Agroforest Syst
https://doi.org/10.1007/s10457-020-00570-x

Wooded hay meadows as viable production systems in sustainable small-scale farming

Knut Rydgren · Ingvild Austad · Liv Norunn Hamre · Joachim P. Töpper

Received: 6 June 2020 / Accepted: 21 November 2020

Abstract Wooded hay meadows provide livestock fodder in the form of both foliage from pollarded trees and hay from the understorey, and can be part of an environmentally friendly agroforestry system. However, trees may also have a negative effect on fodder production. Such trade-offs between productivity and sustainability in farming are poorly understood, especially in high-latitude areas. We studied hay production in two sites in the same wooded meadow in western Norway, one restored 6 years earlier than the other, to examine whether there were differences in hay production over a 4-year pollarding cycle. We measured production in transects starting from the trunks of pollarded and non-pollarded (reference) trees and running out into open meadow, and transects entirely in open meadow. We examined whether pollarding influenced hay production, and whether hay production was related to the distance from the tree trunk. Total production differed between the two sites, indicating that both time since restoration and differences in overall tree influence affected hay production. We observed a strong and immediate pollarding effect (increase in hay production) due to reduced tree influence. Trees have a negative influence on production as demonstrated by the increase in hay production with increasing distance from the tree trunk. However, additional dry fodder produced by harvesting leaves from pollarded trees more than compensates for reduction in hay production under pollarded trees. Moreover, the understorey production in the wooded hay meadow is at the same level as fertilized meadows in Norway when we include the fodder consumed by sheep during spring and autumn grazing. A wooded hay meadow is an environmentally friendly production system that does not compromise food production. Its tree component can also play an important role in climate change adaptation and mitigation, and supports higher biodiversity than industrial food production systems.

Keywords Canopy cover · Management · Plant-plant interactions · Pollarding · Production · Tree-influence

K. Rydgren (✉) · I. Austad · L. N. Hamre
Department of Environmental Sciences, Western Norway University of Applied Sciences, P.O. Box. 133, 6851 Sogndal, Norway
e-mail: knut.rydgren@hvl.no

I. Austad
e-mail: ingvild.austad@hvl.no

L. N. Hamre
e-mail: liv.hamre@hvl.no

J. P. Töpper
Norwegian Institute for Nature Research, Thormøhlensgate 55, 5006 Bergen, Norway
e-mail: Joachim.Topper@nina.no

Introduction

Alongside biodiversity loss and climate change, unsustainable land use is one of the main problems humanity is facing in the Anthropocene (Kremen and Merenlender 2018). Farming, the basis of our civilization, can be more damaging to wild nature than any other sector of human activity (Balmford et al. 2012), causing considerable degradation of land, water, and biodiversity on a global scale (Foley et al. 2011). In addition, industrial agriculture causes deforestation, soil degradation, and loss of soil carbon to the atmosphere (Erb et al. 2018; Kremen and Merenlender 2018), thus contributing to anthropogenic climate change. It also involves heavy use of pesticides and synthetic fertilizers, which further add to the adverse environmental effects of modern agricultural activities (Kremen et al. 2012; Wu et al. 2018). To meet the urgent need to reduce these effects (Lechenet et al. 2017), agriculture must be made more sustainable without compromising food production (Firbank 2012). Fortunately, there may be several ways of increasing production without degrading the environment, using biodiversity-based techniques such as agroforestry, silvopasture, diversified farming, and ecosystem-based forest management (Kremen and Merenlender 2018).

Agroforestry systems, which combine trees with crops and/or livestock, have long traditions around the world (Mosquera-Losada et al. 2018; Peri et al. 2016; Soler et al. 2018), but changes in agricultural practice and policy since the Middle Ages have led to a decline in agroforestry systems worldwide (Smith et al. 2012). However, such systems may once again become more important in mitigating and adapting to climate change, enhancing biodiversity and maintaining important ecosystem services (Jose 2009; Mosquera-Losada et al. 2018). This means that we need better knowledge of how trees influence agricultural production in the understorey, since farmers today often perceive trees as having a negative impact on production (Rivest et al. 2013). Both in forests and in more open ecosystems such as in agroforestry systems, trees considerably affect the understorey by modifying conditions and resource availability for plants, e.g. light, temperature, humidity, and soil conditions (Barbier et al. 2008; Scholes and Archer 1997). In forests, the influence of trees can be so strong that canopy closure gradients (from below trees to gaps) govern clear gradients in understorey species composition, as has been demonstrated in boreal spruce forests (Rydgren 1996; Økland et al. 1999) and northern temperate deciduous forests (Burton et al. 2014). The same applies to silvopasture systems (Sánchez-Jardón et al. 2014b). However, there is little consensus on how trees influence understorey production in agroforestry systems, since different studies have shown the whole range from enhanced to reduced pasture yield under tree canopies (Rivest et al. 2013). According to a recent meta-analysis by Mazía et al. (2016), the climatic context and the characteristics of benefactor trees are the main drivers of both the direction and the magnitude of tree–grass interactions. Although this study comprised data from eight biomes, it only extended to slightly above 40° N latitude. Thus, little is known about these interactions in harsher climates at high northern latitudes, in biomes that account for a considerable proportion of the Earth's land area.

There are many variants of traditional agroforestry systems (Mosquera-Losada et al. 2018; Smith et al. 2012), including wood-pastures where livestock grazing co-occurs with scattered trees and shrubs (Plieninger et al. 2015). In northern parts of Europe, wood-pastures are sometimes only lightly grazed, typically in spring and autumn, and otherwise mowed (Austad and Losvik 1999; Hansson and Fogelfors 2000; Hæggström 1983; Kotiluoto 1998; Sammul et al. 2008). Such wooded hay meadows were common in areas around the southern Baltic Sea (Bergmeier et al. 2010; Wallin and Svensson 2012) and also in Norway (but few are left; Austad and Hauge (2014b)), which was the northernmost outpost of such systems in Europe (Fremstad and Moen 2001). Production from both the trees and the understorey was harvested in wooded hay meadows. One ancient practice is pollarding, which involves cutting tree branches 2–3 m above ground (Smith et al. 2012). The trees provided winter fodder including foliage and twigs, and also firewood and material for tools (Austad et al. 2003; Hæggström 1983; Smith et al. 2012). Pollards were usually harvested in cycles of 4–8 years, depending on the tree species (Austad et al. 2003; Austad and Hauge 2014a; Smith et al. 2012). Pollarding influences the availability of vital resources for plants, and thus affects understorey production. In these systems, there seems to be a gradient of decreasing understorey production towards tree trunks

(Austad et al. 2003), but we know too little about how understorey production varies over a pollarding cycle and how areas beneath trees compare to open meadow, and we do not know how quickly understorey production responds to resumed cycles of pollarding.

We studied understorey production following restoration of a wooded hay meadow in western Norway, using two sites close to each other on the same farm, but differing in pollarding history and time of restoration (one site was restored 6 years before the other). Annual measurements of production were made for 4 years along closed transects from the tree trunk and outwards from pollarded trees and from reference (i.e. non-pollarded) trees, and in open areas in the wooded hay meadow. Our aim was to answer the following questions: (1) Does understorey production differ between the two sites? (2) Does pollarding influence understorey production? (3) Does understorey production vary with distance from the tree trunk? In the following, we discuss our findings in a wider perspective, taking into consideration the triple challenge of the Anthropocene, i.e. how we can address loss of biodiversity, climate change and unsustainable land use (Kremen and Merenlender 2018).

Materials and methods

Study area

The study area is part of Grinde farm, which is in Sogndal municipality, situated on the northern side of the Sognefjord in western Norway (61°11‘N, 6°45‘E). The area is steeply sloping (> 30°) and lies at an altitude of 100 to 125 metres above sea level in the southern boreal vegetation zone (Moen 1999). The climate is slightly oceanic (Moen 1999), with a mean annual precipitation of 979 mm and a mean annual temperature of 6.6 °C for the normal period 1961–1990 at Njøs, 45 m above sea level and 7 km east of Grinde (eKlima 2019). The area receives 22% of its total precipitation in May to August, and 50% of its precipitation in September to December. Mean monthly temperatures are above 10 °C from May to September, and July is the warmest month (14.9 °C). During our four-year study period (1998–2001), June 2000 stood out as a very cold month, with temperatures well below normal. The bedrock consists of diorite and granite gneisses and migmatite (NGU 2019), and is covered by glacifluvial delta deposits, consisting mostly of leached sand but with some silt and clay as well (Austad and Losvik 1999). On such steep terrain, the soil is influenced by seepage water carrying nutrients from above (Austad and Losvik 1999).

In 2009, Grinde–Engjasete was included on the original list of 20 selected landscapes (Austad and Hauge 2009), chosen to safeguard a representative selection of landscape types, agricultural practices and geographical variation. We studied a wooded hay meadow at Grinde (Fig. 1) that was in continuous use at least since 1874 (Austad and Øye 2001) to the late 1960s or early 1970s, see further details in Austad and Losvik (1999). Traditional use comprised scything, pollarding and shredding of the tree layer, and grazing in spring and autumn, and manure was rarely if ever applied. Ash (*Fraxinus excelsior*) and elm (*Ulmus glabra*) were the most common pollarded trees in the study area. Pollards were traditionally harvested 2–3 m above the ground, in 4–8-year cycles (Austad et al. 2003). From the time the traditional use ended and up to 1992, the wooded hay meadow was only lightly grazed by sheep in spring and autumn, and the trees developed extensive crowns due to the absence of pollarding. In 1992–1993, traditional use was resumed in part of the wooded hay meadow (Austad and Losvik 1999); 17 trees were pollarded and the understorey was mowed (site 1). The remaining area was left untreated until 1998 (site 2). In 1998, three of the trees in site 1 were re-pollarded (and another three in 1999), and in addition we pollarded three trees in site 2. Therefore, the overall influence of trees on the understorey during the study period was greater in the late restored site 2. Furthermore, the crowns of reference trees in site 1 that were pollarded in 1992 had grown for 6 years (1992–1998), while tree crowns of reference trees in site 2 had grown for 25–30 years. From 1998 to 2001, both sites were scythed and grazed by sheep in spring and autumn. The sites are only 100–150 metres apart, so that large-scale climatic and subsurface environmental conditions are the same and their land-use history is similar (Austad and Losvik 1999).

Fig. 1 The wooded hay meadow at Grinde, site 1, in the summer of 1993 (left) just after pollarding and in the summer of 2004 (right). Photo credits: Leif Hauge

Sampling design and data collection

In 1998, we placed 18 closed transects, nine in each of the two sites. The transects were seven metres long, and each had 14 permanently marked sample plots measuring 0.5 × 0. 5 m, giving 252 sample plots in total. In both sites (Fig. 2), there were three transects in more open areas (treatment "open meadow"), three transects starting from the trunk of a non-pollarded tree (treatment "reference tree"), and three starting from the trunk of a pollarded tree (treatment "pollarded tree"). The "tree" transects ran from the trunk of a specimen of *Ulmus glabra*, *Fraxinus excelsior* or *Salix caprea* out into open meadow.

We measured hay production in the sample plots every year from 1998 to 2001 by cutting the understorey with shears at the end of July, 4 to 6 cm above the ground. The harvested material was collected in bags, dried for 32 h at 60 °C in a drying cabinet, and then weighed to the nearest gram.

Statistical analyses

We analysed hay production as a function of (i) distance from the start of the transect, (ii) treatment, (iii) year, and (iv) plot by parameterizing linear mixed effects models separately for site 1 and site 2 under Bayesian inference. Distance was modelled as a continuous fixed effects variable, treatment and year as categorical fixed effects variables, and plot as a random factor. The coefficients for the intercept (α) and for distance ($\beta1$) were evaluated for every combination of treatment t and year y. In site 1, hay production levelled off for longer distances, and we therefore included an overall quadratic term for distance ($\beta2$) in the model for site 1. In addition, we modelled random contributions of plot (γ_p) to the intercept. The model was specified with a Gaussian distribution for the errors (ε) and an identity link.

$$hay\,production \sim \alpha_{ty} + \beta 1_{ty} * dist + \beta 2 * dist + \gamma_p + \varepsilon$$

We specified uninformative priors for all model parameters with a mean of zero and precision of 0.001 for intercepts and distance slopes. For the random effect of plot, we specified a mean of zero and a precision drawn from a uniform distribution from 0 to 100.

For the MCMC sampling, we specified three chains with an adaptation phase of 20,000 iterations and 20,000 iterations for the sampling, yielding a posterior of 60,000 coefficient values for every parameter of the model.

We assessed the appropriateness of the models using (i) visual inspection of the trace plots for every model parameter, (ii) Gelman and Rubin's convergence diagnostic, (iii) a posterior-predictive check with Bayesian p value, and (iv) a predicted vs. residuals plot.

Based on the posterior distributions of the model parameters, we computed 95% credible intervals (the Bayesian equivalent of the frequentist confidence interval) for (i) predictions of hay production for every distance in every treatment and year, (ii) differences in hay production between treatments for every distance

Fig. 2 Location of transects in Site 1 and 2 at the Grinde farm. Springtime (25.5. 2016) aerial photo (www.norgeibilder.no) are used in the background for easier identification of the trees. Trees without leaves are *Fraxinus excelsior*, trees with green leaves are *Ulmus glabra* and trees with greygreen leaves are *Salix caprea*

in every year, and (iii) total hay production along the entire transect for each treatment.

All analyses were performed in R ver. 3.6.2 (R Development Core Team 2019) using the packages 'rjags' for running the Bayesian models (Plummer 2019) as well as 'ggplot2' and 'gridExtra' for visualization (Auguie 2017; Wickham 2016).

Results

In site 1 (restored 1992), hay production was substantially higher in the open meadow transects than in the tree transects (both pollarded and reference), and positively related to distance from the trunk in the tree transects. Hay production in tree transects reached levels comparable to open meadow at ca. 5–7 m from the trunk (Fig. 3). In the year of pollarding (first year), hay production was similar in pollarded and reference tree transects. From the second year on, hay production was higher in pollarded tree transects than in reference tree transects for the first 4–5 metres from the trunk, but similar for the last 2–3 m (Fig. 5). Over the four-year cycle, annual modelled hay production was in the range 179–291 g·m^{-2} (Table 1). Hay production was highest in the open meadow transects in site 2 (restored 1998) as well. However, productivity was generally lower than in site 1 and less dependent on distance from the trunk in tree transects (Fig. 4; Table 1). Moreover, in site 2, hay production was similar in pollarded and reference tree transects for the first three years, and it was not until 2001 that the values were slightly, but significantly, higher in pollarded tree transects than in reference tree transects (Fig. 5). In 2000, hay production was considerably reduced across all treatments in both sites (Figs. 3 and 4). In both sites, total hay production along a transect was significantly higher in open meadow than in tree transects. Total hay production was also higher in pollarded tree transects than in reference tree transects, but this difference was only marginally significant in site 1, which was restored first (slight overlap of 95% bCI), and not significant in site 2 (Table 1).

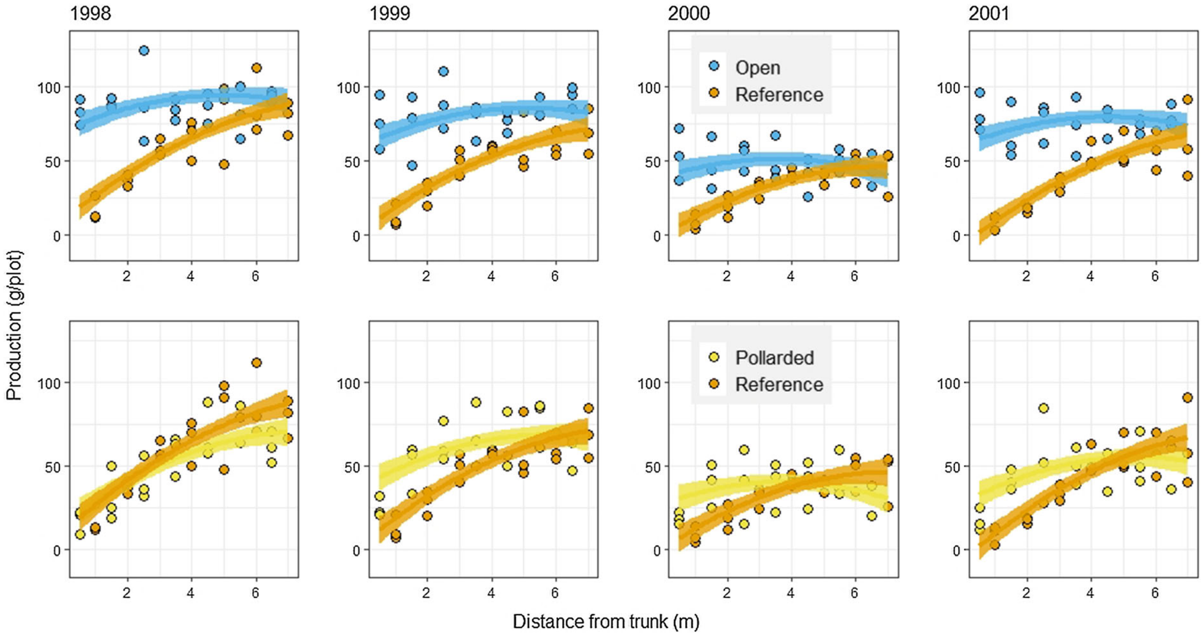

Fig. 3 Plot-level hay production in open meadow (Open) and according to distance from the nearest tree trunk in transects starting at pollarded (Pollarded) and reference trees (Tree-ref) in site 1 during the four-year study period 1998–2001. Plot size = 0.25 m^2. Solid lines and shaded areas represent model predictions and 95% credible intervals of Bayesian mixed effect models

Table 1 Total modelled hay production (g) in one transect (3.5 m^2) for each treatment over the entire four-year study period (1998–2001)

Treatment	Site 1			Site 2		
	Median	CI_{low}	CI_{high}	Median	CI_{low}	CI_{high}
Open meadow	4071	3898	4241	2912	2653	3165
Pollarded tree	2793	2622	2967	2282	2026	2530
Reference tree	2511	2339	2684	2082	1826	2336

The figures shown are medians for the whole transect and the 95% credible interval (CI) of the posterior

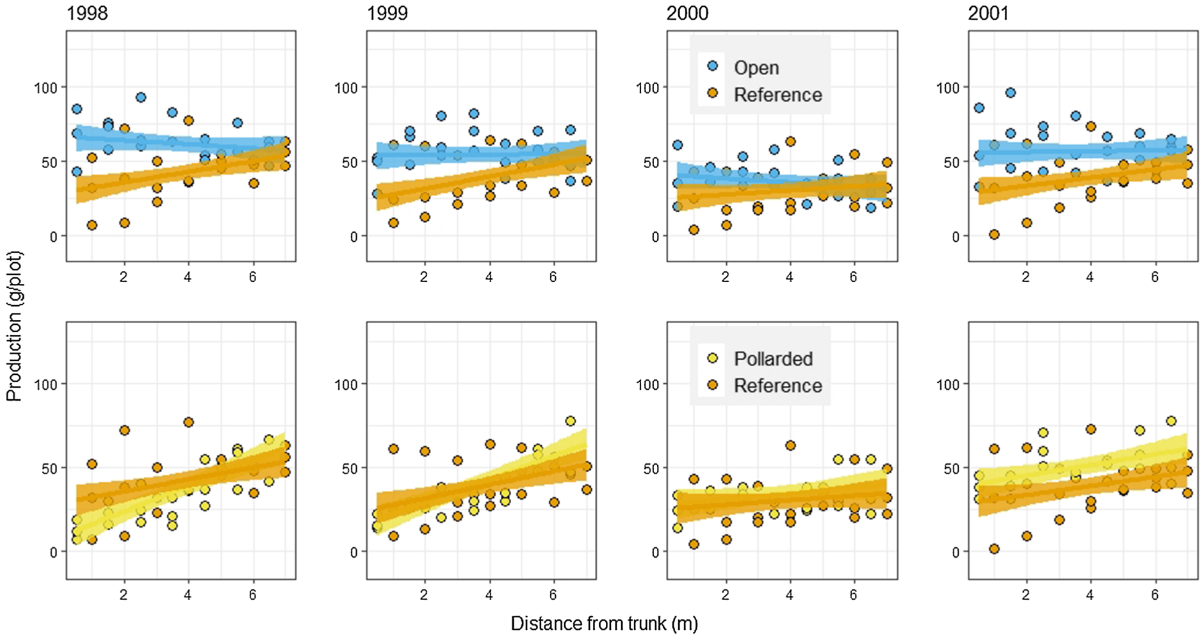

Fig. 4 Plot-level hay production in open meadow (Open) and according to distance from the nearest tree trunk in transects starting at pollarded (Pollarded) and reference trees (Tree-ref) in site 2 during the four-year study period 1998–2001. Plot size = 0.25 m^2. Solid lines and shaded areas represent model predictions and 95% credible intervals of Bayesian mixed effect models

Discussion

Our results show that hay production was substantially higher in site 1, which was restored first, than in site 2 (question 1). In site 1, pollarding immediately increased hay production, while it had a smaller, delayed effect on hay production in site 2, which was restored later (question 2). Proximity to the tree trunk clearly suppressed hay production, particularly in site 1 (question 3).

This difference between the two sites indicates that it takes at least one pollarding cycle before hay production returns to the higher levels that characterize well-managed wooded hay meadows. Restoration of species composition entails recovery times of decades (Jacquet and Prodon 2009; Sarmiento et al. 2003) and sometimes even centuries (Woodcock et al. 2011) in many ecosystems, not at least after severe disturbances (Prach et al. 2016; Rydgren et al. 2020). However, restoration of ecosystem function such as productivity may proceed much faster (Baer et al. 2002). While our results are clearly consistent with this, we cannot be sure that productivity in the site that was restored first (site 1) recovered fully after the one pollarding cycle since restoration. The difference between hay production in the two sites is probably due to a combination of two factors: (i) the length of time since restoration, which gave more time for

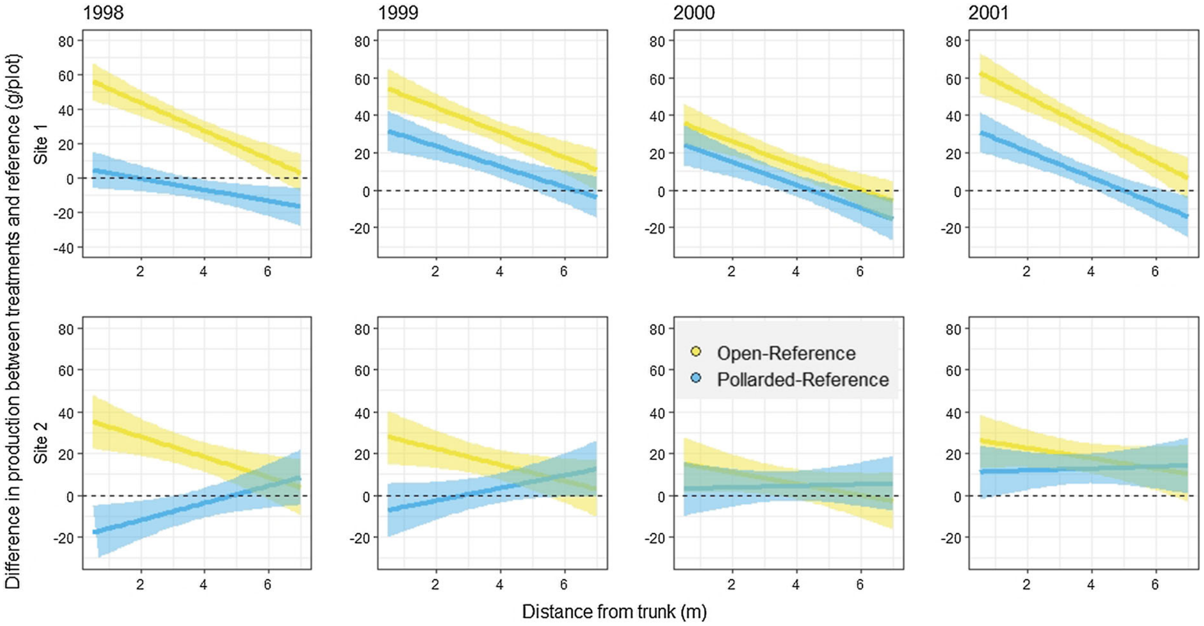

Fig. 5 Difference in plot level hay production between open meadow and reference tree transects (Open vs. ref), and between pollarded and reference tree transects (Pollarded vs. ref) in relation to distance from the nearest tree trunk in both study sites during the four-year study period 1998–2001. Plot size = 0.25 m^2. Solid lines and shaded areas represent model predictions and 95% credible intervals of Bayesian mixed effect models

changes in species composition in site 1, and (ii) differences in the overall influence of trees (cf. Augusto et al. 2015; Økland et al. 1999). Pollarding reduces tree influence, but since fewer trees were restored in site 2, which was restored later, there were more trees here with large crown radii (see Materials and methods) than in site 1 (Austad and Losvik 1999). Overall tree influence was higher in site 2. In the generally wet and cold climate in this area, conditions under trees include less solar radiation, drier soil conditions, and cooler temperatures (cf. Rydgren 1996; Økland et al. 2003), and there are probably also differences in the soil microbial community (cf. Bach et al. 2010; Domínguez-Begines et al. 2019; Saetre and Bååth 2000). When restoring wooded hay meadows, it is therefore important to pollard large enough areas to avoid the understorey being strongly influenced by un-restored trees with large crown radii.

The pollarding effect, i.e. the increase in hay production after pollarding due to the reduction in tree influence, was strong and immediate under the pollarded trees in the site 1, but far weaker under those in site 2, where there had been an extra 6 years of stronger tree influence (1992–1998). In site 1, which was restored first, the pollarding effect was clear the following summer, in 1999. Hay production approached the same level as in open meadow. The pollarding effect became weaker the second year after pollarding (2000) and then strengthened again. This was an unexpected pattern, but is probably explained by the very cold spell of weather in June 2000, which considerably reduced hay production but had least effect where the tree influence is strongest, i.e. under the reference trees. Without the influence of other factors, the effect of pollarding on hay production is expected to be strongest in the first year after pollarding and then gradually decrease as trees regrow and tree influence increases until pollarding is repeated. In 2000, there were non-significant differences in hay production between pollarding and open meadow treatments, which we interpret as the combined effect of weather and tree influence on hay production. In 2000, hay production in open meadow transects in both sites dropped by 41–45% from the year before, a considerably larger decline than for the other two treatments. Thus, cold weather in cool early summer seems to be have a more marked effect in open areas than beneath trees that may buffer between-year weather variations (cf. Sánchez-Jardón et al. 2014a).

Our results clearly demonstrate that there is a gradient in hay production related to the degree of tree influence (see also Soliveres et al. 2015). Previous studies have largely treated the impact of the trees on understorey production as a binary phenomenon, and have distinguished between "beneath trees" and "open" (Dohn et al. 2013; Mazía et al. 2016; Rivest et al. 2013). We found that hay production increased with increasing distance from the tree trunk, indicating that the net balance of the interaction between trees and grasses (and herbs) is negative in our study system. This pattern is also in accordance with the findings of Mazía et al. (2016) that herbaceous productivity is higher outside the tree canopy at higher latitudes and along an increasing aridity index (the ratio between mean annual precipitation and potential evapotranspiration). The relationship between hay production and the tree influence gradient may shift slightly between years in response to variations in weather conditions during the growing season, as shown by Sánchez-Jardón et al. (2010) in their study of *Nothofagus pumilio* forests in Chile. In the relatively cold and moist climate in the region where we conducted our study, the overall availability of fundamental resources for plants, i.e. light, water and nutrients (Thomas and Sadras 2001), improves with decreasing tree influence, but it is not clear from our study which of these was the limiting factor for hay production. However, in such a humid climate, light conditions stand out as the strongest candidate for limiting hay production.

Wooded hay meadows in a wider perspective

Hay production in the wooded hay meadow at Grinde is highest in open meadow areas, indicating that even pollarded trees have a negative effect on understorey yield, i.e. there is net competition between trees and hay production (Mazía et al. 2016). However, the additional dry fodder produced by harvesting leaves from pollarded trees more than compensates for this (Austad et al. 2003). Livestock often prefer dry foliage as fodder, probably because of its high nutritional value (Hauge et al. 2014). Historically, in particular before the agrarian revolution of the 19th Century, dry foliage was an important fodder for livestock in the Nordic countries, especially for sheep and goats (Austad et al. 2014; Hæggström 1998; Slotte 2001). Moreover, the combination of fodder consumed by sheep during spring and autumn grazing and the hay production harvested from the wooded meadow was found to be just below 600 g/m^2, which is similar to average production from fertilized meadows in Norway (Austad et al. 2003). This means that hay production from wooded hay meadows can be maintained at the same level as from an average intensified and simplified production system that is dependent on human inputs of industrial fertilizers and pesticides. A likely explanation for the sustained high production from well-managed wooded hay meadows is that tree roots go deeper into the soil and take up nutrients out of reach of the roots of the understorey species, thus recycling minerals more efficiently (cf. Hoosbeek et al. 2018; Jose et al. 2019). In addition, in steep terrain such as found in western Norway, there is a continuous supply of nutrients from the groundwater. Therefore, at least in such areas, farmers do not need to fear a decline in total biomass production in wooded hay meadows (cf. Rivest et al. 2013).

A wooded hay meadow is a productive agroforestry system that is much less intensified and simplified than an industrial meadow. It is far less dependent on human manipulation with heavy machinery, pesticides and fertilizers, and can play a part in reducing agricultural greenhouse gas emissions (Mosquera-Losada et al. 2018). The trees also play an important role in climate change adaptation and mitigation (Manning et al. 2009; Mosquera-Losada et al. 2018) by moderating the effects of extreme weather events on hay production and by storing carbon. In addition, wooded hay meadows often support high biodiversity and can play a valuable role in biodiversity conservation (Manning et al. 2009; Moe and Botnen 2000; Plieninger et al. 2015; Sammul et al. 2008). Restoring wooded hay meadows and establishing local food production with short supply chains utilizing local resources, instead of inputs transported over long distances between continents, will also make land use more sustainable at larger spatial scales (Kremen et al. 2012). Wooded hay meadows can support a sustained yield of healthy food and play a part in making agriculture more sustainable without compromising food production (cf. Firbank 2012). Maintaining these systems costs more in terms of human labour, but can help us to deal with the triple challenge we are facing in the Anthropocene (Kremen and Merenlender 2018).

Acknowledgements We would like to thank the landowner, Lars Grinde, who gave us enthusiastic support and allowed us a free hand to carry out the experiment. We are grateful to Mary Holmedal Losvik, Ann Norderhaug, Stein Tage Domaas and Torbjørn Stokke for assistance with the field work, and Alison Coulthard for language editing. The project has received financial support from the Research Council of Norway.

Authors' contributions None.

Funding Research Council of Norway.

Availability of data and material We intend to archive our data in a repository.

Code availability Not applicable.

Compliance with ethical standards

Conflict of interest The authors declare that they have no competing interests.

Ethical approval Not applicable.

Consent to participate Not applicable.

Consent for publication All authors have approved the manuscript.

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