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Trees increase soil organic carbon and nutrient availability in temperate agroforestry systems

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ABSTRACT

Agroforestry systems (AFS) have a large potential to deliver a wide range of ecosystem services (ES). In field and crop management, changes to factors such as regulatory ES delivery are rarely taken into account, in part due to the paucity of detailed quantification of how trees affect biophysical field characteristics. This is especially true for arable systems in temperate climates. We have therefore assessed the influence of rows of trees of varying size on the prevailing soil characteristics in arable AFS. Spatial variability of soil organic carbon, acidity and nutrient status (N, P, K, Ca, Mg and Na) of the plough layer were analysed on a set of 17 arable agroforestry fields comprising 6 young (< 5 years) alley cropping fields and 11 fields bordered by a row of trees of moderate to older age (15–47 years) in Belgium. Significantly higher soil organic carbon and soil nutrient concentrations of N, P, K, Mg and Na were observed in the vicinity of trees in field boundaries, most likely resulting from the input of tree litter and nutrient-enriched throughfall water (for K and Na). Observed increases were strongly related to the distance from the tree row, resulting in a gradual change in soil conditions up to at least 30 m into the field. No significant effects of distance from the tree rows on soil characteristics were found in the young alley cropping fields. These results highlight the potential of middle-aged to mature tree rows to increase soil organic carbon stocks and nutrient availability for the agricultural crop in AFS.

1. Introduction

In temperate regions, interest in agroforestry has been growing for 20 years (Borremans et al., 2016; Gillespie et al., 2000; Jose et al., 2004; Nair, 2007) because it is considered as a sustainable agricultural practice that combines primary production with other ecosystem services (ES) (Torralba et al., 2016). In this paper an AFS is defined as a land use system in which trees are grown in combination with agricultural crops, and where both ecological and economic interactions occur between the tree and non-tree components of the system (Oelbermann et al., 2004; Young, 1989). The tree component can be located either inside the field (e.g. “alley cropping”), or on the field edges (e.g. “boundary planting”) (Nair et al., 2009; Young, 1989). Several authors have highlighted the potential beneficial effects of AFS such as carbon sequestration (Cardinael et al., 2015a; Montagnini and Nair, 2004), protection of (ground)water quality through reduction of nitrogen leaching (Allen et al., 2004; Jose, 2009), mitigation of soil erosion (Nair, 2007) and biodiversity conservation (Klaa et al., 2005). However, in large parts of temperate Europe, implementation of agroforestry remains rather limited (Reisner et al., 2007; Rigueiro-Rodríguez et al., 2009). Besides uncertainties on the legislative and economic level (Borremans et al., 2016), this might result from a lack of actual quantification of the ES provided and the lack of knowledge on implications of AFS on field management (Graves et al., 2009; Tsonkova et al., 2014).

Particularly in regions with oceanic and continental climatic conditions (as defined by Peel et al. (2007)), further research and quantification is needed regarding the effect of tree presence on soil organic carbon (SOC) (Cardinael et al., 2015a; Jose, 2009; Peichl et al., 2006) and soil nutrient availability (Cardinael et al., 2015a; Jose, 2009; Jose et al., 2000). For various AFS in the (sub-)tropical regions, the occurrence and magnitude of these effects on SOC (e.g. Albrecht and Kandji, 2003; Gupta et al., 2009) and soil nutrient content (e.g. Nair et al., 1999; Szott et al., 1991) have already been thoroughly studied, where

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tree litterfall and tree root decomposition are considered to be principal drivers for these nutrient cycles (Nair et al., 1999; Schroth, 1995). Also under temperate climatic conditions, soil (organic) carbon storage in AFS has been studied by several authors (e.g. Oelbermann and Voroney, 2007; Peichl et al., 2006; Upson and Burgess, 2013). However, as also argued by Cardinael et al. (2015a) and Nair et al. (2010, 2009), actual quantitative estimates remain extremely scarce. This is particularly true for mature arable AFS (Smith et al., 2012) as the tree component under study is often not older than 10 years and only a limited number of authors has studied a tree component of age older than 15 years (Bambrick et al., 2010; Cardinael et al., 2017; Upson and Burgess, 2013; Wotherspoon et al., 2014). In addition, research is mostly conducted on only 1 or 2 experimental fields (Fagerholm et al., 2016), with several studies even being conducted at the same experimental site and/or fields (Oelbermann et al., 2006, 2004; Oelbermann and Voroney, 2007; Peichl et al., 2006; Thevathasan and Gordon, 2004; Wotherspoon et al., 2014). Similarly, when considering the soil nutrient status, research to date is limited and has almost exclusively focused on nitrogen fluxes in AFS (Jose et al., 2000; Oelbermann and Voroney, 2007; Thevathasan and Gordon, 1997) and the role of trees in reducing nitrate-N leaching (Allen et al., 2004; Bergeron et al., 2011). A broader evaluation and quantification of changes in soil nutrient status in arable AFS is currently lacking.

To fill this knowledge gap, we have assessed the actual effect of tree presence on SOC and nutrient availability within the plough layer (0–23 cm) of a set of alley cropping fields and arable fields bordered by a tree row under temperate climatic conditions in Belgium, at varying distances from the tree rows and with different tree sizes and ages. We hypothesized that (i) SOC and concentrations of total nitrogen (N), potassium (K); phosphorous (P); calcium (Ca); magnesium (Mg) and sodium (Na) are higher in the AFS and that (ii) these effects are dependent on distance to the tree row as well as the size and age of the trees, resulting in the highest values close to the trees and in stronger effects as tree size increases.

2. Material and methods

Two different AFS were studied to quantify the effect of the tree component on the soil characteristics in alley cropping systems of various growth stages. Due to a lack of mature arable alley cropping systems in Belgium, a set of arable fields bordered by a row of high-pruned trees of moderate to older age (15–47 years) was selected as a proxy. These fields are referred to below as “boundary planted fields” (cf. Nair et al., 2009; Torquebiau, 2000; Young, 1989). The selected fields were bordered by a tree row along their longest edges with part of the edge having no trees, which creates a reference situation (Fig. 1). Indeed, the treeless part thereby acts as a control: it isolates the tree effect from effects caused by the grassy field margin or other edge effects (e.g. effects related to slight differences in tillage, fertilisation, etc.). Additionally, 6 young arable alley cropping fields were selected to investigate potential gradients in soil conditions resulting from the presence of a recently established tree component. All fields were located in Belgium, with mean annual temperature of 9.7 °C and mean annual precipitation of 828.1 mm (Grechka et al., 2016). The prevailing wind direction (1981–2010) is South-Southwest (KMI, 2016).

2.1. Boundary planted fields

2.1.1. Study site

All selected fields were cultivated in a direction parallel to the tree row, with no headland located next to the trees or nearby the reference situation. This eliminated factors such as the manoeuvring and turning of agricultural machinery which may affect the present soil conditions. On each field, the orientation of the tree row was approximately North-South as it is commonly accepted that this is the most favourable orientation to limit tree-crop competition for light (Beaton et al., 1999).

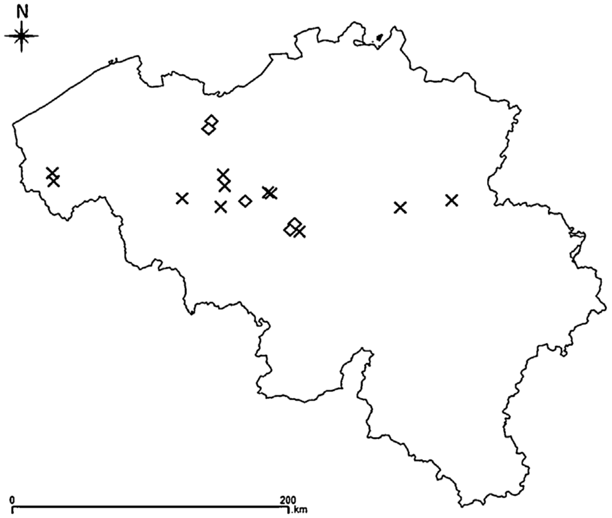

Fig. 1. Locations of experimental fields in Belgium (x boundary planted fields; ◊: alley cropping fields).

To estimate effects of tree growth stage, trees were of uniform size within the field but were of different sizes among the fields (Table 1a). To exclude species-related effects, only tree rows with poplar (*Populus* × *canadensis* Moench.) were considered, a species with high potential for use in temperate silvoarable systems (Reisner et al., 2007). Moreover, the frequent occurrence of poplar in tree rows in Belgium facilitated the selection of appropriate experimental fields. The final set of study sites comprised 11 arable fields bordered with poplars. Intra-row tree distance was always circa 8 m. Despite selection for similar soil type, soils ranged from silt to (sandy) loam. Climatic conditions (1990–2015) for each field are given in Table 1a.

2.1.2. Soil sampling

At each experimental site and perpendicular to the tree row and to the treeless border, 3 and 2 transects were installed, respectively (Fig. 2). Each transect consisted of 5 rectangular sampling plots (1.5 m × 6 m), the centre of which was located at distances 2, 5, 10, 20 and 30 m away from the field edge. If a sampling plot coincided with a tire track resulting from agricultural machinery use, the sampling plot was repositioned slightly to a location next to the track. To ensure a representative sample, each sample consisted of a mixture of 8 subsamples taken within these plots in the 0–23 cm soil layer with a gouge auger. Soil sampling was executed once, between December 2015 and January 2016. After sieving (< 2 mm), the soil samples were analysed by the Soil Service of Belgium for K, P, Mg, Na and Ca using inductively coupled plasma after extraction in ammonium-lactate. Total N was determined by Kjeldahl digestion. A heated potassium dichromate oxidation was used to analyse SOC (BELAC, 2017). pH-KCl of soil samples was determined at a 1:5 soil:liquid (volume fraction) ratio with H_2O and 1 M KCl. When taking the samples in one of the fields in St. Pieters Leeuw (H = 16.7 m, DBH = 0.29 m), strong compaction and anoxic conditions were noticed in the control transects at 2 and 5 m distance. As confirmed by the farmer, this may be the result of the past use of this part of the field-edge zone as an access track for agricultural machinery. In addition, at the Maarkedal site, freshly added compost was locally present at the moment of soil sampling, specifically at the sampling locations located at 5 and 10 m distance in one of the control transects. Strong compaction and/or addition of compost may influence SOC and nutrient dynamics; therefore the samples of all the above-mentioned plots were omitted in all further analyses in this study.

Table 1
Characteristics of boundary planted fields with Populus × canadensis (a) and alley cropping fields (b). Climatic data ("Temp.": annual average air temperature in C° near surface, "Precip.": annual average precipitation in mm yr^{-1}) for the period 1990–2015 (Grechka et al., 2016). Soil type according to soil map of Belgium (OC GIS-Vlaanderen, 2001; PCNSW, 2007), A. silt loam; L. sandy loam; S. loamy sand; Z. sand; .b. well drained .c. moderately well drained; .d. imperfectly drained; .h. poorly drained; .a soils with texture B horizon; .b soils with a structure or colour B horizon; .c soils with strongly mottled or broken texture B horizon; .h soils with a broken iron or humus B horizon. .p soils without any profile development often of alluvium or colluvium.

a)

Location	Coordinates	Soil type	Temp. C°	Precip. mm yr^{-1}	Year of plantation	Height (m)	DBH (m)
Sint Pieters Leeuw	50°47′74"N 4°12′41"O	Acp	10.3	787.9	2001	16.7	0.29
Sint Pieters Leeuw	50°47′45"N 4°12′38"O	Aca	10.3	787.9	2001	17.4	0.34
Haut-Ittre	50°38′19"N 4°17′51"O	Aba, Abp	9.8	836.0	2000	21.5	0.45
Maarkedal	50°49′14"N 3°40′15"O	Abp, Adp	10.1	752.1	1998	26.3	0.59
Tongeren	50°45′14"N 5°26′15"O	Aba, Abp	9.5	842.3	1998	26.7	0.60
Landen	50°43′56"N 5°05′59"O	Abp,Ahp	9.8	814.1	1994	32.3	0.60
Ieper	50°52′47"N 2°47′58"O	Lca	10.1	679.4	1985	27.0	0.73
Geraardsbergen	50°44′11"N 3°56′56"O	Aba	10.2	775.5	1988	33.1	0.70
Herzele	50°52′1"N 3°54′20"O	Aba, Aca	10.0	784.9	1977	33.4	0.69
Steenhuize	50°49′51"N 3°55′2"O	Aba	10.1	781.0	1985	29.9	0.76
Ieper	50°52′34"N 2°47′36"O	Ldc, Lca	10.1	679.4	1969	31.2	0.88

b)

Location	Coordinates	Soil type	Temp.C°	Precip. mm yr^{-1}	Year of plantation	Tree species	Orientation	Interrow distance (m)	Intra-row distance (m)	Tree row width (m)
Lochristi	51°6′32"N 3°49′49"O	Sdb, Zdb	10.2	755.8	2011	*Populus* sp.	EW	26	8	2
Lochristi	51°6′41"N 3°49′47"O	Zdh	10.2	755.8	2011	*Prunus avium*	EW	26	8	2
Lochristi	51°5′35"N 3°48′13"O	Zdh	10.2	755.8	2012	*Juglans regia*	EW	26	8	2
Vollezele	50°45′43"N 4°3′13"O	Aba	10.0	802.5	2010	*Prunus avium*	NS	54	8	2
Haut-Ittre	50°38′54"N 4°17′48"O	Aba	9.8	836.0	2011	*Juglans regia* & *Sorbus torminalis*	NS	28	8	2
Haut-Ittre	50°38′37"N 4°17′40"O	Aba, Lba	9.8	836.0	2011	*Juglans regia* & *Sorbus torminalis*	NS	28	8	2

2.2. Alley cropping fields

2.2.1. Study site

Six recently established arable alley cropping fields (mean tree age of 2–5 years) were selected. The soil type in these fields ranged from silt to sandy. Climatic conditions (1990–2015) for each field are given in Table 1b. The distance between tree rows varied from 26 to 28 m, with the exception of the field in Vollezele where interrow distance was 54 m. Intra-row tree distance was always 8 m. Considering the young age of the tree rows, species-related effects were expected to be of minor importance. Hence, no selection was made regarding tree species composition of the fields. Several tree species were present: *Populus × canadensis*, *Juglans regia* L., *Prunus avium* L. and *Sorbus torminalis* L. Crantz (Table 1b). At Vollezele and Ittre, all available space between the trees was filled in with various shrub species (e.g. *Rosa canina* L., *Cornus* sp. and *Corylus avellana* L.). On each field a minimum of 2 tree rows was present. If more than 2 rows were present, the 2 adjacent tree rows with the highest expected uniformity in terms of soil conditions in the intercropping zone were selected for sampling and analysis.

2.2.2. Soil sampling

In each field, 3 transects were laid out between and perpendicular to both selected tree rows (Fig. 2). At each location and along each transect, soil samples were collected once between December 2015 and January 2016 in rectangular sampling plots (1.5 × 6 m) up to 23 cm depth. Each transect consisted of 6 sampling plots, the centre of which was located at distances 2, 5 and 12 m from the closest tree row. To ensure a representative sample, each sample consisted of a mixture of 8 subsamples taken with a gouge auger. Soil samples were analysed as described above.

2.3. Field management

At all field sites, mainly the following crops are rotated: maize (*Zea mays* L.), winter wheat (*Triticum aestivum* L.), winter barley (*Hordeum vulgare* L.), and potatoes (*Solanum tuberosum* L.). Straw of winter cereals is removed after harvest. Soils are tilled and remaining crop residues are incorporated into the soil. During winter, cover crops (mainly yellow mustard (*Sinapis alba* L.) and perennial and Italian ryegrass

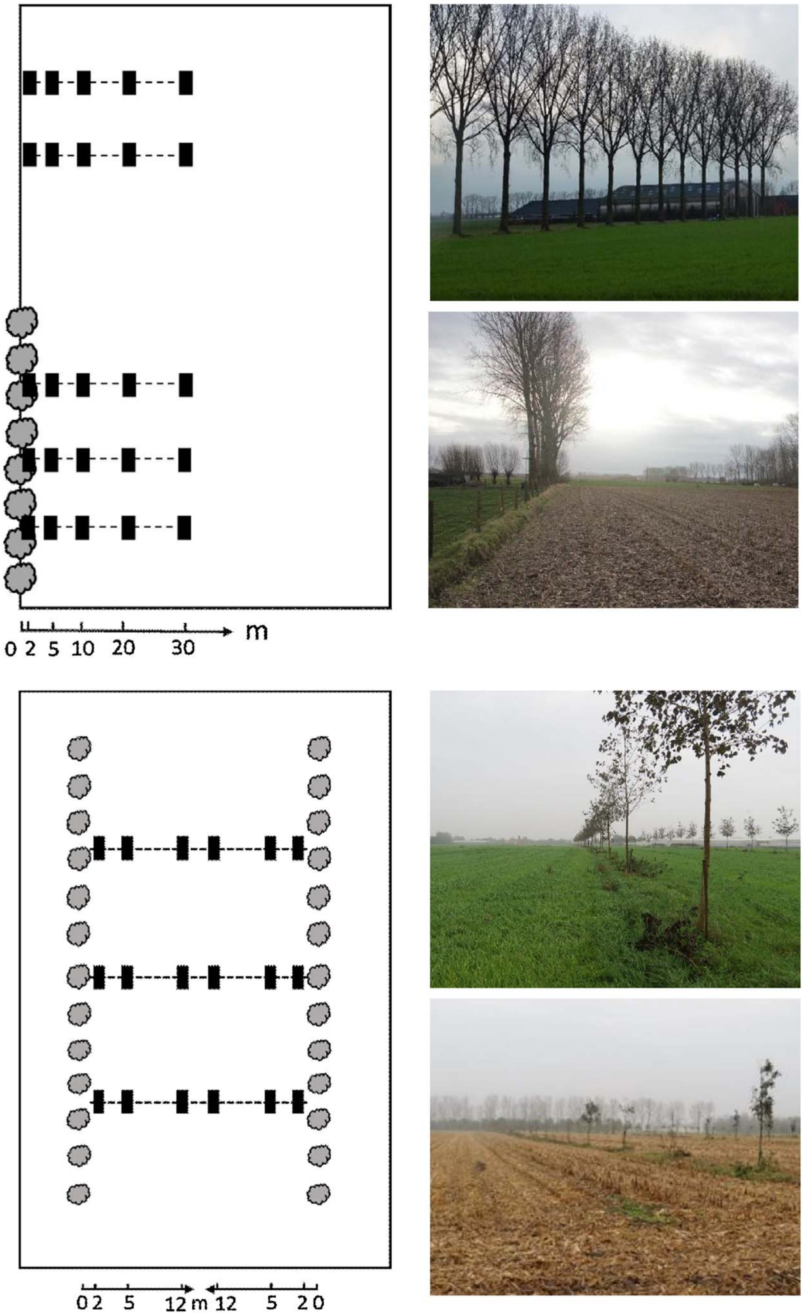

Fig. 2. Location of soil sampling points in the boundary planted (upper) and alley cropping (lower) fields. The black rectangles denote locations where samples were collected. Right: example of boundary planted fields with mature tree row (upper images) and alley cropping fields (lower images).

(*Lolium perenne* L. and *Lolium multiflorum* Lam.)) are applied. Fields are fertilised with animal manure in accordance with Flemish manure regulations (max rate of 170 kg N [ha yr]$^{-1}$ for maize, potatoes, and winter cereals when combined with cover crops, and limitation of P addition as required by VLM, 2014). Additional mineral fertilisation was applied according to crop requirements set forth by VLM (2014) and the Bemex expert system (Vandendriessche et al., 1996).

2.4. Data analyses

The data of all fields have a nested, hierarchical structure with measuring points nested in transects. These transects are in turn nested at the level of the experimental field. Each soil variable was modelled separately for the boundary planted fields with middle-aged to mature tree rows and for the alley cropping fields using a linear-mixed effect model (LMM). For both tree cropping systems, distances to field edges were transformed logarithmically to linearise the response variables. For the boundary planted fields, both the logarithm of the distance to the field edge and the presence/absence of a tree row were included as fixed effects. In case of the alley cropping fields, where no control transects were present, the logarithm of the distance to the nearest tree row was used as a fixed effect. To account for the hierarchical nature and non-independence of the data within fields and transects, “field” and “transect” were included as random effects for both cropping systems. In case of the alley cropping fields, no further analysis were executed for Na, since values for approximately one-third of analysed samples were below the detection limit of 9 mg (kg dm)$^{-1}$. Statistics were performed using the *lme* function in the *nlme* package in R (R Development Core Team, 2016).

For the boundary planted fields, average concentrations of SOC and soil nutrients were obtained for the field zone within 2 and 30 m of the tree rows. This was done based on integration of the LMM effect relations, because soil sampling distances were not homogeneously distributed over the study area with relatively more measuring points being located in the vicinity of the tree rows. Reported stocks of SOC and soil nutrients in the 0–23 cm soil layer are based on bulk densities as estimated by eq. 1 (Adams, 1973).

$$BD = \frac{100}{\frac{\%\,OM}{0.244} + \frac{100 - \%\,OM}{MBD}} \tag{1}$$

BD denotes bulk density (g cm^{-3}), OM organic matter and MBD mineral bulk density. Percentage OM was derived from SOC, based on the assumption that SOM contains approximately 58% OC (e.g. Buringh, 1984; Trigalet et al., 2017). MBD typically has a value of 1.64 g cm^{-3} (Mann, 1986).

To investigate a possible effect of tree growth stage on the boundary planted fields with middle-aged to mature tree rows in case of significant fixed effects, for each tree row the average tree stem volume was calculated. This was done using mean tree height and mean tree diameter at breast height (DBH) of each field and the form factor for *Populus sp*. as given by Jansen et al. (1996) to correct for stem taper. The resulting variable is an indication of tree size, rather than of tree age. This is considered appropriate, however, because tree size is influenced by age as well as other factors such as intra-row distance and soil conditions. Tree size (rather than tree age *sensu stricto)* is therefore presumed to be the major determinant of the effects of trees on soil organic carbon and nutrients. Subsequently, for every field a separate linear mixed model was fitted to the transects perpendicular to the tree row and to the transects in the treeless part of the field. Here the common logarithm of the distance to the tree row or to the treeless edge and the specific transect were considered as fixed and random effects, respectively. For each field the differences in intercept and slope of both linear mixed models were calculated. Finally, Spearman correlation coefficients between these differences and the average tree trunk volume of the different fields were computed (r_s*intercept* and r_s*slope,* respectively). All statistical analysis were performed in R version 3.2.2 (R Development Core Team, 2016).

3. Results

3.1. Boundary planted fields

Significant variations in soil concentration of OC, N, Na, K, Mg and to a lesser extent P were found on the boundary planted fields. These variations were explained by the interaction between the presence/absence of a tree row and the distance to the field edge (Table 2, Fig. 3). Significantly higher values of the abovementioned variables were found in the transects perpendicular to the tree row when compared to the transects located in the control (tree-less) situation of the experimental field (Table 3, Appendix A Table A1). These observed differences decreased exponentially as distance to the field edge increased. At a distance of 30 m from the tree row, levels similar to those in the control part of the field where obtained. No significant variation in soil Ca, pH-KCl and C:N ratio was present.

Within the field area under study, i.e. between the distance of 2 m to 30 m from the field edge, the average soil organic carbon concentration of 1.18 g (100 g)$^{-1}$ in the control part of the field corresponds to a soil organic carbon stock of 39.8 ton OC ha^{-1} in the 0–23 cm soil layer. Close to the tree rows, the average SOC concentration within the same distance to the field edge equaled 1.35 g (100 g)$^{-1}$, corresponding to a soil organic carbon stock of 45.1 ton OC ha^{-1}. A net increase in soil organic carbon stock of 5.3 ton OC ha^{-1} is thus realized in the AFS. Similarly, the observed differences in soil nutrient concentration correspond to an average increase in soil nutrient stocks in the AFS of 108 kg K ha^{-1}; 86 kg P ha^{-1}; 45 kg Mg ha^{-1} and 16 Na kg ha^{-1} when compared to the control part of the field. An average increase in total N stock of 556 kg ha^{-1} was found in the 0–23 cm soil layer of the transects close to the tree row (Table 3).

Significant values of r_s*intercept* were found for SOC, N, Na, and K (Table 4). Differences in soil concentration of these variables between the AFS and control situation increase as tree-size increases (Appendix B). Significant values of r_s*slope* were found for SOC, N, Na, K and P, which indicate that stronger gradients in soil concentration occur in between a distance of 2 to 30 m to the tree row as tree size increases. Neither r_s*slope* nor r_s*intercept* were significant for Mg.

3.2. Alley cropping fields

No significant variation in soil characteristics in relation to the distance from the tree row was observed in the young alley cropping fields (Table 5, Appendix A Table A2).

4. Discussion

Based on the experimental design and the significance of the in-

Table 2
Linear mixed modelling results for the combined set of boundary planted fields. Included fixed effects in the linear mixed model are distance to the field edge, presence or absence of a tree row (“T+/T-”) and their interaction. Model formula: Y = a*log10(distance in m) + b. Bold characters indicate significant effect (P-value < 0.05). (*) indicates 0.05 < P-value < 0.10. Organic carbon content is expressed in g (kg dm)$^{-1}$, soil nutrient concentrations are expressed in mg (kg dm)$^{-1}$.

	Fixed effects			Parameter estimates optimal model		
	Distance to the field edge	Tree row presence (T+/T−)	interaction		slope a	intercept b
SOC	**p < 0.0001**	**p < 0.0001**	**p < 0.0001**	T+	−3.9	18.0
				T−	−0.4	12.2
N	**p < 0.0001**	**p < 0.0001**	**p < 0.0001**	T+	−336.2	1714.6
				T−	+12.5	1136.7
K	**p < 0.0001**	**p = 0.0008**	**p = 0.0001**	T+	−75.4	312.7
				T−	−1.3	193.7
Mg	**p = 0.0079**	**p < 0.0001**	**p = 0.0001**	T+	−21.7	222.4
				T−	+10.2	170.3
P	**p = 0.0271**	p = 0.0631(*)	p = 0.0861 (*)	T+	−31.4	257.2
				T−	+0.2	192.8
Na	**p < 0.0001**	**p < 0.0001**	**p < 0.0001**	T+	−10.6	31.0
				T−	−0.1	14.1
C:N	p = 0.1544	p = 0.7226	p = 0.9178	T+	−0.3	10.6
				T−	−0.3	10.4
Ca	p = 0.5356	p = 0.7005	p = 0.2700	T+	−108.3	2277.5
				T−	+62.8	2055.5
pH-KCl	p = 0.2017	p = 0.7686	p = 0.8854	T+	+0.1	6.4
				T−	+0.1	6.4

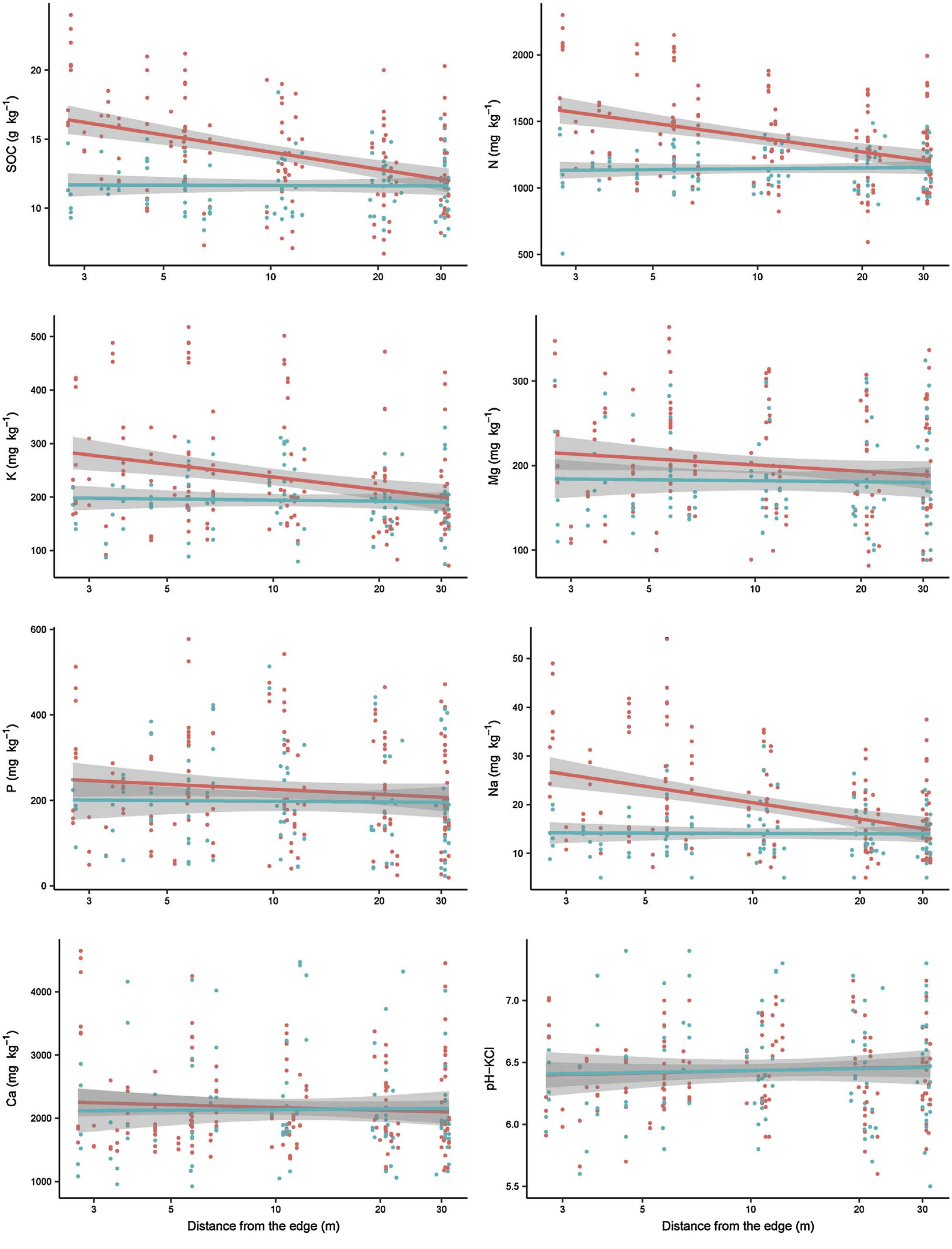

Fig. 3. Soil characteristics as a function of the distance to the field edge in the boundary planted fields. Lines represent regression lines fitted using soil samples per investigated distance. Red: transects perpendicular to the tree row, blue: transects perpendicular to the treeless border. Grey shading shows 95% confidence interval.

Table 3
Average soil organic carbon in g (kg dm)$^{-1}$ and soil nutrient concentrations in mg (kg dm)$^{-1}$ (based on integration of LMM effect relations). SOC- and soil nutrients stocks (kg ha^{-1}) along the evaluated transects (i.e. between a distance of 2 and 30 m from the field edge) as derived from the average SOC and soil nutrient concentrations. Calculated stocks clearly show significantly increased values in the plough layer (0–23 cm) of the combined set of boundary planted fields.

	Average soil nutrient Concentrations (± S.E.)		Soil nutrient stocks	
	Tree row (n = 165)	Control (n = 104)	Tree row	Control
SOC	13.5 ± 1.2	11.8 ± 1.5	45072	39772
N	1335.8 ± 101.2	1150.7 ± 120.5	4446	3890
K	227.7 ± 35.7	192.2 ± 43.0	758	650
Mg	197.9 ± 24.5	181.7 ± 17.7	659	614
P	221.8 ± 47.5	193.0 ± 45.9	738	652
Na	19.0 ± 3.4	14.0 ± 3.7	63	47

Table 4
Spearman correlation between tree size and the difference in intercept ($r_s$intercept) and slope ($r_s$slope) between the AFS and control situation of the linear mixed model of each separate boundary planted field. A positive correlation for $r_s$intercept indicates increasing differences in soil nutrient concentration between the AFS and control situation as tree size increases. A negative correlation for $r_s$slope indicates stronger gradients occur in between a distance of 2 and 30 m to the tree row as tree-size increases. Bold characters indicate significant correlation (P-value < 0.05). (*) indicates 0.05 < P-value < 0.10.

	$r_s$intercept		$r_s$slope	
	r_s	*p*-value	r_s	*p*-value
SOC	0.64	p = 0.0404	−0.60	p = 0.0562 (*)
N	**0.70**	**p = 0.0208**	**−0.80**	**p = 0.0052**
K	**0.77**	**p = 0.0081**	**−0.78**	**p = 0.0070**
Mg	0.28	p = 0.4021	−0.14	p = 0.6935
P	0.35	p = 0.2994	**−0.67**	**p = 0.0281**
Na	**0.86**	**p = 0.0013**	**−0.74**	**p = 0.0134**

Table 5
Linear mixed modelling results for the combined set of alley cropping fields. Included fixed effect in the linear mixed model is distance to the field edge. Model formula: Y = a*log10(distance in m) + b. (*) indicates 0.05 < P-value < 0.10. Organic carbon content is expressed in g (kg dm)$^{-1}$, soil nutrient concentrations are expressed in mg (kg dm) $^{-1}$.

	Fixed effect: distance	Parameter estimates optimal model	
		slope a	intercept b
SOC	p = 0.9696	−0.02	13.8
N	p = 0.1458	+33.8	1200.9
K	p = 0.0778 (*)	+19.7	198.7
Mg	p = 0.4471	−4.2	114.9
P	p = 0.1043	+11.8	241.3
C:N	p = 0.5020	−0.3	11.4
Ca	p = 0.6506	+27.6	1512.6
pH-KCl	p = 0.5721	−0.03	5.8

teraction between distance into the field and the presence/absence of a tree row for each of the observed effects, we can assume that these effects are purely related to the presence of a tree component and not the result of any other edge effect. Although alley cropping and boundary planted fields are 2 distinct AFS when considering their spatial design, the results concerning the boundary planted fields with middle-aged to mature tree rows found in this particular paper can be assumed to be valid for older alley cropping systems as well.

4.1. *Soil organic carbon and nutrient availability in AFS*

4.1.1. *Boundary planted fields*

The potential of AFS to increase both above-ground and below-ground carbon stocks is an important tool for mitigating climate change (Cardinael et al., 2015a; Lorenz and Lal, 2014). This potential influence of trees on SOC was confirmed in our study on the boundary planted fields with significantly higher SOC found nearby the middle-aged to mature tree rows. The observed increase within 2 to 30 m distance from the field edge of 5.3 ton OC ha^{-1} is similar to the findings of Bambrick et al. (2010) where an increase in SOC of 6.2 ton OC ha^{-1} in the 0–20 cm soil layer was observed after 21 years of intercropping with poplar in comparison to arable cropping without trees. On average, the boundary planted trees in our study are older and thus presumably also of larger size than the tree rows studied by Bambrick et al. (2010). The similar magnitude of the noted effect may, however, be explained by the narrow interrow distance of only 15 m in the latter experiment which might have caused a cumulative effect.

As hypothesised, higher soil nutrient concentrations were found in the transects nearby the tree row for K, P, Mg and Na, leading to potentially higher nutrient availabilities in the AFS when compared to the treeless control transects. The increased soil N concentrations in the AFS appeared to be strongly linked to the increase in soil organic carbon concentrations. The average C:N ratio of the soil samples equalled 10.2 ± 0.12 (S.E.) close to the tree row and 10.2 ± 0.17 in the control transects (Appendix A), which is similar to the values for arable land observed by John et al. (2005).

The occurrence of gradients in soil characteristics as a result of tree presence and the resulting spatial variability as noted by Bambrick et al. (2010) and Follain et al. (2007) was confirmed in our research. Some authors suggest this variability may disappear throughout time in alley cropping fields when a more homogeneous tree-influence on the intercropping zone occurs as trees grow larger and tree litter is distributed more evenly in the intercropping zone (Bambrick et al., 2010; Oelbermann et al., 2004; Wotherspoon et al., 2014). However, the observed simultaneous correlation of tree size with both difference in intercept and in slope of the LMM indicates that an increasing tree size primarily results in more pronounced effects close to the tree row, whereas the distance to which the effects extend into the field is less influenced (Table 4).

4.1.2. *Alley cropping fields*

Based on the abovementioned correlation between tree size and increase in SOC and/or soil nutrient concentration nearby the tree rows, the absence of any observed gradients on the young alley cropping fields is assumed to be related to the limited age and size of the tree component present. In contrast to the suggestion that changes in SOC on the field-level in young alley cropping fields under temperate climate are only expected to occur after at least 10 years of establishment (Oelbermann et al. (2006) and Peichl et al. (2006)), higher SOC close to the tree rows has been observed in alley cropping fields of limited age. For example, Thevathasan and Gordon (2004) found a 35% relative increase in SOC (0–15 cm soil layer), within 2 m distance from poplar trees on an alley cropping field in southern Ontario (Canada) 8 years after establishment. It is nearly impossible that the young trees in our setup would have homogenously altered the soil characteristics of the entire intercropping zone, thus the observed SOC and soil nutrient concentrations likely still equal the values before establishment of the trees. The results of our experiment suggest that trees have no significant influence on SOC nor on nutrient availability during at least 3 to 5 years after establishment of temperate silvoarable AFS.

4.2. *Processes affecting carbon input in AFS*

As often argued in studies investigating SOC in AFS (Bambrick et al., 2010; Cardinael et al., 2017; Oelbermann et al., 2004; Oelbermann and

Voroney, 2007), the input of organic matter via tree litter is seen as an important explanatory variable. Following the simulation in Appendix C, a yearly leaf litterfall of 214 g m^{-2}, which seems consistent with literature (e.g. Zhang, 1999), could constitute an average annual net increase in SOC stock of 208 kg. Based on the average tree age on the boundary planted fields of 25.5 yr (Table 1a), this would result in the observed total increase of 5.3 t. Litterfall input typically decreases exponentially with distance from the tree row (Oelbermann et al., 2004). The orientation of the boundary planted tree rows approximately aligns with the prevailing S-SW wind direction, thus we expect that leaf litter input would decrease exponentially as distance from the tree rows increased. This would contribute to the distance-dependency of the noted effects.

Besides leaf litter, tree branches can represent a substantial part of total litter production, ranging from 2 to 25% on a dry weight basis under plantation and/or forest conditions (Berthelot et al., 2000; Meiresonne et al., 2007; Merriam et al., 1982) and characterised by C content of approximately 50% (Zabek and Prescott, 2006). Although the relative importance of this litterfall fraction in AFS is difficult to estimate, the resulting input in the plough layer is supposed to be substantially lower than the abovementioned quantity as trees in AFS are pruned and part of the fallen branches are normally removed from the field before or during harvest of the crop. In addition, a carbon input may be realized through decomposition of (fine) tree roots and root exudates (Nair et al., 2009; Schroth, 1995; Young, 1989). Although poplar root systems generally constitute 25–35% of the whole-plant biomass (Block et al., 2006; Nair, 2012), the actual accretion in the plough layer (0–23 cm) comprises only a very limited fraction since (poplar) tree roots have the tendency to colonise deeper soil layers in arable AFS, avoiding the upper soil layer of the intercropping zone where high competition with the agricultural crop for water and nutrients may occur (Cardinael et al., 2015b; Mulia and Dupraz, 2006; Thevathasan and Gordon, 1997; Upson and Burgess, 2013). Hence, in our case, the OC input originating from tree branches and fine root decomposition is expected to be limited as compared to the input through leaf litter.

4.3. Processes affecting soil nutrient input and export in AFS

Based on the abovementioned estimated average litterfall quantity of 214 g m^{-2} and nutrient concentrations of poplar leaf litter as reported by Meiresonne et al. (2007) and Lihavainen et al. (2016) an estimated yearly nutrient-input of 12.6 kg K ha^{-1}; 10.9 kg P ha^{-1}; 5.8 kg Mg ha^{-1} and 0.1 Na kg ha^{-1} is realised, respectively. The input via leaf litter may thus deliver a substantial contribution to the increased soil nutrient content of K, P, and Mg in the AFS. In general, poplar leaf litter is also characterised by high Ca concentrations. However, the relative increase in soil Ca concentration found in this research is comparatively small when compared to the overall concentration present in the soil which is assumed to be primarily determined by the input of calcium through liming.

In addition a substantial amount of nutrients (K, Na) can be supplemented via throughfall water. For instance, Zhang (1999) found the K-input via throughfall to be 3 times higher compared to the input through leaf litterfall in an alley cropping system with poplar in southern Ontario (Canada). Similar results were found by Meiresonne et al. (2007) in a poplar plantation in Belgium. The apparent relative importance of this source of input may explain the strong distance-dependency of the increase in Na and K in comparison to the other nutrients, since the input through throughfall is assumed to be mostly restricted to the area directly under the tree canopy, whereas deposit of leaf litterfall may also occur at further distances of the tree rows.

In addition to the abovementioned nutrient-inputs, the noted increases may also be caused by a reduced export of nutrients present in the soil. For example, reduced leaching to deeper ground layers may occur nearby the tree rows as the latter may provide a sheltering effect, thereby reducing the amount of rainfall that reaches and subsequently percolates the plough layer (Alva et al., 1999). Additionally, the observed increase in SOC in the AFS may lead to a higher CEC and a subsequent increase in nutrient retention capacity (Bambrick et al., 2010; Lehmann, 2007). Finally, depending on the cultivated crop, an altered crop development and/or a possible reduction in grain production up to 88% may occur nearby the tree rows in AFS due to tree/crop competition for light, water or nutrients (e.g. Reynolds et al., 2007; Van Vooren et al., 2016). This may result in reduced crop-uptake of available soil nutrients (Pessarakli, 1999).

4.4. Fertilisation in AFS

The increase in SOC and soil nutrient concentrations indicate that reduced crop fertilisation might be appropriate in the AFS, as suggested by Cardinael et al. (2015a), Zhang (1999), Jose et al. (2000) and Rivest et al. (2009). Although in our study effects on soil mineral N content were not quantified some authors indicate the occurrence of higher nitrification and N release near poplar tree rows on alley cropping fields resulting from tree leaf biomass input (e.g. Thevathasan and Gordon (1997, 2004)). Those authors concluded that inorganic N addition may therefore be reduced accordingly in AFS. Fertiliser inputs might need reduction in AFS to avoid excessive leaching and reduce input costs for the farmer. However, several complicating factors must be taken into account. As stated above, soil nutrient status might be strongly heterogeneous at field level. In addition, soil nutrient status will continually change as trees grow as shown by positive correlations between tree size and the magnitude of the noted increases. Moreover, when mature trees are harvested and replaced with young specimens, an initial decrease of SOC content and soil nutrient concentrations will occur due to the limited effect of the newly established trees. Furthermore, unlike mineral fertilisers, availability over time of nutrients imported through leaf litter is dependent on mineralisation of the organic material. This mineralisation may not occur in accordance with the needs of the crop. Finally, the occurrence and magnitude of these effects are supposed to be influenced by the choice of tree species and even tree genotype (Bambrick et al., 2010; Fortier et al., 2010; Peichl et al., 2006; Udawatta and Jose, 2011). However, considering the continual evolution of smart farming techniques, these difficulties may be overcome through the development and use of adapted fertilisation software applications that take (changing) field-specific nutrient-gradients into account.

5. Conclusion

The potential of AFS to sequester carbon by increasing the SOC has been confirmed on the boundary planted fields under study with tree rows of moderate to mature age. The significantly higher SOC concentrations in the plough layer of the AFS resulted in an average increase in soil OC stock of 5300 kg ha^{-1} within the field zone (i.e. between 2 and 30 m to the field edge). As hypothesised, higher soil nutrient concentrations for K, Mg, P and Na were also found in the plough layer, corresponding to an average increase in soil nutrient stock of 108 kg K ha^{-1}; 45 kg Mg ha^{-1}; 86 kg P ha^{-1} and 16 kg Na ha^{-1}, respectively. The main causal factor is assumed to be the input of carbon and nutrients in the top soil layer through tree litter, in particular tree leaves, and to a lesser extent via nutrient enriched throughfall water.

The noted increase of these soil variables was strongly related to the distance from the tree row, resulting in considerable spatial gradients.

In addition, the increase in SOC, N, K, and Na was related to the growth stage of the tree component present, indicating a continuous evolution in SOC and soil nutrient status of the AFS as trees mature. Hence, even if a reduced input of fertilisers in AFS might be appropriate, a dynamic and field-specific approach will be necessary that considers factors such as the influence of tree growth stage and interrow distance.

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Appendix A

Tables A1 and A2

Table A1

Boundary planted fields: observed minimum (“Min.”), maximum (“Max.”) and mean value and standard error (“Mean ± S.E.”, based on integration of LMM effect relations) of analysed variables. Parameter estimates following linear mixed model at distances “2m”, “5m”, “10m”, “20m” and “30m”. “T+”: transects perpendicular to tree row. “T-“: transects in the reference part of the field. Organic carbon content is expressed in g (kg dm) $^{-1}$, soil nutrient concentrations are expressed in mg (kg dm) $^{-1}$.

		Min.	Max.	Mean ± S.E	2 m	5 m	10 m	20 m	30 m
SOC	T+	6.7	24.0	13.5 ± 1.2	16.8	15.2	14.0	12.9	12.2
	T−	8.0	18.4	11.8 ± 1.5	12.0	11.9	11.8	11.6	11.6
N	T+	593.3	2300.0	1335.8 ± 101.2	1613.4	1479.6	1378.4	1277.2	1218.0
	T−	506.1	1460.0	1150.7 ± 120.5	1140.4	1145.4	1149.1	1152.9	1155.1
K	T+	71.5	518.0	227.7 ± 35.7	290.0	260.0	237.3	214.6	201.3
	T−	74.3	330.0	192.2 ± 43.0	193.3	192.8	192.4	192.0	191.8
Mg	T+	81.6	364.0	197.9 ± 24.5	215.8	207.2	200.7	194.1	190.3
	T−	88.2	324.4	181.7 ± 17.7	173.3	177.3	180.4	183.5	185.2
P	T+	19.2	577.5	221.8 ± 47.5	247.7	235.2	225.8	216.3	210.8
	T−	23.0	513.2	193.0 ± 45.9	192.9	192.9	193.0	193.0	193.0
Na	T+	7.1	54.0	19.0 ± 3.4	27.8	23.6	20.4	17.2	15.3
	T−	7.9	32.0	14.0 ± 3.7	14.1	14.0	14.0	14.0	14.0
C:N	T+	7.8	18.5	10.2 ± 0.7	10.5	10.3	10.2	10.1	10.1
	T−	7.8	21.7	10.1 ± 1.1	10.4	10.2	10.2	10.1	10.0
Ca	T+	1175.6	4646.7	2155.5 ± 312.6	2244.9	2201.8	2169.2	2136.6	2117.6
	T−	924.3	4472.1	2126.3 ± 369.9	2074.4	2099.4	2118.4	2137.3	2148.3
pH-KCl	T+	5.6	7.2	6.4 ± 0.2	6.4	6.4	6.4	6.5	6.5
	T−	5.5	7.4	6.4 ± 0.2	6.4	6.4	6.4	6.4	6.5

Table A2

Alley cropping fields: mean soil concentration ± S.E. of analysed variables at sampled locations (2m: near tree row, 12m: at centre in between two tree rows). Min. and max. values indicate range of analysed samples. Organic carbon content is expressed in g (kg dm) $^{-1}$, soil nutrient concentrations are expressed in mg (kg dm) $^{-1}$.

	Min.	Max.	Mean ± S.E		
			2 m (edge)	5 m	12 m (centre)
SOC	7.3	26.0	13.6 ± 0.7	14.1 ± 0.7	13.5 ± 0.7
N	960.0	1750.0	1208.1 ± 30.8	1226.4 ± 36.3	1259.7 ± 41.2
K	70.0	400.0	202.7 ± 13.8	217.0 ± 14.1	217.0 ± 13.5
Mg	50.0	200.0	112.7 ± 5.2	111.8 ± 5.5	112.4 ± 5.0
P	70.0	460.0	243.5 ± 22.5	252.1 ± 23.0	242.3 ± 24.2
C:N	6.8	15.9	11.2 ± 0.4	11.4 ± 0.4	10.7 ± 0.3
Ca	460.0	2780.0	1508.1 ± 78.3	1559.8 ± 85.1	1561.5 ± 86.6
pH-KCl	4.4	7.0	5.8 ± 0.1	5.9 ± 0.1	5.9 ± 0.1

Appendix B

Fig. A1

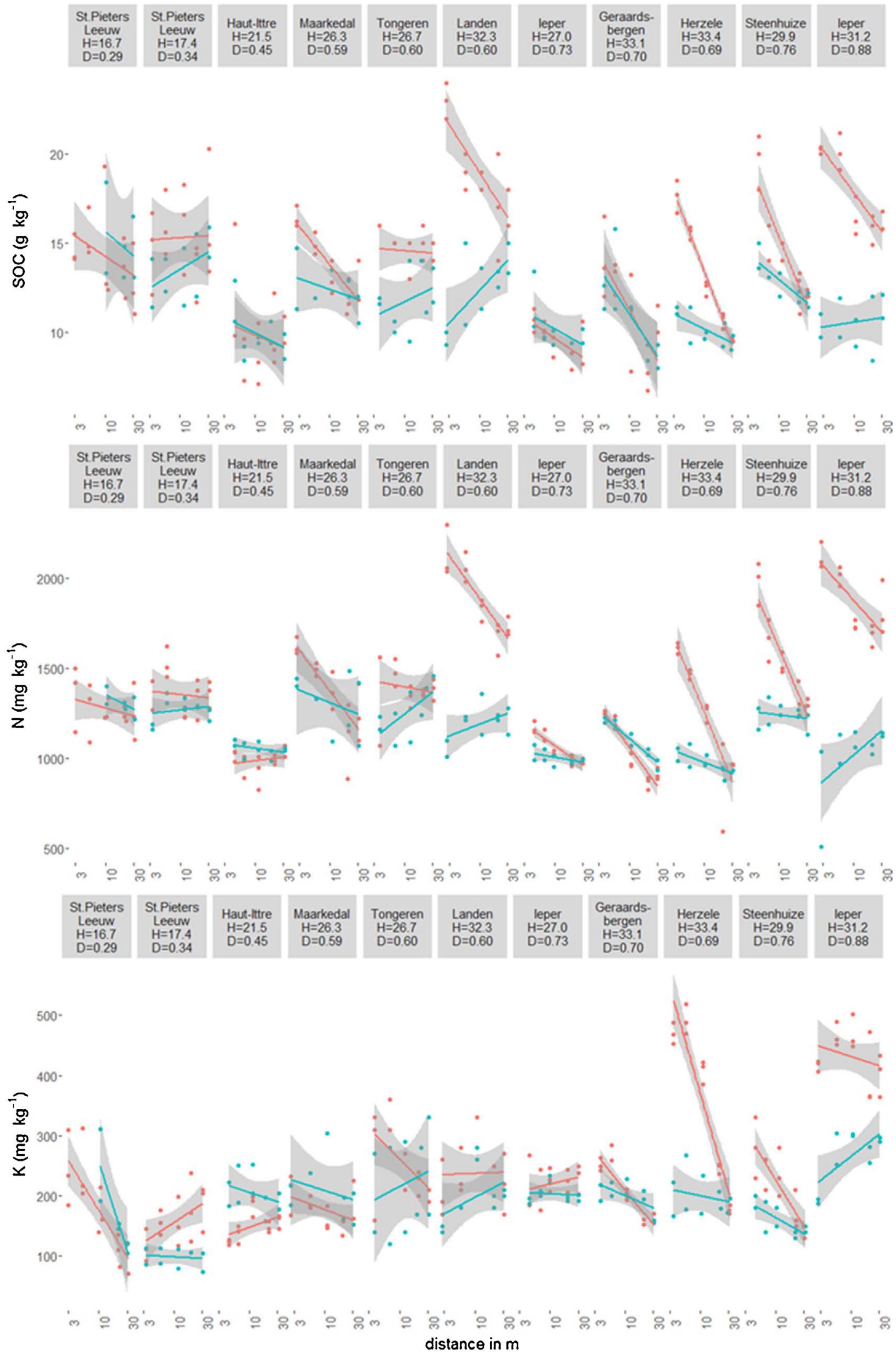

Fig. A1. Concentration of analysed variables in upper soil layer of each boundary planted field bordered by Populus × canadensis as function of the common logarithm of distance to the field edge. Red: transects perpendicular to the tree row. blue: transects perpendicular to the treeless border. H = height (m), D = DBH (m).

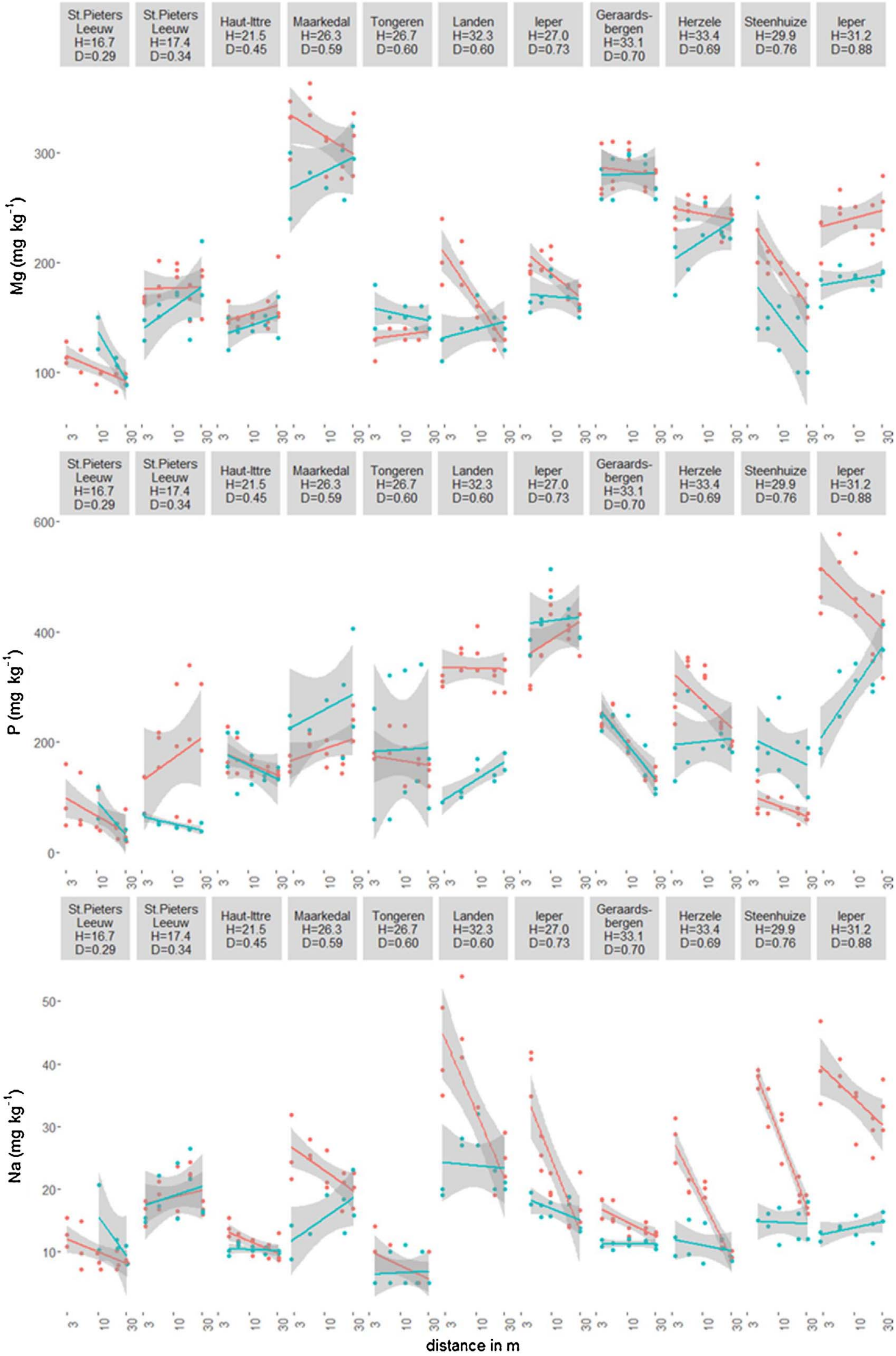

Fig. A1. (*continued*)

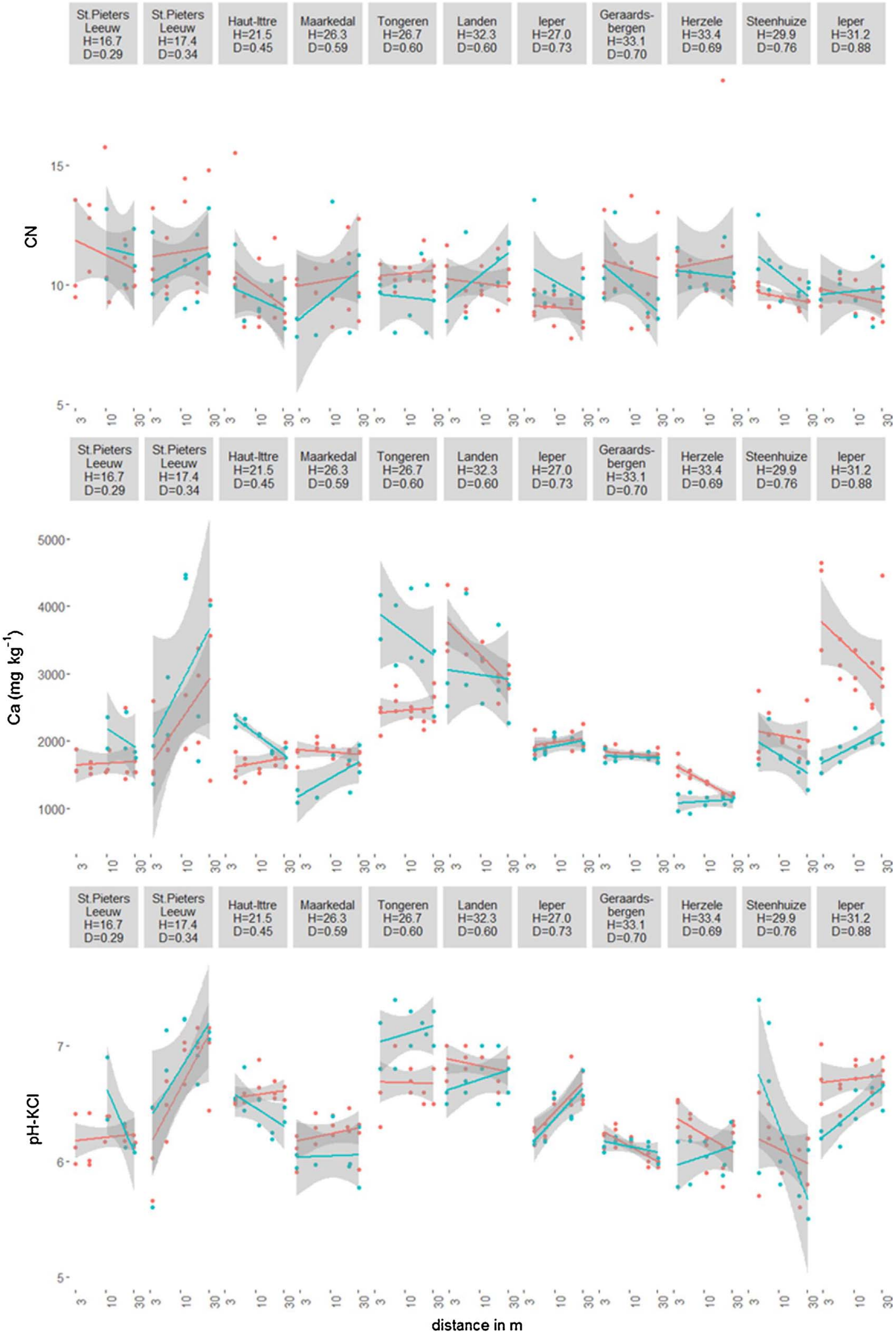

Fig. A1. (continued)

Appendix C

Fig. A2

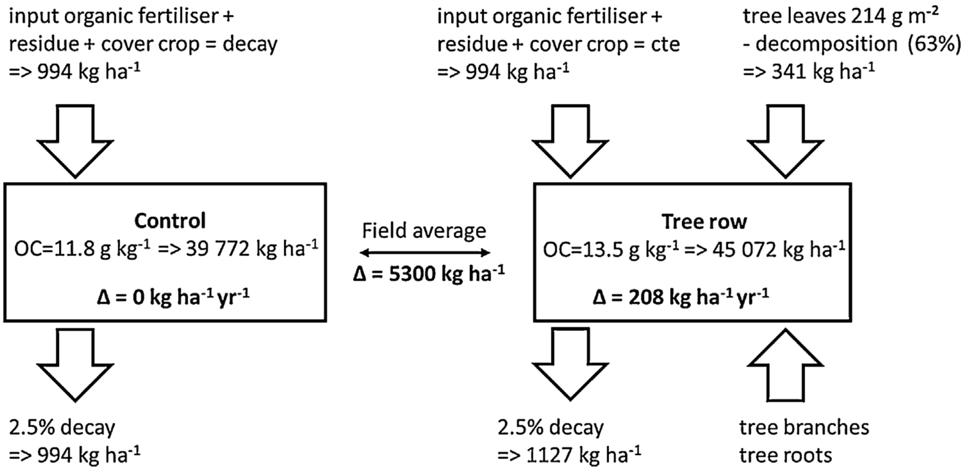

Fig. A2. Carbon flux in the control part of the fields (left) and the AFS (right). Based on the average soil OC content of 39.8 ton ha^{-1} in the control transects and a yearly OC decay of 2.5% (ECCP, 2003) each year circa 994 kg OC ha^{-1} would be lost from the plough layer in the control part of the fields. So at least a similar input of organic matter from organic amendments, crop residues or residues of cover crops is necessary to keep the SOC in equilibrium. If in the AFS the SOC increases up to 45.1 ton ha^{-1}, the predicted loss would be 1127 kg OC ha^{-1}. Hence, a compensation of 133 kg C ha^{-1} would be necessary to keep the balance in equilibrium. Part of this surplus needed may come from tree leaf litter. In addition, based on the observed increase in SOC stock of 5.3 ton ha^{-1} and an average tree age of 25.5 years (Table 1a), an additional average annual OC input of 208 kg ha^{-1} should be realised. Supposing a poplar leaf litter C concentration of 43% (Peichl et al., 2006) and estimating a yearly leaf litter C loss through decomposition of circa 63% (e.g. Wotherspoon et al., 2014), this would require an average yearly leaf litterfall quantity of 214 g m^{-2} which seems consistent with litterfall measurements for poplar in literature (e.g. Wotherspoon et al., 2014; Zhang, 1999).

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