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Impacts of cutting frequency and position to tree line on herbage accumulation in silvopastoral grassland reveal potential for grassland conservation based on land use and cover information

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Abstract

In agricultural grassland, high herbage utilisation efficiency (HEFF), which is the proportion of gross live-green herbage production that is utilised before entering senescence, is ensured by frequent defoliation. The decision upon which defoliation frequency to apply depends on the farming intensity. Assuming a reduced total herbage accumulation near trees in silvopastoral systems, frequent defoliations with high HEFF become less worthwhile—at least in specific spatial configurations. This makes an extensive management near trees an interesting option because it promotes other grassland-related ecosystem services such as biodiversity. The present study first analysed the interaction between defoliation frequency and position to trees on the total, dead and live herbage accumulation and the HEFF at two silvopastoral sites with short-rotation coppices in Germany. In addition, the total grassland–tree interface in Germany was assessed from land use and land cover maps of Germany based on satellite data to approximate the potential of grassland extensification near trees. The total herbage accumulation near trees declined by up to 41% but the HEFF was not affected by the position. Consequently, any intensification is not paid-off by adequate productivity and herbage quality in terms of HEFF and tree-related losses in herbage accumulation are expected up to a distance of 4.5–6 m. Applying a 4.5 m border on satellite data, we found that up to 4.4% (approximately 2200 km^2) of the total grassland area in Germany is at a tree interface and potentially suitable for extensification. These findings indicate substantial potential for biodiversity conservation in grasslands with low trade-off for high-quality yield.

KEYWORDS
agroforestry, defoliation intensity, forage biomass, litter, remote sensing, satellite

1 | INTRODUCTION

Silvopastoralism comprising grassland and trees is gaining importance in Europe (Mosquera-Losada et al., 2018). Alleys of short-rotation coppices integrated into agricultural land are the dominating form of agroforestry systems in Germany (e.g., Kahle & Janssen, 2020). Similar to grassland, silvopastoral systems provide a variability of ecosystem services which likely depend on management intensity, the grassland sward type, their interaction (Belesky et al., 2019) and responses on pastures to trees. The latter, for instance, may cause a growth penalty because of litter fall and soil acidification (Halvorson et al., 2017; Muys et al., 1992).

Usually, the herbage accumulation of grassland is the result of the processes of growth and senescence (Bircham & Hodgson, 1983; Lemaire & Agnusdei, 2000). Both processes are affected by the availability of resources, that is, light, water and nutrients (Whitehead, 1994). In between two tree lines, light becomes a limiting resource at certain spatial positions (Guevara-Escobar et al., 2007) causing losses in grassland herbage accumulation (Ehret et al., 2018; Orefice et al., 2019; Pang et al., 2019). Leaf appearance and growth are functions of light availability and temperature (Gastal & Lemaire, 2015; Hunt & Thomas, 1985). In studies with increasing shading as an experimental factor, net accumulation of herbage in grassland swards consequently declined (Devkota et al., 2009; Grant et al., 1981). Senescence is genetically determined, but the timing and rate of senescence are also controlled by environmental factors (Whitehead, 1994). Shading below the light compensation point causes a negative carbon balance which, in turn, increases the senescence of leaves (Brouwer et al., 2012). Yet, Grant et al. (1981) could not find any change in the senescence rate per tiller because of shading, while, in general, senescence increased linearly with herbage mass. In other words, a constant senescence rate per tiller is an indication of no reaction in the leaf lifespans to shading. All herbage that is not harvested undergoes senescence, and the amount of senesced dead herbage at harvest is therefore influenced by the defoliation intensity and frequency (Parsons & Penning, 1988; Whitehead, 1994). Intervals between defoliation events longer than the leaf lifespan usually increase the herbage mass but also the amount of senesced dead herbage (Gastal & Lemaire, 2015). A modification of the live and dead herbage mass by defoliation frequency will have an impact on the herbage utilisation efficiency (HEFF), which is the proportion of gross live-green herbage production that is utilised before entering senescence (Mazzanti & Lemaire, 1994). Farmers usually adapt their defoliation frequencies in relation to the farming system purposes in order either to increase the herbage accumulation (low HEFF, extensive management) or the amount of digestible herbage (high HEFF, intensive management) (Gastal & Lemaire, 2015).

Several studies on silvopastoral grassland distinguished between the effects on live and dead herbage (e.g., Devkota et al., 2009), but the impact of the defoliation frequency on the HEFF in relation to trees has received little attention under temperate climate in this respect. As stated by Halvorson et al. (2017) studies on appropriate management in silvopastoral systems are extremely important in order to understand interactions between trees and grassland as these interactions are diverse and largely not understood. In silvopastoral grassland with declining growth rates but constant leaf lifespans near trees, no consequences for the HEFF should result from shading. If the HEFF of a specific defoliation system near trees is the same as it is away from trees, but herbage accumulation is lower, then intensive use with frequent defoliations is hardly worthwhile near trees. The limitation for the biological process of growth consequently makes infrequent defoliation an interesting option in the area nearer to trees, because it supports other grassland-related ecosystem services such as invertebrate protection (Kruess & Tscharntke, 2002). Presuming the limited growth potential next to trees in silvopastoral systems or, generally speaking, next to trees along roads, hedges or forests, there is a great potential for biodiversity conservation, which depends on extensive management to support, for example, flowering plants (Smart et al., 2002) or birds (Allen et al., 2020). For an assessment aiming at improved biodiversity support in grasslands near trees, land use land cover (LULC) information from remote sensing is a helpful tool to quantify the large-scale grassland–tree interface reliably (Ali et al., 2016).

This study was the first conducted to test the hypothesis that the HEFF is not affected by the defoliation frequency near tree lines. For this, two contrasting silvopastoral sites were studied over two successive years to investigate the interaction of cutting frequency and position to tree lines (i.e., shading) on the total grassland herbage accumulation and the dead and live herbage tissue in order to elucidate any trade-off between management intensity and herbage production. In addition, we further evaluated to what extent grassland in Germany is potentially affected by tree shading using remote sensing-based LULC information to assess the potential for biodiversity.

2 | MATERIALS AND METHODS

2.1 | Field experimental area, setup and climatic conditions

The field study was conducted over two consecutive growing seasons (2016 and 2017) at two silvopastoral sites integrating short-rotation coppice and grassland. The site Reiffenhausen (RH), 24 km south of Göttingen (51°23′56.1″N and 9°59′13.4″E, 325 m above sea level), was established in 2011 on former arable land with three tree lines and two grassland sward types on a soil type classified as a Stagnosol (Ehret et al., 2018). After tree planting, two grassland mixtures were established in three replications in a split-plot randomised block design between the tree lines, that is, either a perennial ryegrass–white clover sward (*Lolium perenne*, *Trifolium repens*, GC: grass clover) with a sown proportion of 31% legume and 69% grass, or a diverse mixture (DIV) with a proportion of grasses, nonleguminous dicotyledonous herbs and a legume in proportions of 43%, 41% and 16%, respectively. A detailed overview is given in Table S2, Supporting Information. The different swards at site RH will be termed vegetation compositions hereafter. The vegetation compositions were assigned to the main plot with the cutting system treatments as subplots within main plots. Subplots had a size of 59 m^2 and were sampled at three positions per treatment (see below). The setup of the field study at RH consequently refers to a four-factorial (vegetation composition, cutting system, position and year) field experiment. At the second site, Mariensee (MS) 160 km north of Göttingen (52°33′52″N and 9°27′53″E, 41 m above sea level), three tree lines were established in permanent grassland in 2008. The soil type is a heterogenous mixture with a dominance of Histosol containing a conserved peat layer. As the tree lines at site MS had been established into existing permanent grassland, no factor for vegetation composition was investigated here. At site MS, the field experiment refers to a three-factorial split plot design with the factors cutting system, position and year. The cutting system treatment represented main plots (192 m^2) randomised across the site with the position as subplot and a total of six replicates per treatment ($n = 36$ plots).

Both sites differed with respect to the initial setup: the distances between two tree lines at site RH were 9 m with a tree line width of 7.5 m. At MS, tree lines were 48 m apart with a tree line width of 11 m. The tree lines at site RH were planted in a northwest to southeast direction and at site MS from south to north (Figure 1). At RH, the tree lines contained one willow hybrid 'Tordis' ([*Salix schwerinii* × *Salix viminalis*] × *S. viminalis*). At MS, a mixture of several willow hybrids, that is, 'Inger' (*Salix triandra* × *S. viminalis*), 'Tora' (*S. schwerinii* × *S. viminalis*) and 'Tordis' were planted. Trees were harvested for the last time prior to the present study in the beginning of 2015 at RH and 2016 at MS.

The factor position (three levels) comprised a composition of the compass orientation and the spatial distance to the tree lines located either close to one tree line or in the middle between two tree lines. The position consequently represents a proxy for any potential effects of shading by trees. The actual distances of the positions to the tree line differed between sites in response to the setup with 0.5, 4.5 and 0.5 m at RH and 6, 24 and 6 m at MS (Figure 1). In the following the positions for both sites are named as 'Close West', 'Middle' and 'Close East' (i.e., CW, M, CE, respectively). The factor cutting system (two levels) comprises two systems with different frequencies of defoliations and length of interval between defoliations, that is, two or four harvests per year. The dates of harvests are given in Table S1 and only three harvests were realised during 2016 at site RH. During the time of the study, mean proportions of grass and dicots in the two different vegetation compositions at RH did not differ significantly (Welch two sample *t* tests, $p = 0.335$). Legumes were completely absent in the grassland at MS and only scattered shares of herbaceous dicots were present (94% grass on average during 2016 and 2017). No fertiliser was applied.

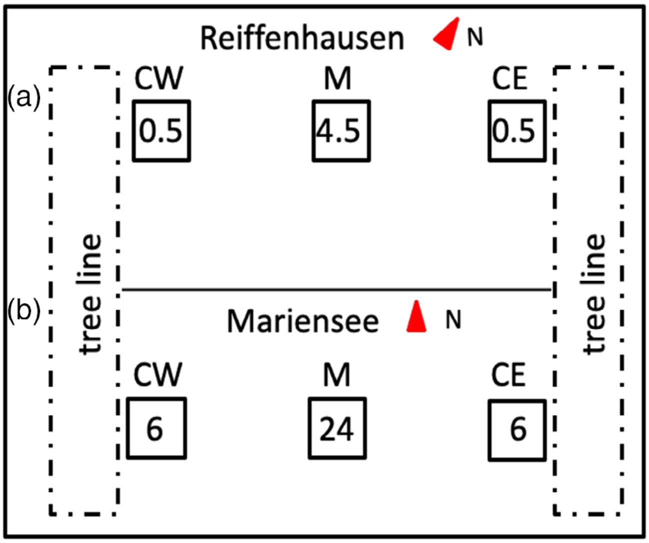

FIGURE 1 Schematic overview (top view) of the setup of the experimental areas at (a) Reiffenhausen and (b) Mariensee. Every position and cutting system plot is replicated six times and they are denominated uniformly as CW, CE and M, that is, Close West and Close East of tree lines or in the Middle between two tree lines, respectively, in this study. Numbers below the position plots show the distances in (m) to the tree lines

Both sites are characterised by a long-term (1981–2010) temperate climate with an average annual air temperature (±*SD*) of 9.2 ± 0.8°C and 9.7 ± 0.8°C, at RH and MS, respectively. The mean annual precipitation sum (±*SD*) is 650 ± 131 mm and 665 ± 111 mm at RH and MS, respectively. During the experimental periods, temperatures during the growing season were higher than the long-term values, whereas precipitation sums were lower in 2016 and higher in 2017 than the long-term values, respectively (Table 1).

2.2 | Total, dead and live herbage and HEFF

At harvest, samples of the standing aboveground grassland herbage were taken from areas measuring 9 × 80 cm and 50 × 50 cm at RH and MS, respectively, by manual cutting at 3 cm stubble height. Subsequently, a representative subsample of the fresh matter was separated manually into dead (>80% dead plant area) and live herbage. Separated samples, as well as the remainder were dried in a forced-air oven at 60°C for 48 h and weighed afterwards to determine the dry-matter (DM) content. The herbage mass at the second harvest in 2017 at site MS had to be calculated from regular measurements of the compressed sward height (CSH) (Dougherty et al., 2011) based on linear regression between CSH and herbage mass from a common double sampling procedure (t'Mannetje, 2000). In cut grassland swards, the total herbage accumulation may be expressed in a simplified way as the sum of live green and dead herbage mass. In this study, the dead and live herbage masses of each harvest were aggregated to constitute the total herbage accumulation. The HEFF was adapted from Mazzanti and Lemaire (1994) and then calculated from the annual sums as follows:

$$\text{HEFF} = \frac{\text{Live herbage mass} - \text{dead herbage mass}}{\text{Live herbage mass}}.$$

2.3 | Site-specific data analysis from field experimental work

Data analyses were performed using R 3.6.1 (R Core Team, 2018). The total herbage accumulation, the live and dead herbage

TABLE 1 Growing season (April–October) weather data (mean temperature [°C], precipitation sum [mm], mean global radiation [J cm^{-2}]) at Reiffenhausen supplied by the German weather service ('Deutscher Wetterdienst' [DWD], station Göttingen) and Mariensee (DWD weather station Hannover airport) during 2016 and 2017 based on daily records compared to the long-term period (1981–2010)

Site		Temperature	Precipitation	Global radiation
Reiffenhausen	2016	14.5 ± 4.4	374.5 ± 30.1	1487.1 ± 517.0
	2017	14.2 ± 3.9	558.7 ± 61.5	1372.6 ± 486.1
	1981–2010	13.7 ± 3.6	379.7 ± 10.2	1407.9 ± 433.5
Mariensee	2016	15.0 ± 4.4	369.7 ± 29.1	1486.0 ± 526.4
	2017	14.6 ± 3.7	541.6 ± 43.9	1334.1 ± 465.0
	1981–2010	14.1 ± 3.7	396.5 ± 9.1	1437.1 ± 454.1

Note: Numbers following ± indicate *SD*.

accumulation (g DM m^{-2}) and the HEFF were analysed using linear mixed-effects models in the *nlme* package (Pinheiro et al., 2018). Model assumptions were tested graphically and data were found generally to follow a Normal distribution. Different variance adjustments were applied in order to meet the criteria of variance homogeneity. Both sites were analysed separately by estimating global models with vegetation composition, cutting system, position and year as well as all possible interactions as fixed effects for site RH. The random effect constituted of the sampling plot nested in each block within the main plot (vegetation composition), subplot (cutting system) and position. Separate variances per year were allowed in the model for the total herbage accumulation and per position in the model for the live herbage accumulation. For the models of the dead herbage accumulation and the HEFF, separate variances were allowed for each level in the interaction of year and cutting system. At site MS, the global models consisted of the cutting system, position and year as well as all interactions as fixed effects and the sampling plot as random effect. The sampling plot resulted from the split-plot design with the main plot (cutting system) and subplot (position). In each model, separate variance was allowed for each level in the interaction of year and cutting system. Automated model selection from the global models was performed using the *MuMIn* package (Barton, 2018). The final model was selected based on the lowest Akaike information criterion corrected (AICc) for small sample sizes. For significant ($p < 0.05$, F test) terms in the final models, treatments were compared post hoc by least squared means ($p < 0.05$) using the package *lsmeans* (Lenth, 2018).

2.4 | Assessment of the area related to grassland–tree interface based on land use and land cover maps

Remote sensing data from, for example, Landsat and Sentinel-2, are well suited to map LULC for national scales with high accuracies (e.g., Griffiths et al., 2019; Pflugmacher et al., 2019). The high temporal resolution achieved by combining satellite sensor time series (e.g., Sentinel-1/2, Landsat) allows for creating detailed LULC maps, which provide information on, for example, grassland and tree cover on a spatial resolution of up to 10 m (Chaves et al., 2020). We used two recent LULC maps for 2016 (Griffiths et al., 2019) and 2018 to obtain tree and grassland cover, respectively. We then derived information on edges between grassland and trees across Germany based on these two LULC classifications by evaluating the 4-pixel neighbourhood of each 10 × 10 m grassland pixel with regard to adjacent forest cover or presence of isolated trees or tree rows. In this, permanent and temporary grassland were included. If a grassland pixel was connected to at least one tree pixel, we mapped a grassland–tree boundary of 10 m corresponding to the spatial resolution of the map. For each of these pixels, the cardinal direction of the neighbouring tree cover was assessed. We calculated the total length of grassland–tree edges for Germany and further evaluated the shares of cardinal directions of those edges. To further characterise the spatial configuration of the grassland–tree interface in Germany, we calculated and compared the grassland area potentially affected by tree shading for federal states corresponding to the Nomenclature of Territorial Units for Statistics (NUTS 2 regions) and administrative districts (corresponding to NUTS 3 regions).

3 | RESULTS

3.1 | Grassland herbage accumulation at site RH

The importance of each harvest to the herbage accumulation was altered by the cutting system (Figure S1) and the output of the linear mixed effects models is given in Table S3. In RH, years differed significantly ($p < 0.001$, F test) with a total herbage accumulation of 711 and 444 g DM m^{-2} in 2016 and 2017, respectively. A significant effect of the vegetation composition ($p < 0.01$, F test) revealed that the GC sward produced more total herbage than the DIV sward (652 vs. 503 g DM m^{-2}, $p < 0.01$). The position had a significant influence on the total herbage accumulation ($p < 0.001$, F test) and the rank between positions was M > CE > CW (791 > 526 > 417, respectively; Figure 2) with a difference of up to 47%. The same pattern as for the total herbage accumulation followed for the live herbage accumulation except that position had no significant effect (Table S3). The vegetation composition effect ($p < 0.01$, F test) revealed that the GC sward produced more live herbage than the DIV sward (531 vs. 434 g DM m^{-2}) and a significant effect of the year resulted in a larger live herbage accumulation in the year 2016 compared with the year 2017 (555 vs. 410 g DM m^{-2}, $p < 0.001$, F test). Position tended to have

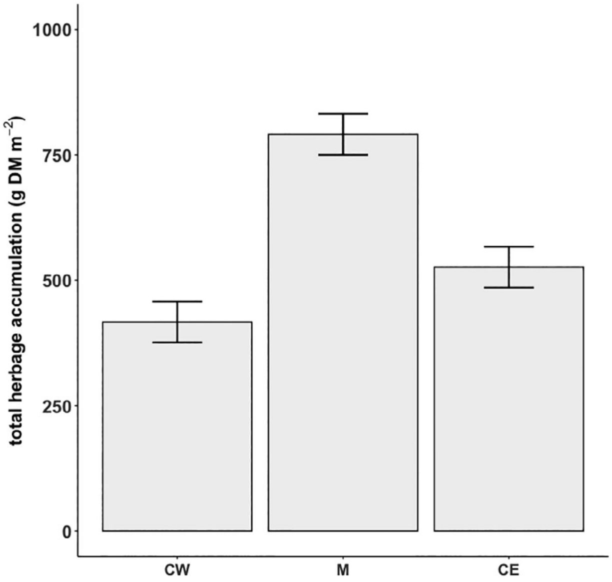

FIGURE 2 Means (±*SE*) of total herbage accumulation at site RH at each position. CE, Close East; CW, Close West; M, Middle

TABLE 2 Means (±*SE*) of the dead herbage accumulation (g DM m^{-2}) separated for the interaction of vegetation composition and position (a) and of the HEFF separated for the interaction of position and year (b) for site RH

(a) Dead herbage accumulation	Position	DIV	GC
	CW	70.7 ± 8.4	109.2 ± 8.4
	M	73.8 ± 8.4	124.5 ± 8.4
	CE	83.4 ± 8.4	109.2 ± 8.4
(b) HEFF	**Position**	**2016**	**2017**
	CW	0.66 ± 0.03	0.89 ± 0.01
	M	0.74 ± 0.03	0.93 ± 0.01
	CE	0.74 ± 0.03	0.90 ± 0.01

Abbreviations: CE, Close East; CW, Close West; DIV, diverse sward; GC, grass-clover sward; M, Middle; RH, Reiffenhausen.

a significant effect ($p < 0.07$, *F* test) on the live herbage with a decline of on average 37% from the middle towards the tree line positions.

The interaction of factors vegetation composition and position was significant for dead herbage accumulation ($p < 0.05$, *F* test). The GC sward accumulated significantly more dead herbage at the M position than the positions adjacent to the tree lines (LSMeans, $p < 0.05$; Table 2(a)). For the DIV sward the dead herbage accumulation at position CE was larger than at position CW (LSMeans, $p < 0.05$) with position M ranging between them (Table 2(a)). Despite the significant interaction between cutting system and vegetation composition ($p < 0.05$, *F* test), the dead herbage accumulation was larger in the infrequent compared with the frequent cutting system (on average: 124.8 vs. 65.5 g DM m^{-2}, *F* test, $p < 0.01$) and the GC sward produced more dead herbage than the DIV sward in both cutting systems (on average: 76 vs. 114.3 g DM m^{-2}, *F* test, $p < 0.01$). The interaction of vegetation composition and year was also significant for the dead herbage accumulation ($p < 0.001$, *F* test). In 2017, the swards did not differ in dead herbage accumulation, whereas in 2016 the GC sward produced significantly more dead herbage compared to the DIV sward (191.3 vs. 121.8 g DM m^{-2}, $p < 0.001$, LSMeans). However, a larger dead herbage accumulation in 2016 compared with 2017 was observed in both vegetation compositions (on average: 156.6 vs. 37.4 g DM m^{-2}, $p < 0.001$, *F* test). The interaction between cutting system and year was also significant for the dead herbage accumulation ($p < 0.01$, *F* test). The infrequent cutting system produced more dead herbage than the frequent cutting system in 2016 (203.8 vs. 109.4 g DM m^{-2}, $p < 0.001$, LSMeans) and in 2017 (45.8 vs. 21.6 g DM m^{-2}, $p < 0.001$, LSMeans); the year 2016 was more productive than 2017 ($p < 0.001$, *F* test).

The HEFF was affected by the significant interaction between position and year ($p < 0.01$, *F* test). In both years, the HEFF was higher at position M than at the positions adjacent to the tree lines, although the difference between M and CE was not significant in 2016 (LSMeans, $p = 0.9$; Table 2(b)). The HEFF was also affected by the significant interaction of vegetation composition and cutting system ($p < 0.01$, *F* test). The HEFF was significantly larger in the frequent cutting system than in the infrequent one for both vegetation compositions (DIV: 0.87 vs. 0.79, $p < 0.01$, GC: 0.87 vs. 0.72, $p < 0.001$, LSMeans). However, in the infrequent cutting system, the DIV sward had a larger HEFF compared with the GC sward (0.79 vs. 0.72, $p < 0.01$, LSMeans) while in the frequent cutting system the vegetation compositions did not differ (on average: 0.87). A significant interaction between vegetation composition and year ($p < 0.001$, *F* test) resulted from a larger HEFF in the DIV compared with the GC sward in 2016 (0.75 vs. 0.67, $p < 0.01$, LSMeans) while in 2017 no differences were found (on average: 0.9). The interaction between cutting system and year ($p < 0.01$, *F* test) was also significant but the HEFF was always larger in the frequent cutting system than in the infrequent cutting system (on average: 0.86 vs. 0.75, $p < 0.001$, *F* test) while in the year 2017 the HEFF was greater than in 2016 in both cutting systems (on average: 0.91 vs. 0.71, $p < 0.001$, *F* test).

3.2 | Grassland herbage accumulation at site MS

At site MS, the total herbage accumulation was affected by the interaction of position and cutting system ($p < 0.01$, *F* test) and by cutting system and year ($p < 0.01$, *F* test). Except at the position CW, the frequent cutting system had significantly larger total herbage accumulation than the infrequent cutting system ($p < 0.05$, LSMeans; Table 3(a)). In the infrequent cutting system, the total herbage accumulation was largest at position CW ($p < 0.01$, LSMeans; Table 3(a)) whereas the positions M and CE did not differ ($p = 0.9$, LSMeans; Table 3(a)). In the frequent cutting system, the total herbage accumulation at position CW was larger only compared to position CE ($p < 0.05$, LSMeans; Table 3(a)). For both cutting systems, the total herbage accumulation in 2016 was larger than in the year 2017 (on average: 908 vs. 443 g DM m^{-2}, $p < 0.001$, *F* test). However, in 2016 the cutting systems did

TABLE 3 Means (±*SE*) of the total herbage accumulation (g DM m^{-2}) separated for the interaction of cutting system and position (a) and of the dead herbage accumulation (g DM m^{-2}) separated for the interaction of cutting system and position (b) and of position and year (c) for site MS

(a) Total herbage accumulation	Position	Infrequent	Frequent
	CW	706 ± 32.4	736 ± 23.5
	M	608 ± 32.4	717 ± 23.5
	CE	613 ± 32.4	668 ± 23.5

(b) Dead herbage accumulation	Position	Infrequent	Frequent
	CW	276 ± 17.5	103 ± 11.2
	M	257 ± 17.5	136 ± 11.2
	CE	226 ± 17.5	111 ± 11.2

(c) Dead herbage accumulation	Position	2016	2017
	CW	275.2 ± 19.5	103.7 ± 8.0
	M	306.3 ± 19.5	86.1 ± 8.0
	CE	236.3 ± 19.5	100.2 ± 8.0

Abbreviations: CE, Close East; CW, Close West; M, Middle; MS, Mariensee.

not differ (on average: 908 g DM m^{-2}, $p = 0.7$, LSMeans) while in 2017 more total herbage (520 vs. 366 g DM m^{-2}, $p < 0.001$, LSMeans) was accumulated in the frequent cutting system. For the live herbage accumulation, a significant effect of the cutting system ($p < 0.001$, *F* test) was observed with a significantly larger amount in the frequent compared with the infrequent cutting system (587 vs. 413 g DM m^{-2}, $p < 0.001$, *F* test). Live herbage differed significantly among years ($p < 0.001$, *F* test) with larger amounts of live herbage in 2016 than in 2017 (653 vs. 347 g DM m^{-2}, $p < 0.001$, *F* test). The dead herbage accumulation was significantly affected by the interaction between cutting system and year ($p < 0.001$, *F* test) with a significantly larger dead herbage accumulation in 2016 compared with 2017 in both cutting systems (on average: 272.6 vs. 96.7 g DM m^{-2}, $p < 0.001$, *F* test). However, in 2017 the difference between the cutting systems was not significant (on average: 96.7 g DM m^{-2}) while in 2016 dead herbage accumulation was larger in the infrequent cutting system than in the frequent one (403.8 vs. 141.4 g DM m^{-2}, $p < 0.001$, LSMeans). The dead herbage was also significantly affected by the interaction of position and cutting system ($p < 0.01$, *F* test) and of position and year ($p < 0.01$, *F* test). No clear pattern among positions was observed between years nor in the cutting systems (Table 3(b), (c)). In the infrequent cutting system, the dead herbage was larger at position CW than at position CE ($p < 0.01$, LSMeans; Table 3(b)) while in the frequent cutting system, the dead herbage accumulation was larger at position M than at CW ($p < 0.05$, LSMeans; Table 3(b)). The dead herbage accumulation was larger in the infrequent compared with the frequent cutting system across positions (Table 3(b)) and also in 2016 compared with 2017 (Table 3(c)). However, among positions in the year 2017 no differences were observed in the dead herbage accumulation (Table 3(c)), while in 2016 a larger accumulation of dead herbage was found at position M compared with position CE ($p < 0.01$, LSMeans; Table 3(c)). A significant effect of the interaction between cutting system and year ($p < 0.001$, *F* test) was observed for the HEFF. In both years, the frequent cutting system resulted in a larger HEFF compared with the infrequent one (on average: 0.79 vs. 0.38, $p < 0.001$, *F* test). The HEFF of the infrequent cutting system in 2016 was significantly lower compared with 2017 (0.14 vs. 0.62, $p < 0.001$, LSMeans) while no difference among years was observed in the frequent cutting system (on average: 0.8).

3.3 | Assessment of the grassland area potentially interfered by trees in Germany

The length of the estimated grassland–tree boundary amounted to approximately 490,000 km across Germany. Consequently, the estimated grassland area within a distance of 4.5 m to forest or tree cover was 2200 km^2 corresponding to 4.4% of the total grassland area of Germany (map estimate of 49,700 km^2) (Figure 3). The orientation of the forest–grassland boundary was equally distributed among the cardinal directions. Among the federal states, the share of grassland as interfered by trees ranged between 2.9 (Bremen) and 5.9% (Saarland) (Table 4). Analysis on the district level revealed further spatial differences (Figure 3). Districts having both the highest overall grassland proportion and the highest percentage of grassland–tree edges were concentrated in the central regions of Germany. Districts with either a low grassland or edge area percentage predominated in southern regions towards the Alps and northeastern Germany.

4 | DISCUSSION

4.1 | Herbage utilisation in silvopastoral grassland

The main results of the field study were that competition by trees played an inconsistent and rather minor role at site MS and that any tree-induced modifications of all investigated herbage accumulation parameters were restricted to site RH. There, the total, live and dead herbage accumulation declined from the middle position towards the tree lines, and the HEFF was related to the cutting system but not strongly to the position or to an interaction between cutting system and position.

The average tree height from the beginning until the end of this study increased from 2.4 ± 0.1 m to 4.5 ± 0.9 m at site RH and from 0.5 m to 4.1 ± 0.6 m at site MS, which is a proxy for the strength of shading caused by trees. The photosynthetically active radiation (PAR) was measured above the grass canopy in the respective positions around noon at site MS during a subsequent year in the continuation of the present study (Sutterlütti et al., 2020). The annual average PAR showed no differences between the different positions. It is likely that the absent tree effects observed at site MS were caused by the chosen positioning rather than by the tree harvest prior to the beginning

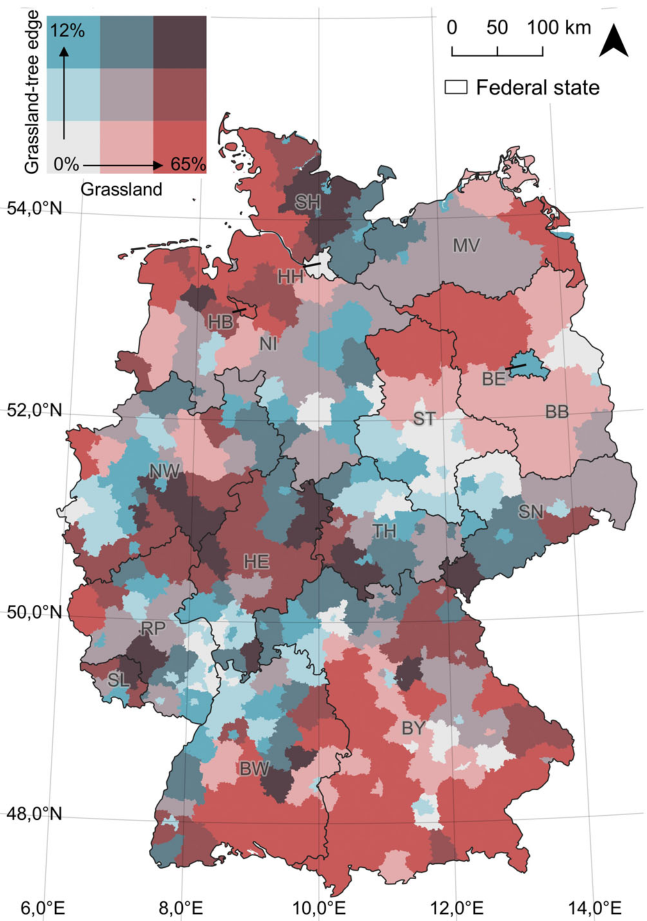

FIGURE 3 Percentage of grassland and grassland at tree interface on the district level in federal states of Germany (abbreviations explained in Table 4) based on land use and land cover information from satellite time series. Values were grouped into terciles (class intervals of grasslands percentage: 0–7.7, 7.8–13.7, 13.7–65 and class intervals of grassland–tree interface percentage: 0–4.5, 4.6–5.6, 5.7–12

of this study. In a previous study, Ehret et al. (2018), however, reported a decline of the incident light near trees at site RH. Competition for nutrients or water play an important role in agroforestry systems (Guevara-Escobar et al., 2007) and these may also dominate during re-establishment after tree pruning where light is likely less limiting (Jones et al., 1998). In addition, the decomposition of leaf fall is likely to cause growth inhibition of silvopastoral grassland (Halvorson et al., 2017).

We hypothesised no differences of HEFF within one cutting system near or at distance from the tree lines. It was assumed that this mechanism is because of lower growth rates and constant leaf lifespans and specific senescence rates (Devkota et al., 2009; Grant et al., 1981) resulting in a constant proportion of live and dead herbage. We consequently investigated an interaction between position and cutting system for the HEFF in order to assure that the differences between the defoliation systems in the middle position without tree interference are the same as close to trees. This interaction was never statistically significant which confirms our hypothesis. No interaction with position was observed because the live and also the dead herbage declined consistently while both these variables responded to the defoliation frequency as could be expected (Gastal & Lemaire, 2015). Following Mazzanti and Lemaire (1994), the HEFF is likely to increase with less senescent dead herbage. This is supported by the present study in view of consistently greater HEFF in the frequent compared with the infrequent cutting system.

The absent effect on HEFF in relation to the position may be addressed by questioning of whether growth or ageing is more strongly influenced by trees. An answer to this question requires consideration of the relative changes of live herbage accumulation among positions at site RH. In relative terms, the live herbage mass declined by 37% from the middle towards the tree line while the dead herbage declined by only 7% in the vicinity of the tree lines compared with the middle position (on average across treatments). This stronger effect on the live herbage illustrates that the senescence rate is less likely affected by shading than the growth rate. This is supported by a study reported on *L. perenne*, where shaded tillers continued to produce leaves, albeit, at a reduced rate (Ong & Marshall, 1979). Shaded grasses had lower tiller densities and, thus, lower herbage accumulation (Thomas & Davies, 1978) which can be attributed to carbohydrate-limited leaf expansion rates (Fulkerson & Donaghy, 2001). An unchanged senescence rate is supported by Grant et al. (1981) who have also found reduced growth rates under shading. The 2-year average senescence rates (± average *SEM*) resulting from the minimum and maximum dead herbage accumulation for the period from the beginning of April until the last harvest of a year in the present study ranged from 0.5 ± 0.04 to 2.1 ± 0.14 g m^{-2} day^{-1} at site MS and from 0.1 ± 0.01 to 1.10 ± 0.1 g m^{-2} day^{-1} at site RH. These values are lower than those reported by Bircham and Hodgson (1983) who have found average daily senescence rates of between 1 and 4.4 g m^{-2} day^{-1} in fertilised swards. Larger values can be attributed to different climatic conditions and fertilisation or are because of different sward types (Binnie & Chestnut, 1994). Especially at site RH greater proportions of dicot species were present which can have effects on the amount of produced dead herbage. For instance, Calvière and Duru (1995) reported that the species-specific growing degree days until 25% of all leaves per shoot show signs of senescence differ between 800 (monocots) and 2000 (dicots). Changes of species-specific leaf-life spans between monocot and dicot species could also explain differences between the two sites observed in the present study because legumes were present at site RH. Legumes are important components for maintaining the nitrogen supply within pasture systems (Andrews et al., 2007) and they obviously contributed positively to the herbage quality at site RH in terms of HEFF which was generally high.

4.2 | Potential implications of grassland extensification near trees

The constantly low HEFF in the infrequent cutting system provides an opportunity to promote other grassland-related ecosystem services

TABLE 4 Estimates of the grassland–tree interface in Germany based on LULC maps generated from satellite time series

			Grassland–tree interface	
Region	**Federal state**	**Grassland area (km^2)**	**km^2**	**%**
East	Berlin (BE)	10.22	0.58	5.65
	Brandenburg (BB)	3604.72	134.82	3.74
	Saxony-Anhalt (ST)	1760.95	68.32	3.88
	Saxony (SN)	1823.22	104.02	5.71
	Thuringia (TH)	1633.40	93.57	5.73
South	Baden-Württemberg (BW)	5340.96	227.18	4.25
	Bavaria (BY)	11844.25	448.24	3.78
	Hesse (HE)	3005.15	167.05	5.56
	Saarland (SL)	346.72	20.40	5.88
West	Lower Saxony (NI)	7248.93	308.15	4.25
	North Rhine-Westphalia (NW)	3830.26	207.44	5.42
	Rhineland-Palatinate (RP)	2451.06	127.14	5.19
North	Bremen (HB)	77.39	2.25	2.91
	Hamburg (HH)	57.55	2.35	4.08
	Mecklenburg-Western Pomerania (MV)	2897.78	133.19	4.60
	Schleswig-Holstein (SH)	3755.45	152.82	4.07
Germany		49688.02	2197.53	4.42

Note: Given are the grassland area (km^2) for each federal state in Germany, the grassland tree–interface (km^2) and the share of grassland–tree interface (%) in that state.

near tree lines such as invertebrate protection which benefit from extensive management (Kruess & Tscharntke, 2002): any intensification of defoliation in order to increase the HEFF is not worth the effort in view of the low productivity and the trade-off with yield of high-quality herbage accumulation is consequently low. This is in accordance with Smart et al. (2002) who attributed a high potential of field edges to promote biodiversity of British grasslands under appropriate management. The frequency of defoliation is critical to attain a high productivity, quality or floristic performance (Belesky et al., 2019) or to support birds (Allen et al., 2020). Cong et al. (2020) showed that designed diverse grassland mixtures harvested twice a year, increased the provision of flower resources in three landscapes of Denmark. A higher value for insect conservation of extensified grassland is also in line with Ekroos et al. (2020), who sampled nearly 300 grasslands across Europe and found a significant decline in bee species richness among other flower visiting invertebrates with intensification in fertiliser use.

The comparison of the two sites in our study allows for an estimation at which distance effects of trees on grassland herbage are likely to decline under the present climate. The middle position differed compared with the close positions at site RH. At MS, no differences between 6 and 24 m distances were observed. Consequently, effects of tree shading by short-rotation coppices reaching a height of up to five meters will likely decline at distances of between 4.5 (or less) to 6 m. Transferring these results to grasslands across Germany, we estimated that 4.4% of the grassland area is affected by shading of trees and is, therefore, potentially suitable for decreasing management intensity without substantial declines of high-quality herbage production. The LULC classifications were validated with high accuracies (overall accuracy ≥80%). Class area estimates were well in line with official statistics (Griffiths et al., 2019; Statistisches Bundesamt, 2019), confirming the reliability of the estimated area of grassland–tree interface. However, we likely overestimated the grassland area near trees that is suitable for extensification as we could not identify different management intensities and thereby were not able to limit the investigation to intensively used grasslands only. Based on our district-level estimates (Figure 3), a high share of grassland–tree edges was found in the middle of Germany which is typically hilly and less intensively utilised than the coastal areas and grasslands in southern Germany. So far, national-scale information on different management systems and their management intensity on grassland has not been derived reliably from remote sensing time series. It is therefore not yet possible to further specify the suitability for extensification of grasslands from remote sensing data alone without consideration of the actual management on site. Most intensive grassland is found in dairy enterprises. In 2018 approximately 61,000 dairy farmers were registered with an average herd size of 64 cows/farm (Tergast et al., 2019). Given that a farm has an average stocking rate of 1.7 livestock units/ha, roughly 38 ha of agricultural land are required per average farm. Assuming dairy livestock is fed on grassland and arable land each with a share of 0.5, then 19 ha of mainly intensive grassland per farm is utilised. The total grassland area under intensive dairy farming would then roughly be 1.16 million ha in Germany. Applying a constant value of 4.4% of grassland at the tree interface would give a rough estimate of 51,040 ha of extensification potential on intensively managed grassland because of trees. However, one has to take into account differences in shade intensity and shadow length between, for example, forests and short-rotation coppices as the canopy affects irradiance that is reached by understorey vegetation (Valladares et al., 2016). Additional remote sensing-based information from satellite sensing regarding tree species, tree height and density of tree cover would further enable the assessment of the shading intensity on grassland and enable a better estimation. By including these factors, most suitable grasslands for the proposed conservation measure of small-scale extensification near trees in intensive grassland could be identified to promote the conservation value of grassland around trees in general. However, the vegetation (whether natural or sown) should be adapted to the low-light environment near trees. When Pang et al. (2019) studied herb production and survival of 22 forage species under artificial shade, they concluded that most species are adapted to less bright environments, although grasses tended to be more suitable than flowering dicot species such as *Trifolium pratense*. On the other hand, coniferous trees in particular may exert strong adverse effects on the understorey vegetation because leaf litter fall decreases the soil pH (Halvorson et al., 2017; Muys et al., 1992). Studies of the tree–grassland interface can contribute to insights in finding appropriate management schemes and vegetation for particular regions and purposes.

5 | IMPLICATIONS

Shading by trees reduces grassland growth more severely than it increases senescence in silvopastoral grassland and this effect is not modified by the defoliation frequency. Although a high HEFF could be maintained by increased defoliation frequencies near tree lines, the total herbage production is generally low. Consequently, shorter harvesting intervals are less desirable near the tree lines. This reveals a potential for providing other grassland-related ecosystem services which benefit from infrequent defoliation because any intensification is not paid-off by adequate productivity and herbage quality. This serves as a basis for setting up an agri-environmental scheme focusing on management extensification at field edges near trees in intensively defoliated grassland. We estimated that approximately 4.4% of the German grassland is at a tree interface and potentially available for extensification, which goes far beyond silvopastoral alley-cropping systems.

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