Microclimate and matter dynamics in transition zones of forest to arable land

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**A R T I C L E   I N F O**

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- Environmental gradients
- Fragmentation
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**A B S T R A C T**

Human-driven fragmentation of landscapes leads to the formation of transition zones between ecosystems that are characterised by fluxes of matter, energy and information. These transition zones may offer rather inhospitable habitats that could jeopardise biodiversity. On the other hand, transition zones are also reported to be hotspots for biodiversity and even evolutionary processes.

The general mechanisms and influence of processes in transition zones are poorly understood. Although heterogeneity and diversity of land use of fragments and the transition zones between them play an important role, most studies only refer to forested transition zones. Often, only an extrapolation of measurements in the different fragments themselves is reported to determine gradients in transition zones.

In this article, we analyse environmental gradients and their effects on biota and matter dynamics along transects between managed continental temperate forests and agricultural land for one year. Accordingly, we found S-shaped microclimatic gradients in transition zones of 50–80 m between arable lands and forests. Aboveground biomass was lower within 65 m of the transition zone, 30 m in the arable land and 35 m in the forest. Soil carbon and nitrogen contents were elevated close to the transition zone’s zero line.

This paper contributes to a quantitative understanding of agricultural landscapes beyond individual ecotopes, and towards connected ecosystem mosaics that may be beneficial for the provision of ecosystem services.

**1. Introduction**

In ecology, fragmentation is defined as the occurrence of discontinuities in prevalent or native land cover and habitat properties (Strayer et al., 2003). Although it is a natural process, fragmentation as we observe it today is mainly caused by humans (Haddad et al., 2015). As fragmentation occurs, it substitutes diverse and biomass-rich ecosystems with intensively used, man-made ecosystems, e.g. agricultural land (Tuff et al., 2016). Between these ecosystems, i.e. at their edges, transition zones occur through fluxes of matter, energy and information (for definitions, see Schmidt et al., 2017).

The processes and effects that occur have been categorised by Murcia (1995) into abiotic, direct biological and indirect biological effects of transition zones. Abiotic conditions – such as temperature – affect biological processes (Tuff et al., 2016) and thus habitat functions (Baker et al., 2016). In the literature, there is evidence that microclimatic gradients alter processes in transition zones, e.g. litter decomposition (Crockatt and Bebb, 2015; Remy et al., 2017b; Schmidt et al., 2017). Altered soil and air moisture and temperature in transition zones (Baker et al., 2016) influence the metabolism of microorganisms, and with that matter dynamics (Riutta et al., 2012). Wind blowing into transition zones of forests carries nutrients that trees and bushes comb out of the air (Draaijers et al., 1988). This leads to higher nitrogen availability in the transition zone, which enhances wood and leaf litter decomposition (Bebb et al., 2011). Higher nitrogen deposition might be beneficial for above- and belowground carbon stocks and sequestration (Remy et al., 2016) in the transition zone, but on the other hand trees are reported to have less wood volume (Veekelk et al., 2017).

Fragmentation-related habitat loss is likely to be the most important threat to biodiversity and one reason for the continued extinction of species (Arroyo-Rodriguez et al., 2017; Ibanez et al., 2017). Fragmentation is most often caused by an expansion of arable land and increases the ratio of edges to forest interior. Magura et al. (2017) have argued that these managed edges with an intensive human impact offer a rather inhospitable habitat in addition to habitat loss caused by fragmentation alone. However, the hospitality of transition zones greatly depends on the species that are investigated. Kark and van Rensburg (2006) as well as Lidicker (1999) have argued that transition zones can
be hotspots for biodiversity and even evolutionary processes as novel niches (see Ries et al., 2004 for a review). Edges caused by roads or with adjacent managed areas can favour exotic species compared to native species (Gehlhausen et al., 2000; Watkins et al., 2003). In a review, Fahrig (2017) argued that fragmentation has a positive effect on biodiversity. On the other hand, Fletcher et al. (2018) argued that this perspective is too onesided and that in fact negative effects on biodiversity occur.

Nonetheless, the general mechanisms and influence of processes in transition zones are poorly understood. As Ries et al. (2017) have noted, scientists have often merely described the edge effect of a single matrix (a “spatial domain where processes, properties or magnitudes” of physical, chemical or biological “variables are sufficiently distinct from those of its neighbors to warrant their segregation,” see Woo, 2004) and then they have extrapolated between matrices. Moreover, many studies focus on the fragment, but Ferrante et al. (2017) argue that the character (land use) of the matrices plays a more important role. In addition, most studies only refer to forested transition, considering it to be 100 m perpendicular to the zero line (Riitters et al., 2010). For arable land, Cleugh (1998); Kort (1988) and Nuberg (1998) reviewed literature on the windbreak effect of forested areas on microclimate, soil conditions and crop productivity. Cleugh and Hughes (2002) also provide models based on wind tunnel experiments and analyses of field experiments. Another article by Bird (1998) highlights similar positive effects of windbreaks and shelter on pasture.

We measured microclimate along different transects between managed continental temperate forests and agricultural land for one year. In addition, we measured soil nitrogen and carbon content as well as litterfall. In this paper, we analyse environmental gradients and their effects on biota and matter dynamics based on the following hypotheses:

1. The width of the transition zone from arable land to forest depends on the measured variable.
2. The abiotic environmental gradients are non-linear across ecosystem boundaries.
3. Biotic effects are the consequences of abiotic environmental gradients in the transition zone.

The terminology in this article follows our concept of transition zones in quantitative ecology (Schmidt et al., 2017).

2. Methods

2.1. Experimental design

The measurements for this study were conducted in northeast Germany in the Federal State of Brandenburg in 2016 and 2017. For a detailed description of methods and data, see Schmidt et al. (2018). For hourly microclimatic measurements (air and soil temperature, air and soil moisture, wind speed and direction, air pressure, precipitation and solar radiation with a repetition between n = 26,657 and n = 32,014), an east-facing (the arable land is east of the forest) and a west-facing site were equipped with one transect of five weather stations (Fig. 1) each – one weather station at the zero line, two within the arable land (15 m and 30 m) and two within the forest (-35 m and -70 m). For the sake of brevity, positive values are used for distance from the zero line for the arable land, and negative values for the forest. The distances were chosen according to the results of our literature review (Schmidt et al., 2017). At greater distances no significant effects were expected. In our east- and west-facing study design, we wanted to detect environmental gradients for these opposing cardinal directions rather than compare extremes like in north and south direction.

Aboveground biomass (n = 4) of oilseed rape, wheat, pea and barley was measured at four 1 m² plots at different distances (0–1 m, 7.5 m, 15 m, 30 m) from the zero line on the arable land. The aboveground parts of the plants were harvested, oven-dried and weighed. In the forest, the diameter at breast height (DBH) and the height of trees as proxy for aboveground biomass of pine and larch were measured at three plots (n = 30 trees per plot; 0 to -20 m, -50 to -70 m and -130 to -150 m from the zero line with a width of 80 m). Litterfall was measured at 0 m, -35 m and -70 m in the forest. At each distance, ten litterfall traps were arranged parallel to the zero line with a distance of 1 m towards each other to account for the forest heterogeneity. Soil was sampled at two depths (approx. 20 cm and 40 cm) at the transects (60 m, 30 m, 15 m, 0 m, -35 m, -70 m, -105 m) and analysed for total nitrogen and carbon content (n = 3).

2.2. Data analysis

The goal of the analysis of the time series of meteorological and soil parameters was to identify effects that could be ascribed to the position along the transect and separate them from other effects, like e.g. measurement imprecisions. To do this, each set of five time series of the same variable measured at different positions along the single transects underwent a principal component analysis. The principal component analysis of time series is meant to decompose the total variance of multidimensional data sets. It yields a set of independent principal components that explain most of the variance of the time series (Hohenbrink and Lischeid, 2015). In terms of microclimatic time series this analysis is done, as the variance can be high and might result in misleading interpretations. In mathematical terms, the principal component analysis performs an eigenvalue decomposition of the covariance matrix of the respective time series. Usually the first principal component is very close to the time series of spatial mean values from all considered sites, and depicts the largest fraction of variance of the total data set (Hohenbrink et al., 2016; Lischeid et al., 2017). Each of the remaining principal components then describes deviations from that mean behaviour, which can be ascribed to a specific effect (Hohenbrink et al., 2016). Identification of that specific effect, however, requires additional background data and a sound understanding of the relevant system. Our analysis aimed to identify the principal component that would reflect the effect of position along the transect rather than, e.g., the effect of local soil heterogeneities. We identified the respective component by checking the time series of the relevant principal components for monotonic decrease or increase along the transect.

In cases where such a relationship existed, correlation of the single observed time series x with the time series of the relevant principal component PCy was used as a quantitative measure of the strength of the effect. The correlation coefficients r_{x,PCy} were then normalised in...
such a way that +1 denotes typical time series of the inner forest position, -1 typical time series of positions in the arable land, and any value -1 < x < 1 describing the degree of similarity to either the typical forest or typical arable land time series of the relevant variable.

To do this, the correlation coefficients were transformed in a way analogous to the damping coefficient defined by Hohenbrink and Lischied (2015), below,

$$D_{x,P,C} = \arctan \frac{r_{x,P,C}}{r_{y,P,C}}$$

and were then normalised

$$D^*_{x,P,C} = s \cdot \frac{D_{x,P,C} - \min(D_{x,P,C})}{\max(D_{x,P,C}) - \min(D_{x,P,C})}$$

where

$$s = \begin{cases} 1, & \sum_{\text{forest}} D_{x,P,C} > \sum_{\text{arable}} D_{x,P,C} \\ -1, & \sum_{\text{forest}} D_{x,P,C} < \sum_{\text{arable}} D_{x,P,C} \end{cases}$$

and $\sum_{\text{forest}} D_{x,P,C}$ and $\sum_{\text{arable}} D_{x,P,C}$ is the sum of the coefficients for the two positions within the forest or arable land, respectively.

We also state the cumulative fraction of variance for the first ($\sigma_1^2$) and second ($\sigma_2^2$) principal component (Appendix A).

We carried out a Bonferroni-adjusted post-hoc analysis to compare the data on trees (Fig. 4), litterfall (Fig. 5), soil (Table 1, Appendix B) and above-ground biomass (Fig. 6) with respect to their position in the transect. To verify whether samples originated from the same distribution, we performed Kruskal-Wallis one-way analyses of variance (see Appendix C).

The R programming language (R Development Core Team, 2017) was used to perform all statistical analyses. The data is available in the accompanying method paper (Schmidt et al., 2018).

3. Results

3.1. Microclimate

At the west-facing site, soil moisture ($\sigma_1^2 = .71$, $\sigma_2^2 = .2$) and soil temperature ($\sigma_1^2 = .97$, $\sigma_2^2 = .03$) as well as the average ($\sigma_1^2 = .85$, $\sigma_2^2 = .09$) and maximum wind speed ($\sigma_1^2 = .86$, $\sigma_2^2 = .07$) and wind direction ($\sigma_1^2 = .63$, $\sigma_2^2 = .19$) exhibited a close to monotonic transition from the forest to the arable land (Fig. 2A). These environmental gradients were asymmetric and S-shaped. The transition zone according to the first principal component of these variables was approximately 65 m wide (from at least 30 m in the arable land to -35 m in the forest). For the average wind speed, the transition zone was 85 m.

Wind direction, air and soil temperature tended to be more similar to forest patterns; average wind speed was more similar to arable land. Air pressure, maximum wind speed, precipitation, soil moisture and solar radiation did not exhibit a clear pattern along the transect (Fig. 2D).

The main wind direction for this region is southwest (SW; Fig. 3). At the west-facing site at 0 and 30 m, the main wind direction tends towards the west, while at 15, -35 and -70 m the direction is south. At the east-facing site, the main wind direction at 15 m is more westerly than the main wind direction of the region. At -35 m, it is the same as for the region as a whole. At 15 and 0 m, the wind direction is more to the south, and is to the south at -70 m.

Comparing results from the two transects, only average wind speed and direction as well as soil temperature exhibited roughly monotonic patterns along both transects, while solar radiation and precipitation as well as air pressure did so in only one out of the two transects.

In terms of absolute values, soil temperature was 2–5 °C higher on average in the arable land of the west-facing site compared to the forest interior in June and July 2016 as well as from March to July 2017 (see Schmidt et al., 2018 for data). In winter, the forest soil tended to be warmer. Except for January, February and July 2017, soil moisture was lower on average in the forest. Maximum (approx. 1.5 to 3 m/s) and average wind speeds (approx. 0.2 to 1 m/s) were higher in the arable land compared to the zero line as well as to the forest interior.

At the east-facing site, average soil temperature was approx. 2–4 °C higher on average in the arable land compared to the zero line and the forest interior, except in autumn and winter (October to February). The average air temperature tended to be slightly higher in the arable land, except for the period June to September 2016, when arable lands were considerably warmer than the forest interior, by 0.5–2 °C. The average relative humidity was lower in the arable land, while the average wind speed was higher (up to 1.5 m/s) in all months of measurement.

3.2. Tree height and diameter

The height of the trees per plot (n = 30) is significantly lower at the zero line (0–20 m) at both sites (Fig. 4) with an average height of

Table 1

Significant ($p < 0.05$, Bonferroni-adjusted post-hoc analysis) differences in total soil carbon (indicated by C; above the diagonal) and total soil nitrogen (indicated by N; below the diagonal) merged contents for 20 ± 3 cm and 40 ± 3 cm depth for different positions along the transects. If a capital letter is given with a number, there is only a difference at that depth; otherwise at both depths. ↓ indicates lower and ↑ higher levels at the distance given in columns compared to those in rows.

| Soil carbon content | Forest | Zero line | Arable land |
|---------------------|--------|-----------|-------------|
| Soil nitrogen content |        |           |             |
| Forest              |        |           |             |
| −105 m              | ↓C     | ↓C at 40  | ↓C          |
| −70 m               | ↓C     | ↓C at 40  | ↓C          |
| −35 m               | ↓C     | ↓C at 40  | ↓C          |
| 0 m                 | N      | ↑C        | ↑C          |
| 15 m                | ↑C     | ↑C        | ↑C          |
| 30 m                | ↑C     | ↑C        | ↑C          |
| 60 m                | ↑C     | ↑C        | ↑C          |
| 105 m               | N      | ↑C        | ↑C          |
| 30 m                | ↑C     | ↑C        | ↑C          |
| 60 m                | ↑C     | ↑C        | ↑C          |
| Zero line           |        |           |             |
| Forest              |        |           |             |
| −105 m              | ↓C     | ↓C at 40  | ↓C          |
| −70 m               | ↓C     | ↓C at 40  | ↓C          |
| −35 m               | ↓C     | ↓C at 40  | ↓C          |
| 0 m                 | N      | ↑C        | ↑C          |
| 15 m                | ↑C     | ↑C        | ↑C          |
| 30 m                | ↑C     | ↑C        | ↑C          |
| 60 m                | ↑C     | ↑C        | ↑C          |
| Arable land         |        |           |             |
| −105 m              | N      | ↑C        | ↑C          |
| −70 m               | ↑C     | ↑C        | ↑C          |
| −35 m               | ↑C     | ↑C        | ↑C          |
| 0 m                 | N      | ↑C        | ↑C          |
| 15 m                | ↑C     | ↑C        | ↑C          |
| 30 m                | ↑C     | ↑C        | ↑C          |
| 60 m                | ↑C     | ↑C        | ↑C          |
18.98 m (east-facing, 50-70: 1.1 \times 10^{-6}, 130-150: 8.7 \times 10^{-10}) and 20.52 m (west-facing, 50-70: 1.1 \times 10^{-6}, 130-150: 2.4 \times 10^{-5}) compared to the interior plots. This figure does not differ significantly between the plots from 50 to 70 m and 130 to 150 m (west-facing: 21.95 m and 22.82; east-facing: 25.4 and 24.73 m). The diameter at breast height (not shown) was not significantly different except for the east-facing site in the 0 to 20 m plot (zero line; 24.94 cm compared to 27.8 cm (50 to 70 m) and 25.78 cm (130 to 150 m).

### 3.3. Litterfall

At the east-facing site, the mean dry mass of litterfall of pine (*Pinus sylvestris* L.) was not significantly different with respect to distance to the zero line (Fig. 5). The mean dry mass of the litter of larch (*Larix decidua*) at the west-facing site was significantly lower in the plot at the zero line (6.1 g) compared to 35 m (8.9 g) and 70 m (12.2 g) towards the forest core matrix. It is not pertinent to compare both sites because of their different tree species and tree ages.

### 3.4. Aboveground biomass in the arable land

For barley, the mean dry biomass was significantly higher at 7.5, 15 and 30 m (p = 3.5 \times 10^{-7}, 7.9 \times 10^{-9}, 1.2 \times 10^{-7}) compared to the zero line. At 7.5 and 30 m, mean dry biomass of barley was not significantly different, while at the 15 m mean, the dry biomass was significantly higher (7.5: p = .0031, 30: p = .0269).

Pea had significantly higher mean dry biomass at 7.5 and 30 m (p = .0052, p = .0092) compared to the plot at the zero line. At 15 m, the mean dry biomass of pea was significantly lower than at 7.5 m and 30 m (p = .0233, p = .0422).

The mean dry biomass of oilseed rape was significantly higher at 7.5, 15 and 30 m (p = .0074, p = .0001, p = .0005) compared to the zero line. The mean dry biomass at all other distances was not significantly different.

Wheat had the statistically highest mean dry biomasses at 15 m, but not different at 30 m. However, the mean dry biomass was lowest at the zero line (p = .001, p = 5.1 \times 10^{-8}, p = 5.9 \times 10^{-7}). At 7.5 m, it was also significantly lower than the figures observed at 15 and 30 m (p = 1.0 \times 10^{-5}, p = .4.4 \times 10^{-4}).

### 3.5. Soil carbon and nitrogen content

The highest mean values for total soil carbon content (C*) were found at the zero line, with 1.56% at the east-facing site and 1.67% at the west-facing site at a 20 cm depth (Appendix B). These values are significantly higher than all other distances except 70 m in the forest (Table 1). The same holds true for the samples from the 40 cm depth, except for 35 m from the transect in the forest. The lowest values for C* were found in the arable land, with less than 0.2%. Additionally, C* was significantly different between 15 m in the arable land and 35 m in the
forest at 40 cm depth as well as between 60 m in the arable land and 70 m in the forest at 20 cm depth. In terms of $N_t$, the highest values were also at the zero line, with 0.13% at both sites. Here, the zero line differs significantly from all other distances (Table 1). The ratio between total soil carbon and nitrogen content (C:N) was – with values between 4.17 and 6.12 – the lowest at a depth of 40 cm and in the arable land, except for 105 m in the forest on the west-facing site, where it was 5.13 (Appendix B). The widest C:N relationship was found at the 20 cm depth in the forest at both sites, with values between 13.35 and
16.07.

4. Discussion

4.1. Properties of environmental gradients in transition zones

We hypothesised that the width of the transition zone from arable land to forest depends on the measured variable. We found that it is smaller for some microclimatic gradients according to the shape of the correlation coefficients of the first principal components (approx. 50 or 85 m) compared to other authors (e.g. Haddad et al., 2015). This is in line with other authors (e.g. Hennenberg et al., 2008). In most cases, the forested transition zone was approx. 35 m, which is only one-third smaller for some microclimatic gradients according to the shape of the land to forest depends on the measured variable. We found that it is

4.2. The significance of biotic effects in transition zones

A transition zone between forest and arable land of altered above-ground biomasses has a width of up to 65 m perpendicular to the zero line. Because of the distances between the plots, this is just an approximation. Nevertheless, the extent appears to be in line with the approximated extent of altered environmental gradients. Considering the whole transition zone, aboveground biomass has an inverted bell shape.

With respect to tree height and diameter as an indicator, we found lower aboveground biomass in the forest at the zero line. This was also reported for decreased tree heights at distances of 25 to 30 m by Ibanez et al. (2017) and for an urban pine forest by Veselkin et al. (2017). Wright et al. (2010) found the basal area to be lowest at the zero line but then stabilised at 20 m from the zero line. More generally, Islam et al. (2017) have found trees next to the zero line to be smaller and lower in diameter in fragmented forests, which could mean reduced
carbon storage or wood volume (Veselkin et al., 2017). This is contrary to Hernandez-Santana et al. (2011) and Dodonov et al. (2013), who reported an increase in height towards the zero line. Remy et al. (2016) argued that wood volume was higher towards the zero line due to increased atmospheric N deposition (Remy et al., 2017a) and favourable light conditions compared to forest interior (Chen et al., 1993; Dodonov et al., 2013; Schmidt et al., 2017). Similar results are reported bywicklein et al. (2012) who, in addition, found higher sapling density in north and south-facing transition zones. Most studies like ours only took trees into account, but not the bush and shrub layer. Islam et al. (2017) have described this as a problem, albeit a minor one. However, Erdös et al. (2014) report the highest vegetation cover in the transition zone between forest and steppe. In the light of this, height and diameter as proxies for belowground biomass in forested transition zones might be not sufficient as shrubs, higher sapling density and herb biomass are not accounted for. These measures should be considered when calculating biomass in transition zones. The influence of this, however, might be case specific.

Litterfall was lower at the west-facing site. One reason might be the windward direction of this site (Fig. 2), as wind can carry litter into the forest and away from the zero line. In addition, the two to threefold higher average wind speed compared to the interior forest would substantially enhance litter removal in the forested transition zone. Lower litter cover and litter depth was also found byWatkins et al. (2003) close to roads compared to the forest interior.

The biomass in the cropped transition zone increased as distance from the zero line increased. This was also found by Mitchell et al. (2014) for soybean, with an increase of 55% to 117% from the zero line to 100 m in the arable land. Mitchell et al. (2014) argued that pest regulation has an influence on crop growth, and vice versa. On the other hand, pest regulation is influenced by the distance to forest as well as the general landscape structure (maximum pest regulation near the forest fragment; Mitchell et al., 2014).

Like other authors, we report spatially explicit environmental gradients, their biotic effects and feedback relations. For deeper understandings of landscape processes, researchers often apply mechanistic modelling (Ries et al., 2017). In most of the modelling studies that include more than just one ecotope, different ecosystems are modelled independently, without consideration for any lateral connections. Some habitat models have considered at least biotic exchange through individual movement (Fletcher et al., 2016), and hydrological models at watershed level have also included lateral water flows (Hwang et al., 2012). However, cross-ecosystem relations are rare in models for biomass growth and ecosystem service assessment. Depending on the goal of the model, it may be necessary to account for transition zone gradients and their effects, e.g. when applying forest and crop growth models or biogeochemical models on the landscape scale. Some of the feedback relations seem obvious: soils close to the zero line may contain higher soil carbon content due to litterfall from adjacent trees, while trees are smaller towards the zero line and may store less carbon. Crop yield depressions in the transition zone might result from shading or from competition for water. Higher air humidity at the edge of the forest could decrease evaportranspiration and thus increase the risk of fungal infections, which could consequently affect yields and the quality of agricultural products. These effects – and probably many more – all affect the provision of ecosystem services and hence human wellbeing. With deeper insights into transition zones, we may be able to connect up forest and crop growth models at their ecological boundaries and explore more of these assumed feedback patterns, disentangling some of the complexity. This would be an important step from fertilisation and higher atmospheric N deposition (Remy et al., 2017a, b). In terms of carbon, a strip of approximately two to three meters with a grassland character directly at the edge (see a photo in Schmidt et al., 2018) might have accumulated carbon in the soil over the years. Therefore, a transition zone can have a maximum width of 50 m perpendicular to the zero line in our experiment. This width is in line with our findings that altered conditions in soils of transition zones occur within 10 to 20 m with a maximum of 50 m (Schmidt et al., 2017). In general, the levels of soil carbon and soil nitrogen were low, most likely due to the sandy soils (Schmidt et al., 2018) in this region. This and the rather intensive use of N mineral fertilisers leads to low C:N ratios in the mineral soil. The gradients for C and N levels are most likely bell-shaped, because there was no statistical difference between the arable land and the forest – in spite of what we generally expected and in part due to findings by other authors regarding soil and litter deposition (Stanton et al., 2013; Toledo-Aceves and Garcia-Oliva, 2008) – but there were higher values at the zero line.

Higher C and N content levels cannot be ascribed to reduced litter input, as Remy et al. (2016) found no effect of distance for C and N in needles and leaves. In addition, we only found significantly less litterfall at one site. However, C and N stocks in the mineral soil were higher at the zero line by approximately one-third (Remy et al., 2016), which is in line with our findings. For N, the reason might be higher atmospheric N deposition at the zero line (Remy et al., 2017a; Wuyts et al., 2008), and N being released more quickly from litter and wood (Bebber et al., 2011; Didham, 1998; Remy et al., 2017b). On the other hand, Moreno et al. (2014) as well as Vasconcelos and Laurance (2005) reported no difference in litter decomposition rates at the zero line relative to the forest interior. It is still unclear what role soil moisture plays in this context. Didham (1998) and Remy et al. (2017b) also found no effect for air temperature (Didham, 1998). However, Riutta et al. (2012) and Simpson et al. (2012) reported a correlation between soil moisture, microbial activity and litter decomposition. It could be that the effect of single trees on litter decomposition is underestimated (Hastwell and Morris, 2013), which makes processes even more complex.

5. Conclusions and outlook

Like other authors, we report spatially explicit environmental gradients, their biotic effects and feedback relations. For deeper understandings of landscape processes, researchers often apply mechanistic modelling (Ries et al., 2017). In most of the modelling studies that include more than just one ecotope, different ecosystems are modelled independently, without consideration for any lateral connections. Some habitat models have considered at least biotic exchange through individual movement (Fletcher et al., 2016), and hydrological models at watershed level have also included lateral water flows (Hwang et al., 2012). However, cross-ecosystem relations are rare in models for biomass growth and ecosystem service assessment. Depending on the goal of the model, it may be necessary to account for transition zone gradients and their effects, e.g. when applying forest and crop growth models or biogeochemical models on the landscape scale. Some of the feedback relations seem obvious: soils close to the zero line may contain higher soil carbon content due to litterfall from adjacent trees, while trees are smaller towards the zero line and may store less carbon. Crop yield depressions in the transition zone might result from shading or from competition for water. Higher air humidity at the edge of the forest could decrease evaportranspiration and thus increase the risk of fungal infections, which could consequently affect yields and the quality of agricultural products. These effects – and probably many more – all affect the provision of ecosystem services and hence human wellbeing. With deeper insights into transition zones, we may be able to connect up forest and crop growth models at their ecological boundaries and explore more of these assumed feedback patterns, disentangling some of the complexity. This would be an important step
towards a holistic understanding of processes on the landscape scale.

**Declarations of interest**

None.

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**Appendix A. Variance of the first and second principal component for Z-transformed variables at a west-facing and an east-facing site**

| Site          | Measured variable | First principal component | Second principal component |
|---------------|-------------------|----------------------------|-----------------------------|
| West-facing   |                   |                            |                             |
|               | Air pressure      | 0.97                       | 0.02                        |
|               | Air temperature   | 0.99                       | 0.01                        |
|               | Precipitation     | 0.81                       | 0.13                        |
|               | Relative humidity | 0.95                       | 0.03                        |
|               | Soil moisture     | 0.71                       | 0.2                         |
|               | Soil temperature | 0.97                       | 0.03                        |
|               | Solar radiation  | 0.84                       | 0.1                         |
|               | Average wind speed| 0.85                       | 0.09                        |
|               | Wind direction    | 0.63                       | 0.19                        |
|               | Maximum wind speed| 0.86                       | 0.07                        |
| East-facing   |                   |                            |                             |
|               | Air pressure      | 1                          | –                           |
|               | Air temperature   | 1                          | –                           |
|               | Precipitation     | 0.86                       | 0.09                        |
|               | Relative humidity | 0.98                       | 0.01                        |
|               | Soil moisture     | 0.76                       | 0.13                        |
|               | Soil temperature | 0.99                       | 0.01                        |
|               | Solar radiation  | 0.86                       | 0.09                        |
|               | Average wind speed| 0.65                       | 0.19                        |
|               | Wind direction    | 0.63                       | 0.2                         |
|               | Maximum wind speed| 0.7                        | 0.15                        |

**Appendix B. Levels of total soil carbon (C) and total soil nitrogen (N) depending on the distance to the zero line of a forest (negative values) to arable land (positive values) at a west-facing (W) and an east-facing (E) site. Soil was sampled at two depths (±3 cm)**

| Distance to zero line | Site | Depth of sampling | Mean Ct, % (n = 3) | Mean Nt, % (n = 3) | C:N |
|-----------------------|------|-------------------|--------------------|--------------------|-----|
| 60                    | E    | −20               | 0.39               | 0.05               | 8.57 |
| 60                    | W    | −20               | 0.51               | 0.06               | 9.31 |
| 60                    | E    | −40               | 0.13               | 0.03               | 4.17 |
| 60                    | W    | −40               | 0.24               | 0.03               | 7.50 |
| 30                    | E    | −20               | 0.50               | 0.06               | 8.43 |
| 30                    | W    | −20               | 0.62               | 0.07               | 9.23 |
| 30                    | E    | −40               | 0.28               | 0.05               | 6.12 |
| 30                    | W    | −40               | 0.28               | 0.03               | 9.10 |
| 15                    | E    | −20               | 0.43               | 0.06               | 6.66 |
| 15                    | W    | −20               | 0.65               | 0.07               | 8.99 |
| 15                    | E    | −40               | 0.12               | 0.02               | 5.42 |
| 15                    | W    | −40               | 0.19               | 0.03               | 5.88 |
| 0                     | E    | −20               | 1.56               | 0.13               | 12.28 |
| 0                     | W    | −20               | 1.67               | 0.13               | 13.04 |
| 0                     | E    | −40               | 0.51               | 0.07               | 7.49 |
| 0                     | W    | −40               | 0.47               | 0.06               | 7.88 |
| −35                   | E    | −20               | 1.02               | 0.06               | 16.07 |
| −35                   | W    | −20               | 0.65               | 0.06               | 11.15 |
| −35                   | E    | −40               | 0.41               | 0.04               | 9.89 |
| −35                   | W    | −40               | 0.28               | 0.03               | 10.05 |
| −70                   | E    | −20               | 0.84               | 0.06               | 14.33 |
| −70                   | W    | −20               | 1.38               | 0.09               | 15.93 |
| −70                   | E    | −40               | 0.35               | 0.04               | 9.96 |
| −70                   | W    | −40               | 0.26               | 0.03               | 9.33 |
| −105                  | E    | −20               | 0.65               | 0.07               | 9.44 |
| −105                  | W    | −20               | 0.73               | 0.05               | 13.35 |
| −105                  | E    | −40               | 0.36               | 0.03               | 11.44 |
| −105                  | W    | −40               | 0.20               | 0.04               | 5.13 |
Appendix C. Results of Kruskal-Wallis one-way analysis of variance for different measured variables with respect to their spatial distribution in the transition zone. The right column is the p-value for the Kruskal-Wallis test.

| Variables | Kruskal-Wallis test (p) |
|-----------|------------------------|
| Diameter at breast height at east-facing site (n = 30) | 0.0658 |
| Diameter at breast height at west-facing site (n = 30) | 0.2887 |
| Height at east-facing site (n = 30) | 3.50 × 10⁻²⁸ |
| Height at west-facing site (n = 30) | 2.52 × 10⁻⁷ |
| Litterfall at east-facing site (n = 150) | 0.9351 |
| Litterfall at west-facing site (n = 150) | 0.0002 |
| Barley (n = 4) | 0.0048 |
| Pea (n = 4) | 0.0122 |
| Oilsed rapeseed (n = 4) | 0.0097 |
| Wheat (n = 4) | 0.0037 |
| Soil total C at 20 ± 3 cm (n = 3) | 0.0002 |
| Soil total N at 20 ± 3 cm (n = 3) | 0.0036 |
| Soil total N at 40 ± 3 cm (n = 3) | 0.0173 |

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