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SCALE-DEPENDENT EFFECTS OF FOREST EDGES ON MOUNTAIN GRASSLAND BIOGEOCHEMISTRY

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Abstract

Current landscapes have been intensively modified by humans and forest fragmentation has created substantial increases of forest edges. So far, scale-dependence between observable ecological patterns and the underlying processes affected by forest fragmentation have been widely ignored. To overcome the widespread ambiguity in selecting relevant spatial scales for studying the ecological effects of forest fragmentation, we investigated the effect of forest prevalence and edge length on carbon stocks, organic matter and plant-available nutrients (nitrate and ammonium) across varying spatial scales in a temperate mountainous grassland landscape of Romania. We calculated forest prevalence and edge length in the surroundings of 60 grassland plots with different spatial extents and quantified the effects of both factors on grassland productivity and soil biogeochemistry. We found a strong decreasing effect of forest edge length on soil carbon stock and organic matter and a contrasting increased effect on plant-available nutrients in the range of 100 m to 300 m radius, particularly for nitrate in the first 150 m (marginal $r^2=0.22 \pm 0.02$, $p<0.1$). As the scale increased, we identified either an increasing tendency for carbon stock, organic matter and plant-available nutrients or an almost constant effect across the range of scales. Grassland above-ground biomass showed no clear trend with scale. In this study, we observed that the effect of forest prevalence and edge length on grassland soil biogeochemistry and productivity strongly varied with the spatial scale of investigation. Such profound scale-dependence of key ecosystem properties must be considered in management strategies aiming for sustainable ecosystem functioning.

Key words: carbon storage, edge effects, nitrogen availability, scale, spatial heterogeneity

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1. Introduction

The characterization of landscape structures and their effects on ecological processes and patterns is one of the main objectives of landscape ecology (Chave, 2013; Levin, 1992; Turner, 2005; Wiens et al., 1993). Dissimilarities in observable traits (e.g. diversity, height, color, seasonality) between patches are a pre-requisite to designate ecological patterns. Landscapes exhibit different degrees of non-randomly arranged heterogeneity caused by non-random anthropogenic and/or ecological processes. Patterns emerge at different spatial scales and may disappear

when scaling up or down (Turner, 1989; Wiens, 1989). In cultural landscapes, typical for large parts of Europe, human management and land use are prominent drivers of ecological processes and pattern formation. Common structural characteristics of human-induced heterogeneity are hedgerows or forest edges. Such linear features emerge from the interaction of anthropogenic drivers such as land use or management of edges with abiotic and biotic factors. Contributing processes are manifold but vary in importance on different spatial and temporal scales (Laurance, 2000; Turner and Gardner, 2015; Ries et al., 2017). Identifying the major processes underlying

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pattern formation is, therefore, a key to understand landscape structures and dynamics. Conversely, landscape structures such as forest edges are controlling important ecological processes. They affect the spatial and temporal distribution of energy and matter far beyond their spatial extent (Cadenasso et al., 2003; Ries et al., 2004). Landscape heterogeneity and ecosystem functioning are, therefore, strongly intertwined across a wide range of spatial scales (Caughlin et al., 2019; Goodwin and Fahrig, 2002; Prevedello and Vieira, 2009).

Investigations on forest edge effects mainly focus on plant community dynamics (Burst et al., 2017; Fagan et al., 1999; Fletcher, 2005; Murphy and Lovett-Doust, 2004). Biogeochemical effects of forest edges are still understudied although they are important determinants of plant community dynamics, and thus, landscape structure (Singh et al., 2017). Several studies emphasized the role of forest edges as three-dimensional spatial units that link fluxes of matter and energy between neighboring areas through biotic and abiotic processes (Alignier et al., 2014; Burst et al., 2020; Porensky and Young, 2013). Nevertheless, there is a lack of knowledge regarding the role of forest edges for the carbon (C) and nitrogen (N) fluxes and for the productivity of adjacent grasslands. In times of accelerating climatic changes, there is an increasing need to quantify the vulnerability of soil C sequestration and nutrient enrichment in fragmented landscapes. At the scale of soil-plant system, the rate of organic matter that is bounded in soil structure or becomes available to plants, as well as nitrogen becomes available for root systems uptake, depends on site-specific parameters as soil temperature, moisture and substrate quality and supply (Davidson and Janssens, 2006; Nieder and Banbi, 2008; Thevenot et al., 2010). Evidence suggests that in mountain grasslands, near forest margins, soil temperature decreases while soil moisture increases (Murcia, 1995). Thus, it is expected that biogeochemical processes, like organic matter formation or C storage, highly dependent on abiotic factors to be modified (Likens, 2013; Nieder and Banbi, 2008). Moreover, variations in species and biomass patterns generated by edges influence small-scale properties of soil (Holmes et al., 2005; Klaus et al., 2016; Lützow et al., 2006) through the quantity and quality of dead organic matter that differ in the composition of C and N chemical-based compounds (Chen et al., 2019; De Deyn et al., 2008; Steinbeiss et al., 2008). In consequence, under increased forest edges the rate at which organic matter or nitrogen are bounded to soil structures or are made available to plants is expected to decrease (Davidson and Janssens, 2006; Dungait et al., 2012; Thevenot et al., 2010).

The configuration of a mountainous landscape exhibits heterogeneity throughout a wide range of spatial extents, from small patches of grassland or forest to the entire landscape matrix. In such a multiscale landscape, the effect of forest edges on the soil biogeochemistry act in scale-related and additive manner (Ickes and Williamson, 2000; Malcolm,

1994). Forest edges are, therefore, expected to have weaker effects on grassland carbon pools when studied at finer scales than at larger scales. However, there is a consistent lack of empirical knowledge about scale-specific thresholds related to the importance of environmental drivers that act at forest edges (Allen, 2006; Nash et al., 2014). Generally, scale related effects that influence biogeochemical processes along forest edges are poorly understood. Studies on processes that are controlling ecological patterns (like e.g. carbon storage, nitrogen availability) can result in contradicting conclusions if different spatial scales are addressed (Wiens, 1989, 1995). In consequence, the interpretation of ecological patterns and their causes must refer to the scale of investigation (Chave, 2013; Kie et al., 2002; Wu and Li, 2006). Misconclusions based on the scale of investigation can impede the implementation of reasonable management strategies to sustain ecosystem functioning (Nassauer and Opdam, 2008).

To overcome ambiguity and arbitrariness in the selection of spatial scales for investigations, interactions between landscape structures, environmental drivers and biotic responses need to be investigated across scales (Brown et al., 2002; Turner et al., 2015; Wu, 2004). In this study, we investigated the effects of forest edges on the biogeochemistry and productivity of temperate mountainous grasslands in Romania. This type of landscape displays a variety of spatial arrangements of grasslands and forest patches demarcated by sharp boundaries and therefore provides an ideal case study to investigate the scale dependence of forest edge effects on grassland biogeochemistry and productivity as major ecological properties of cultural landscape in the temperate zone. We investigated the scale-dependent effects of forest edges on (1) soil N availability, (2) soil C stocks and (3) above-ground biomass across varying spatial extents from 50 m to 500 m. We focus on forest edge length as a surrogate for the ecologically 'active' area between forested and non-forested areas, but also account for the general prevalence of forest in the surrounding. We hypothesize that all three variables of interest will respond differently to surrounding forest prevalence and edge length on different spatial scales of investigation. The prime goal of this study is to link this variation in scale-dependence of forest edge effects on ecological properties related to nitrogen and carbon turnover to the relevant, underlying ecological processes. We, therefore, aim to identify spatial scales at which the spatial heterogeneity of the considered biogeochemical and biological properties is best explained by the variability of landscape structures, i.e. forest edges.

2. Material and methods

2.1. Study site

The study site is located in the Bucegi Natural Park in the Carpathian Mountains, in the upper basin of the Ialomița River in Romania (Fig. 1). The target

habitat of the study are species-rich *Nardus* grasslands on siliceous substrates surrounded by acidophilous *Picea abies* forests. The study site is a secondary-type of grassland resulting from historic forest fragmentation and is located at 1600 m a.s.l. During the last 50 years the grassland was used as pasture. Mean annual air temperature is approximately 5 °C with a mean annual precipitation of 1000 mm. The soil type is classified as Leptic Podzol (FAO-Unesco, 1997).

2.2. Sampling design

Sampling was conducted in August 2014 in mountain grasslands differently connected with the forest edges, at varying distances to the nearest forest edge (Fig. 1). Plot areas were selected in grassland locations with the same type of soil (Leptic Podzol), slope (20°), aspect (SE) and elevation (1600 m a.s.l.). Along a gradient to forest edges, 12 plots of 25 m² were established. Within each plot of 25 m² were randomly located 5 sub-plots of 0.25 m² (0.5 x 0.5 m), with a total amount of 60 sub-plots. Sub-plots were randomly selected using the ‘create random points’ geoprocessing tool in ArcGIS which generates random positions in a pre-defined area.

2.3. Scale assessment

Locations for all plots were recorded using GPS Garmin eTrex 30 in WGS83 projection. Acquired data were transformed to Stereographic 1970 projection and datum to Dealul Piscului 1970.

Elevation data were extracted from a DEM (Digital Elevation Model) based on topographic maps dating 1981, at a 1:25 000 scale. Land cover was extracted from orthophotoplans at 0.5 m resolution from 2009 updated with Google images dating from 2014 and field surveys.

We used geoprocessing tools of ArcGIS 10.1 to construct masks with different radius length around the grassland sampling points (surrogate for discrete spatial scales) and to assess: (1) the length of the mask circumference that intersects the forest area, and (2) the length of the forest edge, as an irregular line, that intersects the inside area of the circle defined by a specific radius (i.e. Buffer, Polygon to line and Intersect). Criticism against former approaches in edge effect assessment at the landscape scale emphasizes the lack of consideration of edge additive effects that occur as spatial extent increases (Ries et al., 2004). To overcome this issue we assess the effect of the forest edge for each sample point by constructing masks of radius ranging from 50 m to 500 m centred at that point. In our study, we assume that each radius dimension of the mask from 50 m to 500 m represents a discrete scale in terms of spatial extent.

We assessed forest edge length and prevalence in the surroundings of the grassland plots by using two approaches. We defined: (1) fL (i.e. forest edge length) to be the length of the forest edge, as an irregular line, that is found inside the marked circumference (i.e. mask radius) and (2) fC (as a surrogate for the prevalence of forest in the surrounding) to be the length of the mask radius that intersects the forest area (Fig. 1).

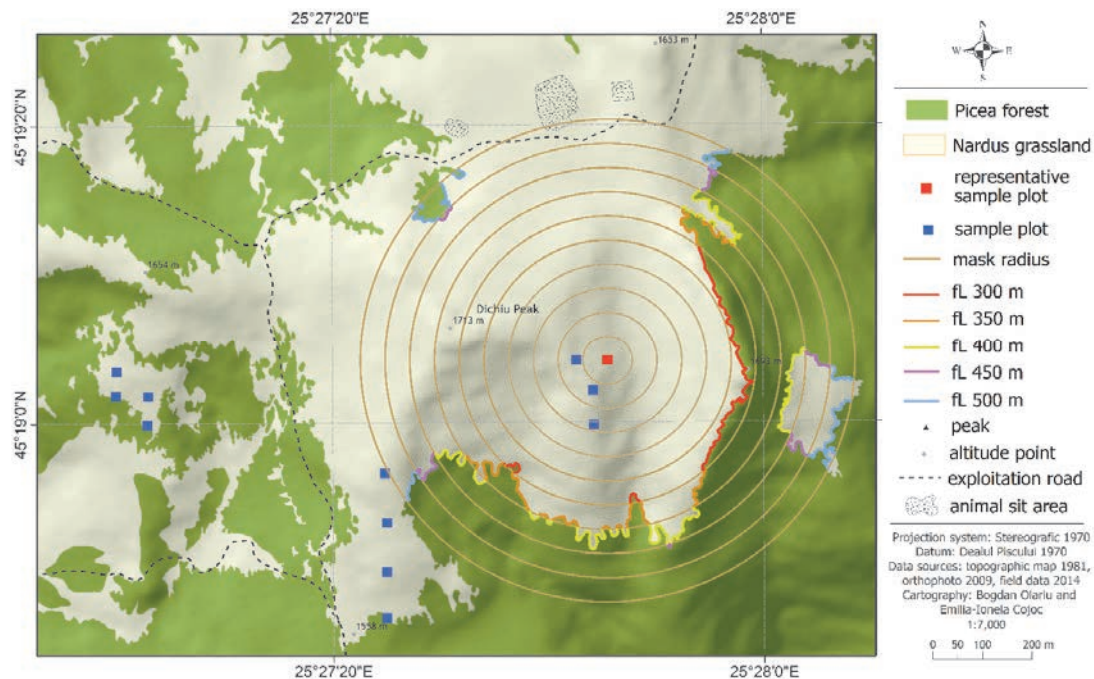


Fig. 1. Study area location, plots distribution and the representation of edge discrete scales assessed as fL (i.e. the intersection of forest area with mask circumference, represented as an irregular line, displayed inside the mask radius). The forest edge is graphically displayed as fL, each color represents the edge length characteristic as the additive difference for each scale. Each sample plot (25 m²) contains 5 sub-plots (0.25 m², not represented). Mask radius is displayed for one plot (i.e. representative sample plot) from 50 m to 500 m (in steps of 50 m)

Further, we used the length of fC and fL in combination with the radius dimension to investigate the scale-dependent effect of surrounding forest prevalence and edge length for each plot across the landscape.

2.4. Laboratory analysis

2.4.1. Above-ground biomass

The above-ground vegetative material was clipped at ground level for the entire surface of all subplots. Plant material was separated into individual species and allochthonous material (small branches and cones from *Picea abies*). The material was oven-dried at 65 °C for 72 hours and weighted to the nearest 0.01 g. Above-ground net primary production (ANPP) was calculated as the sum of photosynthetically active grass, herb, bryophyte and shrub biomass by excluding biomass from previous years stored in persistent graminoid leaf sheaths and dwarf-shrub branches. Above-ground net primary production was estimated based on peak live biomass (Scurlock et al., 2002).

2.4.2. Soil total C and N and plant available-nutrients

Soil samples were taken at each subplot in 5 cm depth corresponding to the maximum of biological activity (Lange et al., 2015). The soil samples were dried at 105°C and milled (3 min, 800 rpm - Pulverisette 7 – Planetary Micro Mill). Total carbon and nitrogen were determined on two replicates for each sample using an elemental analyzer (vario PYRO cube CHNS Elemental Analyzer, Elementar Analysensysteme GmbH, Hanau, Germany). Total carbon stock was calculated using the product between percentage of carbon concentration, bulk soil density and soil sampling depth (Guo and Gifford, 2002). In addition, plant-available nutrients (NH_4^+ -N, NO_3^- -N) were determined from wet soil samples for each subplot. Inorganic forms of nitrogen were extracted with 0.2 M KCl (Keeney and Nelson, 1982) and spectrophotometrically analyzed (Thermo Spectronic Helios Gamma UV-VIS Spectrophotometer). The indophenol-blue method was used for ammonium determination (Bremner, 1965) and the phenol disulphonic acid method for nitrate (Jagessar and Sooknundun 2011). All analytical results were normalized to dry soil weight.

2.5. Data analysis

To evaluate the effect of forest edge length and prevalence on soil N availability, C stocks and above-ground biomass across scales we performed regression analysis based on linear mixed effect models by using the lmer()-command of the lmerTest-R-package (v. 2.0-33, Kuznetsova et al. 2016). For the analysis of forest edge length and prevalence effects on the response variables on a particular scale it seems to be critical to account for the effect of forest edge length/prevalence on the other (smaller and larger)

spatial scales. We accounted for this potential cross-scale influence in the random effect of the performed regression analyses. For each spatial scale under consideration (forest edge length/prevalence at the particular scale), we, therefore re-ran the regression analysis by accounting for the effect of forest edge length/prevalence at each other spatial scale in the random effect term. We used Marginal r^2 to quantify the independent single effect of forest edge length/prevalence at the particular scale by varying the cross-scale influence (scale considered in the random effect term). Conditional r^2 was used to quantify the joint effect of forest edge length/prevalence at the particular scale and the cross-scale influence of each other spatial scale.

Both statistics were calculated using the r.squaredGLMM()-command of the MuMIn-R-package (v. 1.40.0, Barton 2017). This procedure resulted in 9 model runs for each of the considered spatial scales (50 to 500 m mask radius) from which the model statistics (Marginal r^2 , Conditional r^2 and p-values) were subsequently summarized for the presentation of the results by calculating the mean and standard deviation. For each model run we tested the predictor variable of the fixed effect term (forest edge length/prevalence at the particular scale) as untransformed (linear) as well as transformed ($\log()+0.001$) term and selected the best performing model version based on the statistical requirements for parametric regression analyses (normal distribution of residuals, homoscedasticity) and model performance (AIC). All statistical analyses were performed using R (R Core Team, 2017) with a level of significance of $\alpha = 0.05$.

3. Results and discussion

Forest edge length (fL) had the strongest effect on above-ground biomass at the smallest considered radius of 50 m with Marginal $r^2 = 0.33 \pm 0.02$ (mean and standard deviation) and $p < 0.001$ (Fig. 2, Table 1). The same is true for the effect of forest prevalence (fC) on ABG (above-ground biomass) with the strongest effect occurring at 50 m (Marginal $r^2 = 0.33 \pm 0.02$, $p < 0.01$; Fig. 3, Table 2).

The available forms of nitrogen (nitrate and ammonium) pools of the studied grasslands were significantly affected by the edge length of the surrounding forests almost across the whole range of considered spatial scales (Table 1) with a maximum effect at 200 to 250 m (Fig. 2). Forest prevalence in contrast showed lower and just exceptionally significant effects on the nitrogen pool across the considered range of spatial scales with an effect maximum for nitrate at 200 m (Marginal $r^2 = 0.31 \pm 0$, $p < 0.001$) and for ammonium at 250 m (Marginal $r^2 = 0.47 \pm 0$, $p < 0.01$). Spatial variability was high for both N available forms ammonium (CV = 143.99%) and nitrate (CV = 85.11%) but low for C stock (CV = 32.36%), OM (28.17%) and above-ground biomass (CV = 63.33%) (Table 3).

Forest edge length showed strong effects on carbon stock and organic matter at small spatial scales (50 to 150 m) as well as scales above 350 m but a drop in effect at intermediate spatial scales (Fig. 2, Table 1). Carbon stock and organic matter was generally less affected by forest prevalence in comparison to the forest edge length effects with strongest effects of forest prevalence begin observed on small spatial scales (below 150 m) at a gradual decrease in effect size towards larger spatial scales (Fig. 3, Table 2).

The prime goal of this study was to gain a more process-based understanding about the scale dependent effects of forest edges on ecological properties linked to carbon and nitrogen turnover in grasslands by identifying spatial scales at which the

spatial heterogeneity of the considered properties is best explained by forest prevalence and edge length. In our study, forest edge length and prevalence influenced above-ground biomass, C stock and organic matter at fine scales, but also at higher scales, while for nitrogen available forms (nitrate and ammonium) no clear tendency was detected.

Some studies, as Weathers et al. (2001), provided evidence that nitrogen fluxes are enhanced at small spatial scales, near forest edges compared to interior forest areas. Except for above-ground biomass, in our study, the highest significant influence of forest edge was not highlighted only at the smallest scale tested (i.e. 50 m, near the edge), but also in the range of 200 m to 300 m (Figs. 2, 3).

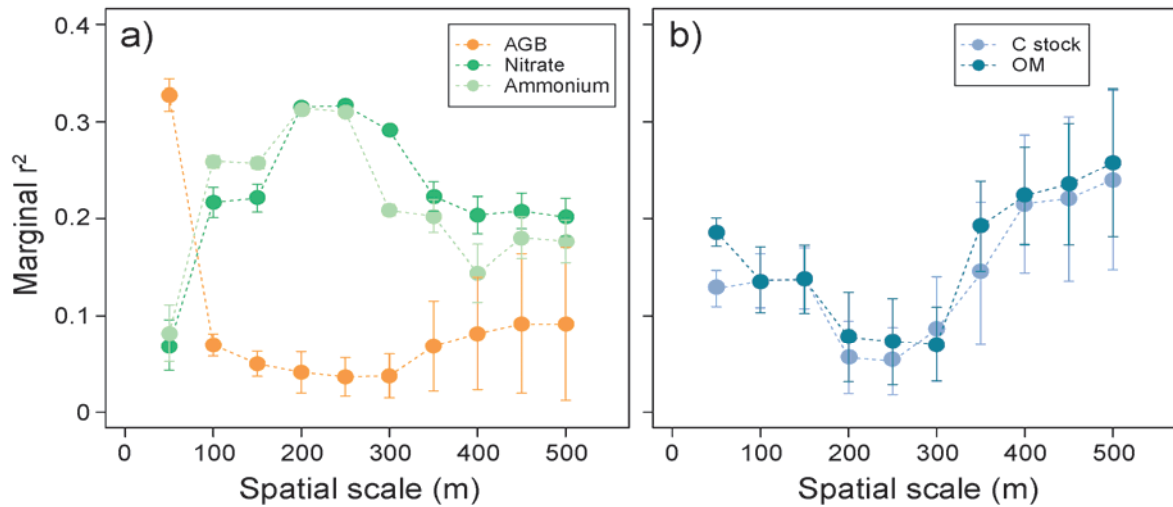


Fig. 2. Scale-dependence of the effect of forest edge length (fL) on (a) above-ground biomass (AGB), nitrate and ammonium and (b) on Carbon (C) stock and organic matter (OM) of temperate mountain grasslands in Romania. The effect of forest edge length on each spatial scales of observation by considering its effect on all other, considered spatial scales is depicted as mean (points) and standard deviation (error bars) of marginal r^2 of linear mixed effect models (details see Materials and methods, data analysis). Spatial scales represent the mask radii around the sampling points used for forest edge length calculation

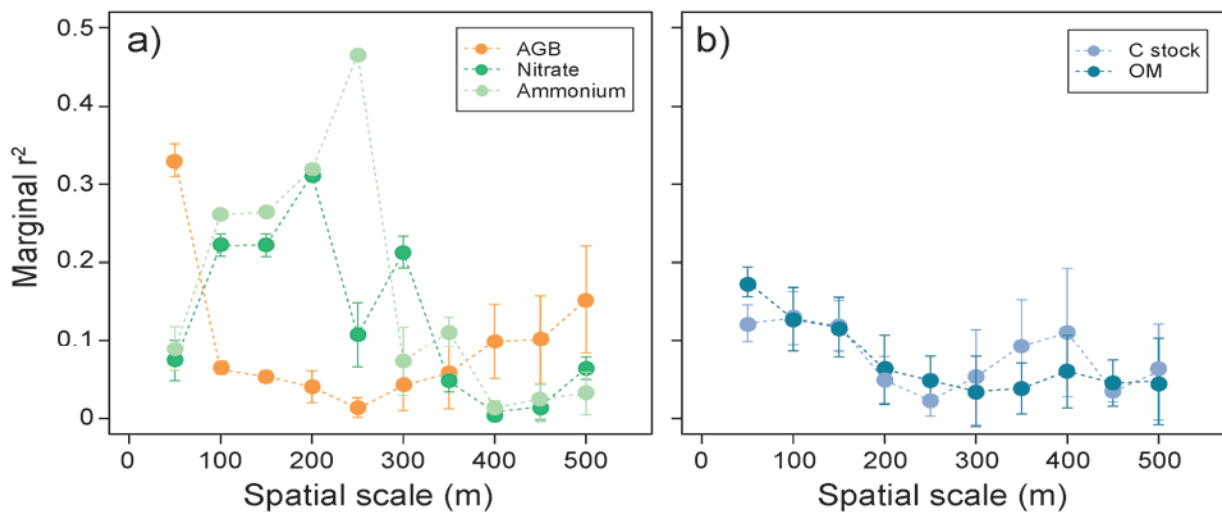


Fig. 3. Scale-dependence of the effect of forest prevalence (fC) on (a) above-ground biomass (AGB), nitrate and ammonium, and (b) on Carbon (C) stock and organic matter (OM) of temperate mountain grasslands in Romania. The effect of forest prevalence on each spatial scales of observation by considering its effect on all other, considered spatial scales is depicted as mean (points) and standard deviation (error bars) of marginal r^2 of linear mixed effect models (details see Materials and methods, data analysis). Spatial scales represent the mask radii around the sampling points used for forest prevalence calculation

Table 1. Model statistics for the effect of forest edge length (fL) on above-ground biomass (AGB), nitrate, ammonium, C stock and organic matter (OM) of temperate mountain grasslands in Romania based on linear mixed effect models (n = 60)

Scale	ABG			Nitrate			Ammonium			C stock			Organic matter		
	Mar. r ²	Cond. r ²	P-value	Mar. r ²	Cond. r ²	P-value	Mar. r ²	Cond. r ²	P-value	Mar. r ²	Cond. r ²	P-value	Mar. r ²	Cond. r ²	P-value
50	0.3 (0.02)	0.44 (0.05)	0 (0)	0.07 (0.03)	0.22 (0.04)	0.18 (0.1)	0.08 (0.03)	0.33 (0.12)	0.17 (0.07)	0.13 (0.02)	0.57 (0.07)	0.15 (0.07)	0.19 (0.01)	0.47 (0.08)	0.06 (0.03)
100	0.07 (0.01)	0.47 (0.05)	0.27 (0.1)	0.22 (0.02)	0.23 (0)	0.01 (0.01)	0.26 (0)	0.35 (0.08)	0.01 (0)	0.14 (0.03)	0.56 (0.11)	0.15 (0.08)	0.14 (0.03)	0.48 (0.1)	0.13 (0.07)
150	0.05 (0.01)	0.46 (0.04)	0.34 (0.17)	0.22 (0.01)	0.23 (0)	0.01 (0.01)	0.26 (0)	0.35 (0.08)	0.01 (0)	0.14 (0.03)	0.55 (0.11)	0.14 (0.04)	0.14 (0.04)	0.46 (0.1)	0.12 (0.04)
200	0.04 (0.02)	0.44 (0.07)	0.37 (0.12)	0.32 (0)	0.32 (0)	0 (0)	0.31 (0)	0.37 (0.05)	0 (0)	0.06 (0.04)	0.54 (0.12)	0.39 (0.23)	0.08 (0.05)	0.45 (0.12)	0.27 (0.19)
250	0.04 (0.02)	0.44 (0.07)	0.4 (0.13)	0.32 (0)	0.32 (0)	0 (0)	0.31 (0)	0.36 (0.05)	0 (0)	0.05 (0.03)	0.54 (0.12)	0.4 (0.21)	0.07 (0.04)	0.45 (0.12)	0.29 (0.2)
300	0.04 (0.02)	0.45 (0.05)	0.4 (0.23)	0.29 (0)	0.29 (0)	0 (0)	0.21 (0)	0.3 (0.11)	0.02 (0.01)	0.09 (0.05)	0.6 (0.16)	0.24 (0.2)	0.07 (0.04)	0.49 (0.15)	0.25 (0.17)
350	0.07 (0.05)	0.52 (0.08)	0.31 (0.19)	0.22 (0.02)	0.23 (0)	0.01 (0.01)	0.2 (0.02)	0.31 (0.1)	0.02 (0.02)	0.14 (0.07)	0.54 (0.08)	0.2 (0.31)	0.19 (0.05)	0.45 (0.07)	0.07 (0.07)
400	0.08 (0.06)	0.53 (0.1)	0.27 (0.17)	0.2 (0.02)	0.23 (0.01)	0.01 (0.01)	0.14 (0.03)	0.29 (0.13)	0.08 (0.06)	0.22 (0.07)	0.57 (0.07)	0.07 (0.07)	0.22 (0.05)	0.47 (0.07)	0.04 (0.04)
450	0.09 (0.07)	0.53 (0.11)	0.26 (0.17)	0.21 (0.02)	0.23 (0.01)	0.01 (0.01)	0.18 (0.02)	0.3 (0.11)	0.03 (0.03)	0.22 (0.08)	0.58 (0.09)	0.07 (0.06)	0.24 (0.06)	0.49 (0.08)	0.04 (0.03)
500	0.09 (0.08)	0.54 (0.12)	0.27 (0.18)	0.2 (0.02)	0.23 (0.01)	0.01 (0.01)	0.18 (0.02)	0.3 (0.11)	0.03 (0.03)	0.24 (0.09)	0.6 (0.09)	0.06 (0.05)	0.26 (0.08)	0.5 (0.09)	0.03 (0.02)

Scale: scale of observation quantified as mask radius used to calculate forest edge length around the grassland plots. Marginal r² (Mar. r²): Mean and standard deviation (in parenthesis) of marginal r² quantifying the proportion of variance explained by fL on each particular scale (as fixed effect). Conditional r² (Cond. r²): Mean and standard deviation (in parenthesis) of conditional r² quantifying the proportion of variance explained by both the fixed effect (fL of the particular spatial scale) and the random factor (fL of each other considered spatial scale). P-value: mean and standard deviation (in parenthesis) of the p-values for the models fixed effects (fL of the particular spatial scale)

Table 2. Model statistics for the effect of forest prevalence (fC) on above-ground biomass (AGB), nitrate, ammonium, C stock and organic matter (OM) of temperate mountain grasslands in Romania based on linear mixed effect models (n = 60)

Scale	ABG			Nitrate			Ammonium			C stock			Organic matter		
	Mar. r ²	Cond. r ²	P-value	Mar. r ²	Cond. r ²	P-value	Mar. r ²	Cond. r ²	P-value	Mar. r ²	Cond. r ²	P-value	Mar. r ²	Cond. r ²	P-value
50	0.3 (0.02)	0.46 (0.04)	0 (0)	0.07 (0.02)	0.23 (0.04)	0.16 (0.1)	0.09 (0.03)	0.35 (0.12)	0.16 (0.06)	0.12 (0.02)	0.59 (0.02)	0.17 (0.09)	0.18 (0.02)	0.5 (0.01)	0.07 (0.05)
100	0.06 (0)	0.48 (0.05)	0.28 (0.13)	0.22 (0.01)	0.23 (0)	0 (0.01)	0.26 (0)	0.36 (0.07)	0.01 (0)	0.13 (0.03)	0.59 (0.04)	0.15 (0.08)	0.13 (0.04)	0.51 (0.02)	0.15 (0.1)
150	0.05 (0)	0.48 (0.04)	0.31 (0.15)	0.22 (0.01)	0.23 (0)	0 (0.01)	0.26 (0)	0.36 (0.07)	0.01 (0)	0.12 (0.03)	0.59 (0.04)	0.17 (0.09)	0.12 (0.04)	0.51 (0.02)	0.17 (0.11)
200	0.04 (0.02)	0.47 (0.02)	0.34 (0.12)	0.31 (0)	0.31 (0)	0 (0)	0.32 (0)	0.38 (0.04)	0 (0)	0.05 (0.03)	0.59 (0.04)	0.37 (0.14)	0.06 (0.04)	0.5 (0.03)	0.36 (0.28)
250	0.01 (0.01)	0.47 (0.02)	0.6 (0.19)	0.11 (0.04)	0.2 (0.06)	0.08 (0.13)	0.47 (0)	0.47 (0)	0 (0)	0.02 (0.02)	0.57 (0.05)	0.57 (0.2)	0.05 (0.03)	0.5 (0.03)	0.27 (0.06)
300	0.04 (0.03)	0.46 (0.02)	0.36 (0.17)	0.21 (0.02)	0.23 (0)	0 (0)	0.07 (0.04)	0.3 (0.15)	0.25 (0.28)	0.05 (0.06)	0.62 (0.03)	0.44 (0.41)	0.03 (0.04)	0.54 (0.03)	0.56 (0.5)
350	0.06 (0.05)	0.45 (0.03)	0.33 (0.24)	0.05 (0.01)	0.22 (0.05)	0.21 (0.09)	0.11 (0.02)	0.32 (0.12)	0.07 (0.03)	0.09 (0.06)	0.62 (0.01)	0.22 (0.21)	0.04 (0.03)	0.52 (0.01)	0.39 (0.31)
400	0.1 (0.05)	0.44 (0.02)	0.12 (0.05)	0.01 (0)	0.22 (0.07)	0.63 (0.12)	0.01 (0.01)	0.32 (0.15)	0.56 (0.1)	0.11 (0.08)	0.65 (0.06)	0.22 (0.21)	0.06 (0.05)	0.55 (0.03)	0.31 (0.26)
450	0.1 (0.06)	0.46 (0.02)	0.21 (0.25)	0.01 (0.01)	0.22 (0.06)	0.53 (0.13)	0.02 (0.02)	0.35 (0.12)	0.52 (0.23)	0.03 (0.01)	0.59 (0.03)	0.44 (0.14)	0.04 (0.03)	0.5 (0.02)	0.4 (0.19)
500	0.15 (0.07)	0.43 (0.03)	0.08 (0.12)	0.06 (0.01)	0.22 (0.06)	0.15 (0.04)	0.03 (0.03)	0.37 (0.12)	0.46 (0.27)	0.06 (0.06)	0.61 (0)	0.4 (0.35)	0.05 (0.06)	0.55 (0.03)	0.52 (0.46)

Scale: scale of observation quantified as mask radius used to calculate forest edge length around the grassland plots. Marginal r² (Mar. r²): mean and standard deviation (in parenthesis) of marginal r² quantifying the proportion of variance explained by fC on each particular scale (as fixed effect). Conditional r² (Cond. r²): mean and standard deviation (in parenthesis) of conditional r² quantifying the proportion of variance explained by both the fixed effect (fC of the particular spatial scale) and the random factor (fC of each other considered spatial scale). P-value: mean and standard deviation (in parenthesis) of the p-values for the models fixed effect (fC of the particular spatial scale)

Table 3. Summary statistics of above-ground biomass (AGB), nitrate, ammonium, C stock and organic matter (OM) of temperate mountain grasslands in Romania

	AGB (g/m ²)	Nitrate (µg/g)	Ammonium (µg/g)	C stock (Mg/ha)	OM (%)
Minimum	53.68	1.93	1.78	47.53	11.41
Maximum	933.9	27.24	163.4	157.9	43.88
Mean	399.6	6.13	21.31	96.55	25.41
Std. Deviation	253	0.67	3.96	4.03	0.92
Coeff. of variation	63.33%	85.11%	143.99%	32.36%	28.17%

We account this maximum of scale effect to the spatial arrangement of the grassland-forest continuum, in line with results of Singh et al. (2017). At this distinctive range of scales, the highest additive effect of edges is generated, in agreement with the findings of Malcom (1994), where the magnitude of the edge effect increases with the length of edges from all spatial directions.

The scale dependence of C and N based compounds we observed in our study are grouped in the same range of spatial scales, indicating a consistency of process–pattern relationship. A specific scale emerged as a break point and afterwards the effect of scale was opposed, increasing to a maximum the distribution of N available nutrients and diminishing to a minimum the distribution of C stock and organic matter. Forest prevalence and edge length showed a similar effect with increasing distance from forest edges for above-ground biomass, C stock and organic matter. Thus, the magnitude of forest edge decreased to a minimum at a specific scale (i.e. 200 m) similarly for C stock and organic matter and antithetical increased for N available nutrients, while above-ground biomass showed no clear discontinuity with increasing spatial scale.

The opposite effect of scale on the observed C and N based compounds might be related to (1) different biochemical properties of C and N based compounds that modify the rate of processes, and (2) grazing pressure. As the scale of observation extends, the length of forest edges are increased. Edge effect have been shown to intrude on more than 200 m (Chen et al., 1995) depending on vegetation composition, landscape geometry and microclimatic conditions (Riutta et al., 2012). Typical vegetation near edges, higher in concentration of polyphenolics and secondary defense chemicals characterized by abiotic conditions having lower temperature and higher moisture favor a decrease in the rate of carbon storage, in agreement with findings of Jackson et al. (2002). Soil moisture and temperature modify the process rates of C and N by modifying soil physicochemical and microbial properties (Srivasta et al., 2017). Furthermore, low temperature and high moisture levels affect the biological capacity to decompose organic matter and lower the rate of processes that regulate primary productivity (Grant et al., 2001; Stevenson and Cole, 1999). The process of carbon storage is limited by nutrients availability (Wieder et al., 2015), thus, as C stock values are low it would imply that also the N available nutrients (nitrate and ammonium) values are low, but our results showed an opposite pattern. In this scenario, we sustain that high values of N available nutrients are also a consequence of grazing pressure, concentrated along the edges, as found in several studies (e.g. Duncan et al., 2008), that enhances locally the supply of N. It is also important to point out that C and N cycles are strongly interconnected and the composition of soil organic matter includes these two chemical elements that participate in common processes, but at different rates,

as mineralization and immobilization (Dungait et al., 2012; Nieder and Banbi, 2008). Besides a clear discontinuity in the scale effect of forest edges and prevalence at 250 m, two different patterns emerged for higher scales. A decreasing tendency with increasing scale for C stock, organic matter and N available nutrients occurred as an effect of forest prevalence. Forest edge length effect induced a contradictory pattern, N available nutrients decreased at 300 m and then remain constant with increasing scale, and C stock and organic matter increased at 300 m and then remain constant with increasing scale.

However, we argue in favor of the approach to assess forest edge as the irregular line displayed inside a circle of a specific established radius (i.e. r_L) to be the most significant from an ecological perspective, since it is in agreement with the general view on what a forest edge is considered. Limits on the general applicability of the method to assess effects of forest edges that are scale-dependent arise from the specificity of each landscape in terms of geometrical distribution of different habitat patches. Nevertheless, we pursue different perspectives to assess forest edge to: (1) show methodological possibilities to investigate how the dependency of scale can be tackled, and (2) explore the consistency of results.

A complementary perspective on the evaluation of scale effects across the landscape that needs to be considered, comes from the distribution of soil properties. Thus, the variability of soil properties is spatially displayed from small-scale (soil chemical composition associated with the plant-soil system), over medium-scale (the type of soil corresponding to land cover types) to large scale (parent material associated with geological units) (Holmes et al., 2005). Our data indicated that the variability of plant available nutrient concentrations (exemplified by $\text{NH}_4^+\text{-N}$, $\text{NO}_3^-\text{-N}$) exceeded three times the variability of C stock and organic matter, while total N had almost the same variability as C stock values. Ammonium concentrations showed the highest variability, a feasible indicator for grazing pressure that acts at larger spatial scales. The narrow spectrum of variability for C stocks, compared to the values of available forms of N, indicates the dependence of C storage on soil properties, such as silt and clay content (Lützwow et al., 2006), varying on larger spatial scales as investigated in our study.

4. Conclusions

The research results presented above emerged from a field study designed in one landscape, but the importance of our findings reaches far beyond the actual spatial cover. We tackle as a pioneer the cross-scale evaluation of forest edges effects and we found consistent scale-related patterns. However, to achieve a more in-depth understanding about the scale dependence of ecological effects of prominent landscape features further research should address the issues of replicated results in several landscapes.

Our study shows that the effects of forest edges on soil biogeochemistry vary strongly across scales. We proposed different approaches to assess the scale-dependent effect of forest edges. We demonstrated furthermore that the scale dependence of biogeochemical and biotic properties occurs at specific ranges of scale, a fact that could be related to the different turnover rates of biogeochemical processes.

However, our findings revealed the continuous limits of the attempt to generalize the effects of forest edge in a specific range of scales, mainly because of the heterogeneity of the landscapes. To establish discontinuities in domains of scales, where forest edge effects generate scale-related patterns, further research should address explicitly the involvement of temporal scales in modulating the dependence of edge effects on process dynamics. Moreover, additional investigations should rigorously address the circumstances under which strong scale-dependence emerges and high cross-scale similarity exists for the underlying drivers.

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