	State	SNUS	Pasture	Low herb
17	Aplared	Västra Götaland	Municipality	–	Wooded pasture, meadow	Low herb
18	Stöpen	Västra Götaland	Municipality	Partly WKH	Pasture, meadow	Low herb, tall herb
19	Bokhultet	Kronoberg	Municipality	NR, Natura 2000	Military training ground with trees	Low herb
20	Motala	Östergötland	Municipality	–	Pasture, meadow	Tall herb
21	Aspenäs	Östergötland	Private	WKH, planned NR	Wooded pasture	Low herb
22	Slaka	Östergötland	Municipality	–	Pasture, meadow	Low herb
23	Hovetorp	Östergötland	Private	–	Pasture, meadow	Low herb, bilberry
24	Kvarntorp	Östergötland	Private	Partly WKH	Pasture, meadow	Low herb
25	Klockare-torpet	Östergötland	Municipality	–	Field, pasture, meadow	Low herb
26	Tullgarn	Stockholm	State	–	Wooded pasture, meadow	Low herb

[a]LPA = Landscape protection area, NR = Nature reserve, NP = National park, PWPA = Plant and wildlife protection area, WKH = Woodland key habitat, SNUS = Protection-worthy state owned forest.
[b]Classified from arial photos from around 1960 and field inspection. The categories refer to the probable main use during the period of most extensive land-use in the late 1800s.
[c]Refers to the dominating vegetation type(s): low-herb woodland, tall-herb woodland, bilberry woodland (Fremstad 1997).

For some Swedish sites, we did not have access to the real costs and used the reported number of hours together with the hourly costs of forest machinery (harvester and forwarder) and manual labour for estimation. The revenue was assessed using the reported harvested timber and chips volumes and average chips and timber prices. Details about the sites and revenue assessments are given below (Table 2). We regressed the net revenue against total harvested volume using

Table 2. Extracted volumes and economic result (per hectare). Only costs and revenues related to timber harvest are included.

Site no.	Timber, m^{3}s	Chips, m^{3}s	Gross income, €[a]	Total cost, €[a]	Net cost, €[a]	Machinery used
1	35	0	1313	1565	−252	Chain saw + tractor
2	53	0	1780	1072	708	Chain saw + tractor + trailer
3	100	0	4021	2948	1072	Chain saw + forwarder
4	35	0	1179	1072	107	Chain saw + tractor
5	11	0	236	991	−755	Bush saw + chain saw
6	40	0	1501	1940	−439	Chain saw + tractor skidding
7	40	0	1608	2016	−407	Chain saw + tractor
8	60	0	2627	1940	687	Chain saw, felling only
9	25	0	965	2160	−1195	Chain saw + tractor skidding
10	20	0	751	1973	−1222	Chain saw + tractor skidding
11	41	0	1833	2520	−686	Harvester + forwarder
12	30	0	643	3399	−2755	Chain saw + harvester + forwarder
13	65	0	3002	1072	1930	Chain saw + tractor
14	60	30	2802	2081	721	Harvester + forwarder
15	1	12	285	6276	−5990	Chain saw + forwarder
16	15	25	1064	2854	−1790	Chain saw + forwarder
17	22	20	1214	11,173	−9959	Chain saw + forwarder
18	na	na	na	na	na	na
19	45	25	2154	2248	−95	Harvester + forwarder
20	50	240	6798	18,251	−11454	Chain saw + tractor + trailer
21	92	0	3342	1026	2316	Harvester + forwarder
22	19	86	2475	8776	−6301	Chain saw + tractor + trailer
23	97	0	3523	2445	1078	Harvester + forwarder
24	na	na	na	na	na	na
25	0	112	2325	7923	−5598	Chain saw + ATV + forestry trailer
26	40	0	1453	1213	240	Harvester + forwarder
Mean	41.5	22.9	2037.3	3705.6	−1668.3	
SD	27.5	54.2	1437.6	4103.1	3603.4	

[a]The annual average exchange rate for 2017 as reported by the central bank of Norway was used when converting NOK and SEK to €. All economic figures are without VAT.

ordinary least squares (using PROC REG in SAS Enterprise Guide 6.1, SAS Institute Inc., 2011).

Estimation of forest area

To quantify the area of potentially available young mixed Norway spruce/TDF for restoration, we obtained data from the National Forest Inventories (NFI) of Norway (Tomter et al. 2010; Granhus et al. 2012) and Sweden (Fridman and Wulff 2018). We defined suitable forest as 40–80 years old mixed forest with 25–75% basal area of TD trees, and the rest mainly spruce, as well as birch and pine. Data was available for two classes of forest, forest with 25–50% TD trees and forest with >50% TD trees, and we make the assumption that half of the area of the latter category have 50–75% TD trees. For Swedish mixed TDF, forest area of different age/size classes with potential conservation and restoration values have earlier also been estimated through NFI, see Götmark (2010).

Estimation of standing volume and growth

Prior to the selective cutting, tree species and diameter at breast height (1.3 m) were determined for all individual trees (>5 cm) in three randomly located circular plots (10 m radius) per treatment plot and site. In total, we measured 2042 trees in the thinning plots and 1835 in the reference plots. In addition, we measured the height of 5–10 sample trees per circular plot, in total 757 observations. These measurements were used to estimate the relationship between tree diameter and tree height. We tested a number of different functional forms yielding about the same goodness of fit (r^2 and root mean square error, RMSE). The chosen function was $\log(\text{height}) = \alpha_i + \beta_j \log(\text{diameter})$, where log() is the natural logarithm, height is tree height in meter, diameter is the breast height diameter in cm, subscript i indicates site (Figure 1) and subscript j indicates tree species. All parameters were significant at 1% level, except for the β for red *Sambucus racemosa* (elderberry; significant at 10%). However, only one tree of this species was registered. Thus the lack of significance for this parameter does not have any practical consequences. The r^2 was 0.86, root mean square error (RMSE) was 0.16 and coefficient of variation was 5.6%, indicating rather good fit. The estimation of the height function was based on all trees with recorded height, i.e. sample trees from both selective cutting and control plots.

The height of the sample trees was estimated using the fitted height function mentioned above. We then used the measured diameter and estimated height to estimate tree volume. For this we used volume functions widely used in Norway (Børset 1954, Braastad 1967, Brantseg 1967, Vestjordet 1967, Hagberg and Matérn 1975). We then used the result from this procedure to produce stand level estimates, including total tree biomass estimates using functions from Eid et al. (2016).

For the study of stand development, we used data from an ongoing long-term study with identical design performed in forest with similar tree species composition but with older oak trees, the Swedish Oak Project (2019). At the 13 sites (Bokhultet, Bondberget, Fagerhult, Fröåsa, Getebro, Hallingeberg, Långhult, Skölvene, Stafsätter, Ulvsdal, Vickleby, Ytterhult, Åtvidaberg), we measured the living trees and CWD (standing and lying dead wood with a diameter >10 cm) in the selective cutting plots in the summer of 2018, 16 years after selective cutting (removal of spruce, birches, and some other trees and large shrubs). To estimate basal area, we used the same methods as in the main study (see above). The result was compared with data on living trees in 2001 presented in Leonardsson and Götmark (2014), Leonardsson (2015), Leonardsson et al. (2015). For CWD, we followed the methods and compared with data presented in Tönnberg (2001) and Nordén et al. (2004).

Results

Extraction of wood and economic results

On average 41.5 ± 27.5 m^3 or ca 22% of the total volume solid of timber (mainly spruce and birch) was removed from the 1 ha thinned plots (Table 2). In addition, the average removal of wood for chips was 50.0 ± 72.6 m^3 solid on the Swedish sites. Chips were not produced at any of the Norwegian sites, and at some of the Swedish sites no or almost no timber was harvested. The chips were, however, mainly produced from harvest residues (branches and tops). In the majority of cases, the trees were felled manually with chain saw, but a harvester was used in seven cases (Table 2). Transportation from the forest to the landing was mainly carried out by forwarders in Sweden, while tractors were mainly used in Norway.

The large variation between and within the plots resulted in a large variation in harvested volumes, and thereby a wide variation in the economic result (Table 2). The mean net timber revenue was negative: −1668 €. The average revenues, costs and net economic results were 31.6, 57.5 and −25.9 €/m^3 solid under bark for timber and chips combined, respectively (Table 3). Some of the Swedish sites (15, 17, 20, 22 and 25) were managed by municipalities and to a large degree used for job training programmes. Cost data from these sites are thus not representative for the restoration costs in general. Excluding these five Swedish sites, data reveals a positive correlation between net revenue and the total volume harvested (chips and timber combined), yielding an equation with parameters significant at 1% level (Table 3).

Although the parameters of the regression equation are highly significant, there is still a large portion of unexplained variation and large error term. This results in a rather wide prediction interval, as shown in Figure 2.

Area of mixed forest on abandoned agricultural land

The area covered by 40–80-year-old TDF forest mixed with Norway spruce and other broadleaves is about 53,000 and

Table 3. Net revenue (€/ha) as a function of harvested volume (timber and chips combined, m^3/ha) including both Norwegian and Swedish sites. $N = 19$, $R^2 = 0.55$ and RMSE = 861.

Variable	Parameter estimate	Standard error	t value	p value
Intercept	−1819	436.66	−4.17	<0.01
Harvested volume	34.4	7.52	4.57	<0.01

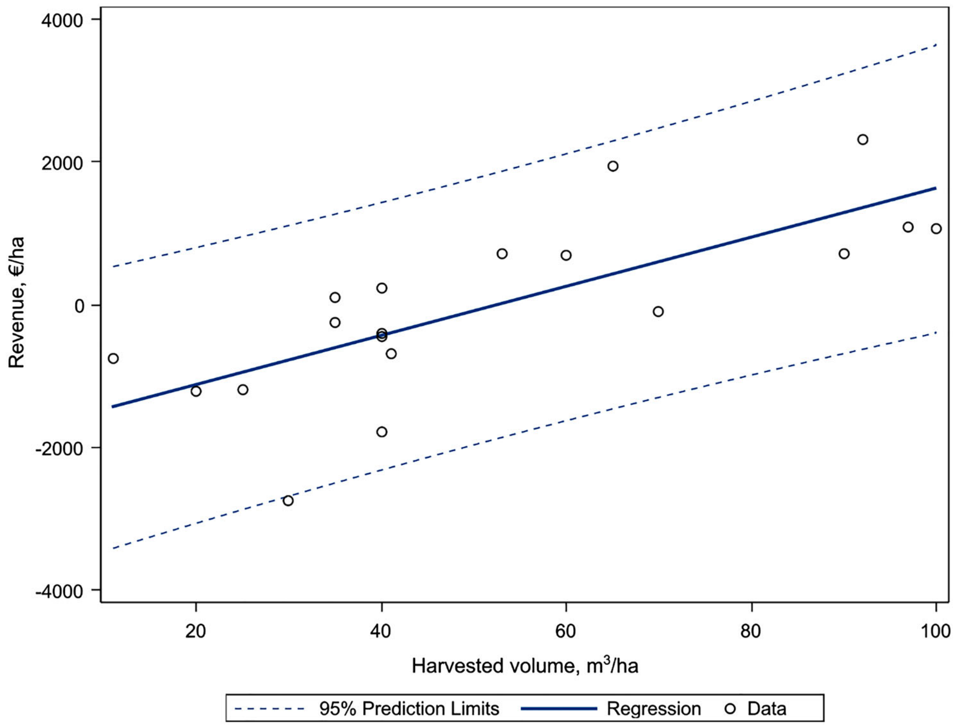

Figure 2. Estimated revenue as a function of reported harvested volume (timber and chips combined). Expected break-even is reached at a volume of about 53 m^3/ha (1819/34.4). There are differences among the sites in terms of forest composition, structure and operating conditions, leading to significant variation in the cost of selective cutting and the value of the wood. For instance, in Sweden transportation from the forest to the landing was mainly done by forwarders, while tractor was the used by the majority in Norway. The main reason for the latter is that the harvesting to a larger degree was done by forest owners or small scale contractors in Norway.

96000 ha in Norway and Sweden, respectively (Table 4). We excluded half of the area of forest with >50% TD trees assuming that the share of TD trees is too high to motivate selective cutting. Following this logic, the restoration of TDF is relevant on about 75% of the area in Norway and about 64% in Sweden, which means in total ca. 101,000 ha.

Forest structure

The basal area in the investigated stands consisted of on average 38 ± 23% SD TD trees, 26 ± 28% SD coniferous trees (mainly Norway spruce), and the rest 36 ± 25% SD of other (boreal) deciduous trees (for details see Table S1, Supporting Information).

The coarsest trees were *Pinus sylvestris* (Scots pine), oak and birch (Figure 3). The forests were dense with spacing index (Hart-Becking spacing index or S-percent: ratio between average distance between trees and dominant height) in the range 5.6–21.4% with a mean value of 11.2%. Tree species were generally well mixed in the plots, with 9.7 ± 2.1 SD tree species per site. The canopy was often even-aged but with a few older pines and oaks at some sites. Main regeneration was from young ash seedlings.

Table 4. The area (ha) of 40–80-year old mixed TD trees and Norway spruce in Norway and Sweden.

TD trees, %	Area	Area relevant for restoration[a]
Norway[b]		
25–50	26000	26000
>50	27000	13500
Sum Norway	53000	39500
Sweden[c]		
25–50	27000	27000
>50	69000	34500
Sum Sweden	96000	61500
Total area	149000	101000

[a]The figures are based on the assumption that half of the area of forest with >50% TD trees has 75–100% TD trees, and this is subtracted from the total area since restoration may be less relevant as well as less profitable in more or less pure TD stands.
[b]Data ordered from the national forest inventory of Norway.
[c]Data ordered from the national forest inventory of Sweden. Both datasets represent productive forest (forest with an increase in volume of >1 m^3 per ha and year), and outside of protected areas.

Stand development after 16 years

The study of stand development in the long-term study (the Swedish Oak Project) showed that the mean basal area of living trees in 2003 was 79% of the initial one in 2001 and had increased to 89% of the initial one in 2018 (Table 5). The mean volume of CWD had increased by 78% from 2001 to 2018. There was considerable variation among the sites studied, particularly concerning CWD, ranging from 1.5 to 48.5 m^3 per hectare in 2018. The CWD measurements were sometimes influenced by large windthrows in plots.

Discussion

Economy and potential area of selective cutting

How much of the potential area that can be restored is probably determined in part by profitability. The cost of selective

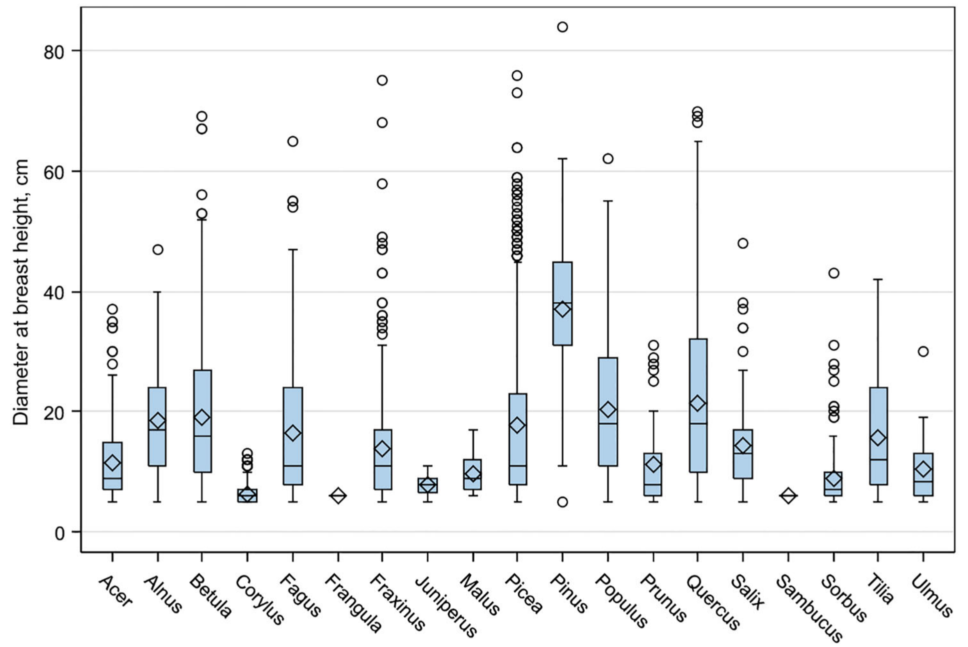

Figure 3. Distribution of diameter at breast height of the various tree species. The diamond inside the box indicates the group mean and the horizontal the median. The lover boundary of the box is the 25th percentile, while the upper is the 75th percentile. The whiskers are 1.5 interquartile range (IQR: difference between the 75th and 25th percentile) constrained by the range. Circles are outliers. Numbers are number of trees in the sample.

cutting (57.5 €/m^3) could be compared to the average cost of coniferous thinning in south Sweden of 23.4 €/m^3 (Swedish Forest Agency 2017). There are no detailed cost statistics in Norway, but using Vennesland et al. (2013), a representative cost of selective cuttings in Norway is about 28 €/m^3. The Swedish sites contain both the sites with the lowest and highest net revenue. Timber prices are about the same in Norway and Sweden, hence, this must be due to the large variation in costs. Normally, harvesting is cheaper in Sweden due to a generally lower cost level and a more developed timber industry. If we compare figures for the sites harvested by professional contractors using harvesters and forwarders (sites 3, 11, 23 and 26), we see that the cost level in terms of unit cost (€/m^3) is lower in Sweden. The Swedish sites with the lowest economic result (i.e. highest costs) show a very low total productivity: less than 1 m^3 per hour (sites 15, 17, 20, 22 and 25). These sites are mainly owned by municipalities and to a large degree used for job training programs. Thus using the same wage rate for these sites as for the other sites bias the cost estimates. In other words, the estimates for these sites are not representative.

Table 5. Basal area of living trees (m^2 per ha) in the long-term study (the Swedish oak project) plots before and after selective cutting in 2003 and after 16 years in 2018, and volume of CWD 2001 and 2018.

	Basal area, m^2/ha	Basal area, m^2/ha	Basal area, m^2/ha	CWD, m^3/ha	CWD, m^3/ha
	2001	2003	2018	2001	2018
Bokhultet	28.8	22.9	23.8	27.2	10.3
Bondberget	26.4	23.2	24.3	19.1	26.0
Fagerhult	22.6	17.5	35.1	3.8	20.4
Fröåsa	35.9	24.2	29.0	6.9	13.9
Getebro	31.5	25.6	23.8	6.8	28.2
Hallingeberg	27.3	22.9	32.8	9.2	23.1
Långhult	23.9	17.4	16.4	5.8	1.5
Skölvene	26.1	20.8	20.2	9.0	11.4
Stafsätter	19.4	17.2	15.7	8.6	38.4
Ulvsdal	26.6	20.9	24.1	4.7	8.6
Vickleby	28.1	26.5	16.9	10.4	48.6
Ytterhult	23.4	16.0	22.3	7.8	10.7
Åtvidaberg	31.7	24.4	29.5	21.6	10.0
Mean	27.1	21.5	24.1	10.8	19.3
SD	4.4	3.5	6.1	7.2	13.3

The costs are likely to decrease when selective cutting is implemented at a larger scale than in our fragmented experiment, but may remain higher than regular thinning due to the scattered occurrence of TDF (Löf et al. 2012). Also at the stand level, there are limitations to profitability. Cutting of scattered Norway spruce and birch, less uniformly distributed compared to even-aged commercial forests, is less suitable for fully mechanised harvesting. Further, the stands are rather dense, with high spacing index. Our mean value of 11.2 can be compared to a sample of Norwegian broadleaved-dominated NFI plots; Eid and Tuhus (2001) and Eid and Øyen (2003) report a range of 9.0–250.0, with a mean value of 33.1. The high tree density may increase the cost of selective cutting compared to even-aged stands since there may be increased need for manual work for shrub cutting and planning different forestry operations. Nevertheless, selective cutting may be a cost-effective restoration method, especially when natural regeneration is taken into account. For comparison, the costs for the regeneration of TDF by planting and fencing amount to about 5000–7000 euros per hectare in Sweden (see e.g. Löf et al. 2010 and 2012), and probably more in Norway due to the generally higher cost levels in this country. A potentially important factor affecting growth of TDF trees in forests may be ungulate browsing, but in the long-term experiment also reported here, other shrubs, broadleaves other than oak and spruce regenerated well (Leonardsson et al. 2015; Leonardsson 2015). Therefore, browsing inside dense mixed TDF might be less severe such that no fencing is needed.

The potential area of forest suitable for restoration, in total about 100,000 ha, is probably an underestimate since the NFIs cover only productive forest outside of protected areas. This is supported also by alternative NFI estimates, although older, for additional types of mixed TDFs of different ages and heights (Götmark 2010). The respective areas in this study represent potential increases of TDF of about 38% in Norway and 28% in Sweden, respectively (based on total present area of TDF in Norway; 104,000 ha, Tomter et al. 2010 and Sweden; 220,000 ha, Fridman and Wulff 2018). This is about half of the Nagoya commitments of restoration of 15% of degraded ecosystems.

Stand development and future management

The figures from the Swedish long-term experiment indicate that about half of the cut volume had regrown after 16 years. This regrowth was composed of large shrubs, other deciduous trees and spruce – especially where this tree was more abundant initially, at 5–6 sites of the in total 25 sites in the long-term experiment (Leonardsson and Götmark 2014; Leonardsson et al. 2015). Interestingly, spruce generates well if some trees are left at the partial cutting, or occur nearby, and since it is not affected by browsing (Leonardsson 2015), spruce may be harvested at intervals of 40–50 years to favour oak and other conservation values at such mixed TDF sites.

There are few studies on the regeneration ecology of spruce in mixed broadleaf-dominated TDF. The species is usually regarded as shade-tolerant, but in the type of older well-stocked closed-canopy mixed TDF used in the long-term experiment, spruce does not regenerate under minimal intervention, or does so very poorly and slowly in the shade (Johansson 2016). However, opening of the canopy means more spruce in the future stand unless it is eliminated totally at the partial cutting sites and in their surroundings (Leonardsson 2015). Some proportion of mixed closed canopy-TDF is probably best left as minimal intervention sites for conservation purposes (Götmark 2013), subject only to monitoring of the spruce component.

Interestingly, in the long-term experiment, after the selective cutting CWD had increased by 78% (from a low level), partly as a result of increased windthrow. Thus stand structure changed relatively rapidly in the direction of more natural conditions, which may have favoured biodiversity of, e.g. beetles (Gran and Götmark 2019).

Implementation within the Norwegian and Swedish policy frameworks

We suggest that the selective cutting of recent mixed forests has potential to increase the area of TD woodland, and that this method should be promoted by policy for biodiversity and for climate change adaptation. There is a need to develop new instruments, also encompassing future management needed to maintain the semi-open canopy and desired species composition. One possibility in Norway may be a subsidy scheme regulated by the Forestry Act known as "support for business and environmental measures in forestry". Payments are distributed annually as applied for by forest owners and encompass coverage of additional costs or losses by implementing management measures to safeguard and develop environmental values. As per today, selective cutting in TDF is not specifically mentioned as an eligible measure, but the guidelines are currently under review.

In Sweden, it is not allowed to convert TDF with "noble trees" (mainly oak and beech-dominated) to coniferous plantations according to law, and grants are available for the high silvicultural costs in TDF (Anonymous 2008). On the other hand, subsidies for the restoration of TDF on former conifer sites are normally low and not always available since they depend on temporal governmental programmes. Swedish programmes financed by the European Union have also been launched with the aim of converting Norway spruce stands to TDF, but have been little used due to inflexible rules and other factors (Löf et al. 2012). Therefore, new instruments may need to be developed to increase selective cutting.

Conclusion

We conclude that selective cutting targeting mainly spruce may be a rapid way to improve ecosystem quality in recent forests with TD trees. The long-term development of the sites should be followed, and monitoring of biodiversity and adaptive management applied. Some portion of mixed TDF should be preserved under minimal intervention to create habitat variation and as references for evaluation. By converting little used mixed forests on abandoned agricultural land, increasing TDF at the landscape scale could be realistic in some regions, especially if appropriate long-term incentives for landowners are developed.

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