Early Tree Diversity and Composition Effects on Topsoil Chemistry in Young Forest Plantations Depend on Site Context

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Abstract

Trees have a strong influence on the chemical properties of the soil in which they grow. Establishing plantations with different tree species combinations thus potentially leads to divergence in soil chemistry. To study the degree to which differentiation already occurs during the first years after establishment, we made use of a biodiversityecosystem functioning experiment in Belgium, FORBIO. The multi-site experiment replicates tree species richness (1-4 species) and composition in three sites. The sites represent contrasting site contexts, mostly land-use history, soil, and climate. Soil samples (0–10 cm) were taken at the time of planting and approximately 8 years later. We measured the total C and N concentration, the Olsen P, the pH- H_2O , and the concentration of base and Al cations.

Supplementary Information: The online version contains supplementary material available at https://doi.org/10.1007/s10021-021-0060 5-z.

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The change in chemical composition was strongly dependent on site conditions including former land use. Afforestation on former cropland had a positive impact on total C and Olsen P and a negative effect on base cations and pH. On sites reforested after clearcut, soil texture and particular site preparation played an important role. On top of that, we found several significant effects of species composition. Strongest composition effects were detected in the reforested site on loamy soil with little soil disturbance. This study highlights that species choice can already affect soil chemistry in early stages of forest development, but that the nature of the effects may strongly depend on the context in which the plantations are established. Further research is needed to identify the most important contextual factors.

Key words: FORBIO; TreeDivNet; Forest soil chemistry; Tree species diversity; *Quercus* sp.; *Fagus sylvatica; Pinus sylvestris; Pseudotsuga menziesii; Betula pendula; Acer pseudoplatanus.*

Received 11 August 2020; accepted 10 January 2021

Author contributions: E.D., K.V., P.D.S., and L.B. conceived the conceptual idea and outline. K.V., Q.P., and L.B. designed the FORBIO experiment. E.D. helped with soil sampling. E.D. and L.B. performed the statistical analysis. E.D. wrote the manuscript with support from K.V., P.D.S., Q.P., and L.B. All authors discussed the results and contributed to the final manuscript.

HIGHLIGHTS

- We studied change in soil elements after planting trees with varying compositions.
- Direction and strength of changes depended strongly on context.
- The composition effect was most visible at loamy soil with little soil disturbance.

INTRODUCTION

The area of planted forests has strongly increased in the last decades and is likely to increase more in the future (FAO and UNEP 2020). These largescale land-use changes will not only affect the vegetation, but also other ecosystem components, including the soil. Indeed, trees affect the biotic and abiotic characteristics of the soil and this effect is largely dependent on the tree species identity (Augusto and others 2002). Differences in litter chemistry influence the decomposition rate (Hobbie and others 2006), and the quantity of litter and the tree biomass further determine the trees' impact on the soil chemistry (Liu and others 2009), which suggests that fast growing pioneers that produce more litter in early stages of forest development will have a stronger impact on soil chemistry at that same stage. Furthermore, trees differ in vertical root distribution (Brassard and others 2011), in the acidification of the rhizosphere due to acidic exudates (Eviner and Chapin 2003), and in the degree to which their canopy intercepts acidic deposition (De Schrijver and others 2007). In this way, tree species impact a myriad of components related to the soil chemistry, including litter layer thickness (Schulp and others 2008), soil microbial (Prescott and Grayston 2013), and fauna (Bocock 1964; Schelfhout and others 2017) activity and abundance, which consecutively affect processes like nutrient cycling (Vesterdal and others 2008) and carbon storage (Kirby and Potvin 2007). This shows that the soil development may strongly depend on the choice between different tree species when establishing forest plantations.

Although the majority of plantation forests currently consist of monocultures, there is increasing awareness about the benefits of planting more diverse forests (Verheyen and others 2016). When planting trees in mixtures, their influence on the soil may not be easily predicted from their monoculture effects due to the fact that there can be non-additive 'diversity' effects. Previous studies in mature stands found evidence for a positive effect

of tree species diversity on the C stock (Schleuß and others 2014; Dawud and others 2016), pH (Guckland and others 2009; Dawud and others 2016), and base saturation (BS) (Guckland and others 2009). The effects on C:N ratio were more variable (Guckland and others 2009; Schleuß and others 2014; Dawud and others 2016). Schmidt and others (2015) found predominantly additive effects for most nutrients, but this study involved only broadleaved species, and in more functionally diverse forest, stronger diversity effects can be expected (Díaz and Cabido 2001). In addition, many of the existing insights on tree species identity and diversity effects come from studies that focused on monocultures (for example, Augusto and others 2002; Hagen-Thorn and others 2004; Hobbie and others 2006) and two species mixtures (for example, Cremer and others 2016; Langenbruch and others 2012). Larger gradients in tree species diversity have been studied to a much lesser extent.

The effects of individual tree species and mixtures on the forest ecosystem properties and functioning, including the soil, are not necessarily consistent across contrasting site contexts (Augusto and others 2002; Eviner and Hawkes 2008; Ratcliffe and others 2017). First, some of these context variables are inherent site conditions. For instance, soil texture determines in part the binding capacity of the soil that in its turn influences the availability of many nutrients (Jenny 1980). Climatic conditions determine the growth of trees (Twine and Kucharik 2009) and therefore the intensity of altering the soil properties as well as the decomposition rate (Prescott 2010). Climate also impacts nutrient losses by water drainage (Schreiber and others 1990). Second, the legacies of the past land use of a plantation site provide an important template for the expected changes in soil. On formerly cultivated land, past agricultural practices lead to higher concentrations of available P and a lower C:N ratio and reduced soil organic matter (Bárcena and others 2014; Falkengren-Grerup and others 2006; Kepfer-Rojas and others 2015; Verheyen and others 1999). This soil organic matter has, in turn, a positive effect on the binding capacity of the soil and nutrient availability (Jenny 1980). Previous studies have shown increases in C (Li and others 2012) and decreases in pH (De Schrijver and others 2012) and base cations (Berthrong and others 2009) after afforestation of agricultural land. Third, the site preparation prior to planting forms an instant disturbance of the soil, which will have a great impact on the chemical dynamics within the soil after forestation. For instance, post-clear-cut mulching can lead to increases in C, N, and P, as well as base cations (Mendham and others 2003; Mack and others 2014), whereas soil tillage has been suggested to lead to a reduction in those elements during the first years of forest development (Sutinen and others 2019), although this effect has been contradicted (for example, Strömgren and others 2017).

Although previous studies provide evidence that the chemical composition of the soil may strongly depend on the species diversity and composition of the tree community, these studies mostly relied on spatial comparisons of well-established to mature forest stands with different species. Here we studied the direct early tree species effects, that is, the actual temporal changes that can be observed in the first few years after planting. An additional benefit of these plantation experiments over established natural forests is that that they allow testing effects of various species compositions on sites that initially show relatively homogeneous soil conditions. In natural forests, the species composition itself is, at least partly, already determined by the soil conditions. We sampled soils in a multi-site tree biodiversity experiment that replicates tree species richness (1-4 species) and species composition in three sites (FORBIO; Verheyen and others 2013). The sites represent contrasting site contexts: (1) an afforestation of former cropland on sandy soil, (2) a reforestation after a clear-cut followed by uprooting the stumps and disking of the soil on sandy soil, and (3) a reforestation after a clear-cut and mulching on loamy soil. The topsoil was sampled twice in the same locations: just before/after the tree planting (after soil preparation) and after approximately eight growing seasons. In this way, we can quantify direct temporal changes under different tree species and site conditions as supposed to a space for time substitution. Firstly, we expect a difference in change between the three sites, depending on the context. More specifically, we predict a decrease in pH and an increase in total C and base cations after afforestation of agricultural land on sandy soil. For the sites established after a clear cut, we anticipate a decrease in total C and N, Olsen P and base cations after intensive site preparation on sandy soil and the opposite effect after mulching of logging debris on loamy soil. Secondly, even though the plantations are still very young, we expect to already find effects of tree species composition and diversity. More specifically, we predict that species with high-quality litter (that is, low C:N ratio and high Ca concentration) will lead to more nutrient-rich soils than low-quality litter species and the effect will be stronger for fast growing pioneers. We expect nonadditive effects in mixtures of these species, with higher concentrations of C and available nutrients when species are mixed.

MATERIALS AND METHODS

Experimental Sites

The study was conducted in a tree diversity experiment in Belgium (FORBIO, FORest BIOdiversity and Ecosystem Functioning (Verheyen and others 2013)). It is a multi-site experiment that is part of a larger network of tree diversity experiments, TreeDivNet (Verheyen and others 2016), and which replicates its design across three sites that are contrasting in site conditions (Table 1; Figure 1). One site is a former agricultural field, where arable crops (potatoes and maize) and grass were grown. It was ploughed prior to the tree planting (Zedelgem). The two other sites are former forest plantations, which were clear-cut. At the Gedinne site, logging residue was chipped and left on site as mulch. In Hechtel-Eksel, the stumps were removed and the whole site was disked. None of the sites were fertilized during or after site preperation. The site-level design of the plantations follows a classical synthetic community approach. Each site is forested with five species that are well adapted to the local environment, functionally dissimilar, and of importance for forest management in Belgium. Per site, a diversity gradient was created with four levels of species richness (1-4 species). In total, twenty treatments were established per site: all five monocultures, all five possible four-species mixtures, and a random selection of five two- and five three-species combinations. These were all replicated once, resulting in 40 plots per site. In Zedelgem and Gedinne, each plot is 42 by 42 m in size. Hechtel-Eksel consist of 36 by 36 m plots. In all three sites, trees are planted on a 1.5 by 1.5 m grid. In mixed plots, trees are planted in small monospecific patches of 3×3 trees. Patches were arranged in a checkerboard pattern in the two-species mixtures and randomly mixed in the three- and four-species mixtures. More information can be found in Verheyen and others (2013).

Measurements

Soil Sampling

Although tree species effects have been found in deeper soil layers (Guckland and others 2009; Da-wud and others 2016), the impact of trees on the chemical composition of the soil is largest in the

Site	Gedinne	Hechtel–Eksel	Zedelgem
Coordinates	49° 60' N 4° 59' E (Gr) ^a 49° 59' N 4° 59' E (Go)	51° 10′ N 5° 19′ E	51° 9′ N 3° 7′ E
Soil type (WRB code ^b)	Moderately dry stony loamy soil (Cam- bisol)	Dry sandy soil with gravel substrate (Podzol)	Relatively dry sandy soil (Podzol) to moder- ately wet loamy sand soil (Gleysol)
Climate Precipitation (mm)	1021	799	687
MAT (°C)	6.9	9.0	9.4
Former land use	Forest (spruce planta- tion; estimated final cut: $600 \text{ m}^3 \text{ ha}^{-1}$) ^c	Forest (pine planta- tion; estimated final cut: $300 \text{ m}^3 \text{ ha}^{-1}$)	Agriculture (mainly arable)
Site preparation before planting	Logging debris was mulched	Stumps were re- moved and soil was disked	Compacted layer at bottom of plough horizon was loosened and vegetation was superfi- cially removed by a rotary cultivator
Year of planting	2010	2012	2009–2010
Tree species	Acer pseudoplatanus	Betula pendula	Betula pendula
•	Fagus sylvatica	Larix kaempferi	Fagus sylvatica
	Quercus petraea	Pinus sylvestris	Pinus sylvestris
	Larix x eurolepis	Pseudotsuga menziesii	Quercus robur
	Pseudotsuga menziesii	Quercus petraea	Tilia cordata
Understorey vegeta- tion (percentage cover per plot; min– average–max) ^d	3-85-100	0–26–90	0.1-56-100

Table 1. Site Characteristics of the Three Sites Within the FORBIO Exper

^aThe Gedinne site consists of two subsites ca. 2 km apart: Gribelle (Gr) and Gouverneurs (Go).

^b(IUSS Working Group WRB 2015). ^cBased on local yield tables (Dagnelie and others 1988).

^dVegetation survey was conducted in August of 2017 and 2018 (Gedinne), July 2019 (Hechtel-Eksel), and July 2018 (Zedelgem). This cover includes all vascular plants, excluding the planted trees.

topsoil (Hagen-Thorn and others 2004). Therefore, we focused on the topsoil layer only. In each plot, nine soil samples up to 10 cm deep were taken with a soil auger with a diameter of 3 cm, after removing the forest floor, and pooled together. This was done once at the beginning of the experiment (after mulching in Gedinne in 2011, after the final soil disking in Hechtel-Eksel in 2012, and after soil preparation in Zedelgem in 2010) and once in the winter of 2018–2019. To ensure that sampling was done at approximately the same locations at the two sampling periods, samples were taken at nine locations on the two diagonals of each plot with a distance of approximately ten meter between the samples. The samples most distant to the center of the plot were also taken at a distance of 10 m to the corners of the plot, to prevent influence of the adjacent plots. With this sampling scheme, our pooled sample is representative for the soil conditions across the entire plot, averaging acros the small-scale heterogeneity, that is, with some

within-plot sampling points located in the small monospecific patches and others at the intersection between species. We did not include the forest floor in our study, since the first sampling was done after site preperation in Hechtel–Eksel and Gedinne and the forest floor was largely distured. Furthermore, the ZE site did not have a forest floor at the time of planting. To maximize comparability, it was important to replicate the exact sampling procedure of the first sampling.

Basal Area

The impact a tree can have on the soil depends at least partly on its size. For instance, larger trees have more extended root systems that potentially influence the soil over larger areas and produce more litter that drives nutrient cycling. Here we use tree basal area as a proxy of tree size. The diameter at breast height (Zedelgem and Gedinne) or 20 cm from the ground (Hechtel–Eksel) of approximately 130 (Zedelgem and Gedinne) or 110 (Hechtel–Ek-



Figure 1. Map of Belgium with the three FORBIO sites and the experimental set up at each site. Tree species richness per plot ranges from one (white) to four (dark gray) (Verheyen and others 2013).

sel) trees per plot was measured with an equal amount of trees per species. This was done in 2016, 2018, and 2019 in Hechtel–Eksel, Zedelgem, and Gedinne, respectively. Basal area per species per plot was calculated based on these diameters (Figure 2).

Chemical Analysis

The soil samples were dried to constant weight at 40 °C for 48 h, ground, sieved over a 2-mm mesh, and homogenized. To analyze the total C and N concentration, samples were combusted at 1150 °C and the gases were measured by a thermal conductivity detector in a CNS elemental analyzer (vario Macro Cube, Elementar, Germany). Samples were analyzed for pH-H₂O by shaking a 1:5 ratio soil/H₂O mixture for 5 min at 300 rpm and measuring with a pH meter Orion 920A with pH electrode model Ross sure-flow 8172 BNWP, Thermo Scientific Orion, USA. Bioavailable P which is available for plants within one growing season (Gilbert and others 2009) was analyzed by extraction in NaHCO3 (Polsen; according to ISO 11,263:1994(E)) and colorimetric measurement

according to the malachite green procedure (Lajtha and others 1999). Exchangeable K⁺, Ca²⁺, Mg²⁺, and Al³⁺ concentrations were measured by atomic absorption spectrophotometry (AA240FS, Fast Sequential AAS) after extraction in 0.1 M BaCl₂ (according to NEN 5738:1996). Effective base saturation (BS) was calculated by the ratio of the sum of K⁺, Ca²⁺, and Mg²⁺ over the sum of K⁺, Ca²⁺, Mg²⁺, and Al³⁺ in cmol_c kg⁻¹. In Zedelgem, all Al concentrations were under the determination limit. To calculate the BS in Zedelgem, the Al concentration was set to 50 mg kg⁻¹, half the determination limit, in all plots.

Statistical Analysis

The significance of the temporal difference in chemical composition per site was tested with a paired *t* test, paired on plot level.

The effect of species composition and diversity on the soil chemical properties was tested using the diversity-interaction modeling framework developed by Kirwan and others (2009). Two models were fitted per site and per element or ratio. A first "null" model is given by: $\Delta y \sim \alpha y_0$, where Δy is the



Figure 2. Basal area $(10^{-3} \text{ m}^2/\text{m}^2)$ of the species within each composition averaged over the two on-site replicates per composition. Basal areas were calculated based on the tree diameters [diameter at breast height (Zedelgem and Gedinne) or 20 cm from the ground (Hechtel–Eksel)], measured at plantation age of 4 (2016), 8 (2018), and 9 (2019) in Hechtel–Eksel, Zedelgem, and Gedinne, respectively.

difference in chemical composition between the second and the first soil sample, y_0 is the concentration or ratio of concentrations of the first sample, and α is a slope parameter. This y_0 term simply controls for the effect of the original composition of the soil, so that this null model assumes no effect of the species. The second "interaction" model is: $\Delta y \sim \sum_{i=1}^{5} \beta_i P_i + \sum_{i,j=1}^{5} \delta_{ij} P_i P_j + \alpha y_0$, where P_i i < j

and P_j are the proportions in basal area within the plot of species *i* and *j*, respectively. The slope β_i expresses the influence of an individual species based on its soil effects when growing in monoculture weighted by its relative proportion in the mixture ("species identity effects"). The parameter δ_{ij} is then the species interaction effect, expressing the difference between the actual soil effects of mixed species and the expected effects from their monoculture effects ("diversity effects"). The interaction model thus includes the main effects of the species as well as the interactions between pairs of species.

The null model does not account for species effects and thus simply quantifies the average temporal changes in soil properties across the plots in a site, controlling for initial soil composition. To calculate which compositions actually differ from this average temporal change (that is, stronger or smaller changes than average), we calculated plotlevel predictions for the change in a chemical variable (that is, predicting Δy) based on the interaction model and subtracted the prediction made by the null model from these. We used simulation to represent the uncertainty in the regression coefficients that were used to produce these predictions, so that we could make inferences about the calculated differences (Gelman and Hill 2007). For the null model, we sampled 1000 times out of a normal distribution with a mean equal to the point estimate of a prediction using the mean of y_0 as the predictor and the standard error on this

prediction as standard deviation. Subsequently, we pulled 1000 samples out of a normal distribution based on predictions of the interaction model. Again, we use the average concentration as value for y_0 and create predictions for monoculture effects (for species 1 this would be: $P_i = 1, P_j = 0$, for i = 1 and $j = \{2, 3, 4, 5\}$; we do the same for the other four species) and effects of two species mixtures (for a two-species mixture of species 1 and 2: $P_i = 0.5, P_i = 0.5$, for i = 1 and j = 2; we do the same for all other combinations of two species). We focus on the monocultures and the two species mixtures, because it provides insight in how species interact when growing together and because it is still relatively easy to visualize. Interaction effects are calculated for all possible two species mixtures from the experimental pool of five species, including those that are not established in the experiment. However, these combinations do interact in the three and four species plots. Finally, we calculated a pairwise difference between the 1000 samples from the interaction and null model, respectively. If the distribution of these differences clearly differs from zero, based on the 5% quantiles, the changes in soil properties under this particular species composition differ significantly from the average trend. Since 5% quantiles are not as conventional as 2.5% quantiles, the p-values are given in Supplementary 1. Due to the relatively small amount of replicates, the test could fail to reject the null hypothesis under 2.5% quantiles (Neyman 1957).

The statistical analysis was performed in R version 3.6.2 (R Core Team 2019).

RESULTS

Temporal Change

The chemical soil properties generally changed significantly over time, but with contrasting directions of changes in different experimental sites (Figure 3, Table 5 in Supplementary 2). The changes of the individual base cations and Al, as well as of N, can be found in Supplementary 3. In Gedinne, the clear-cut on loamy soil, the total C and N concentration, as well as the pH and BS increased significantly. The change in concentration of the base cations (Ca, K, and Mg) and Al follows the direction of the change in BS. Hechtel-Eksel, the other site that was reforested after a clear-cut, but is situated on sandy soil and was pre-treated more intensely by uprooting the previous vegetation and soil tillage, showed a clear decrease in total C, N, C:N ratio, and available P

concentrations. We saw a significant raise in pH, but a drop in BS. This site also shows a significant decrease in base cations, but an increase in Al concentration. In Zedelgem, an afforestation on arable land, there was a significant increase in C, N, and Olsen P and a drop in pH and BS. Ca and Mg concentrations decreased significantly, whereas K decreased in concentration. Al concentrations were found to be below the detection limit.

Change per Composition

Figure 4 shows the extent that the change in concentration or ratio of a certain composition differs from an average change based on model predictions of the interaction model and the null model. To explain how Figure 4 should be read, we will work out an example for the total C concentration in Gedinne for a mixture of Acer and Larix. The average temporal trend in total C was an increase of approximately 10,000 mg kg⁻¹ (Figure 3), but the dark purple color shows that this change was significantly lower in Acer-Larix mixtures (about $10,000 - 80,000 = -70,000 \text{ mg kg}^{-1}$). When we look at their respective monocultures on the diagonal, we actually see a light yellow color for both, which indicates a stronger increase than the average temporal trend. While this increase was significant for *Larix* (10,000 + 10,000 = 20,000)mg kg $^{-1}$), it was not significant for *Acer* (about $10,000 + 1000 = 11,000 \text{ mg kg}^{-1}$). In case of an average temporal decrease, we work out the example of Olsen P in Hechtel-Eksel for a mixture of Quercus and Larix. The average decrease is 26.6. The purple color for the mixture of Quercus and Larix denotes a stronger decrease in this mixture than the average trend (-21 - 7.4 = -28.4), whereas the monocultures of both species show a weaker decrease than the average change (Quercus: -21 + 7.4 = -13.4; Larix: -21 + 8.2 = -12.8), which is indicated by the yellow color. Note that these deviations to the average trend are not significant. The model coefficients and a more detailed calculation can be found in the Supplementary 4 and 5, respectively.

Most compositions were not significantly different from the average change. This was mainly true for the Hechtel–Eksel and Zedelgem site. In Gedinne, we found more composition effects, except for pH. In Gedinne there was a significant increase in C and C:N relative to the average increase for monocultures of *Larix*, but a decrease when this species is mixed with *Acer* or *Pseudotsuga*. These mixtures also showed a significant decrease in total



Figure 3. Chemical composition of the soil of all the plots within each site at the start of the experiment (2011, 2012, and 2010 for Gedinne, Hechtel–Eksel, and Zedelgem, respectively) and in the winter of 2018–2019. Significances of temporal differences within plots (paired test): *p* value: 0; ****0.001; ***0.005; **0.01; *0.05.

N and Olsen P. For C in *Pseudotsuga* stands, we saw a significant relative decrease in a monoculture, but an increase when mixed with *Fagus*. In Hechtel–Eksel, we observed a relative increase in pH and BS for the mixture of *Larix* and *Pinus*. In Zedelgem, we

found a relative decrease in C:N and Olsen P and a relative increase in N for *Tilia* monocultures and an increase in Olsen P of *Betula* monocultures. The results of the individual base cations, total N, and Al can be found in the Supplementary 3.



Figure 4. Compositional effects on the changes in soil properties. The figures show the tree species in each experiment on the axes, so that the changes in soil properties for a particular two-species composition are represented as circles where the two species intersect. Note that monocultures are represented on the diagonal. Colors show the degree to which the temporal change in a particular composition differs from the average temporal change in a site, that is, based on the difference in predictions from the interaction model and the null model (see "Methods" section), with yellow being a positive difference (that is, smaller decrease/stronger increase in case of average decrease/increase) and purple being a negative difference (that is, stronger decrease/smaller increase in case of decrease/increase). Compositions showing significantly different temporal changes than average (p-value < 0.1) are indicated by a black circle. (A, *Acer*; B, *Betula*; F, *Fagus*; L, *Larix*; Ps, *Pinus*; Pm, *Pseudotsuga*; Q, *Quercus*; T, *Tilia*).

DISCUSSION

Important changes in multiple soil variables already occur a few years after forestation. The nature of these changes is different between sites that vary in soil, climate, and land-use history. Sites not only differ in the strength of the observed changes; we even found changes in an opposite direction. We can already see divergence between different species and species compositions, which is also highly dependent on the site conditions. Below, we will first describe the average change in every site and explain the difference amongst the sites. Secondly, we untangle the difference in strength of the composition effects between the sites. Finally, we will look into different compositions themselves.

Temporal Change Differs per Site

The FORBIO experiment consists of three sites differing in soil, land-use history and pre-planting treatment. This led to different overall effects over time since the planting, independent of the species composition (shown in Figure 3 and Supplementary 3). Below we discuss these large differences in effects between the sites. Doing so, we want to highlight the importance of inherent soil variables and previous land use for changes in soil chemistry. An important generality that emerges from these strong site-dependent effects, is that the site context of young plantations matters a lot. This is for example relevant for making predictions of C storage in young forests.

Reforestation After Clear-Cut on Sandy Soil: Hechtel– Eksel

Both Gedinne and Hechtel-Eksel were reforested after a clear-cut of a conifer plantation. However, the context of the planting is completely different. Both sites have a different climate, as well as a difference in soil texture (Table 1). Another major factor is the site preparation. The site preparation in Hechtel-Eksel was considerably more intensive: all stumps and logs were removed, followed by disking of the soil. The removal of virtually all biomass leads to a strong reduction in the availability of essential elements (Achat and others 2015), which can in part explain the reduction in Olsen P and base cations. Whole tree harvest is often believed to reduce the soil C concentration. However, this effect is strongest in the forest floor and is found to be smaller or not significant for the mineral soil in an experimental setup (Mayer and others 2020). The strong reduction in C is likely caused by fast mineralization of the organic matter that was embedded in the topsoil due to mixing of the soil during site preparation after harvesting the previous stand. This explanation is consisent with the decrease in C:N. The degree to which soil conditions change following biomass harvesting also depends on factors such as climate, tree species, soil texture, and soil chemistry (Thiffault and others 2011). The negative effect on C stocks in the soil is thus expected on sandy soils found in our study site (Wan and others 2018). In addition, tillage causes faster mineralization, due to breakage of soil aggregates and subsequent release of SOM (soil organic matter) from physical protection (Balesdent and others 2000), although the positive effect of soil distur-

bance on mineralization has been disputed (for example, Strömgren and others 2017). The loss in SOM causes a reduction in soil exchange sites for cations (Helling and others 1964), an effect that is complemented by the fact that Hechtel-Eksel is situated on coarse sandy soil, with a low clay content. This may also explain the strong drop in BS. A comparable decline in available nutrients because of tillage was described by Sutinen and others (2019). The associated increase in pH is counterintuitive. A decrease in the amount of exchange sites will also impact the number of protons in the soil, that results in an increase in the pH. A decrease in CEC will lower the buffering capacity of the soil and allow for larger changes in pH (Aitken 1992). The reduction in soil C stocks due to the removal of logging debris (Merganičová and others 2005; Ortiz and others 2014) and intensive site preparation (Jandl and others 2007) is shown to be long term. This is especially concerning, considering that soil C storage is an important factor in mitigating climate change (Lal 2004) and has an impact on nutrient cycling. A rapid recovery of this stock is desirable and a good choice in species is key (Jandl and others 2007).

Reforestation After Clear-Cut on Loamy Soil: Gedinne

In contrast, Gedinne is located on loamy soil, logging debris was mulched and left on site, and stumps were left in the soil. This likely prevented a decrease in Olsen P and resulted in a significant increase in C, pH and BS. Previous studies have shown that the addition of mulch increases organic carbon (Mendham and others 2003; Zerpa and others 2014), which can explain the increase in available cations. Others have found increases in the total N (Mack and others 2014), available P (DeByle 1980; Mack and others 2014), and available K, Ca, and Mg (Carlyle 1995; Olsson and others 1996; Bélanger and others 2003; Mendham and others 2003). Sanchez and others (2006) and Butnor and others (2006), however, hypothesize that the initial increase in C after a clear-cut is mainly due to root exudates of the new stand and decomposition of the belowground biomass of the old stand, which was also left in Gedinne, as opposed to Hechtel-Eksel. With our data it is not possible to distinguish the actual cause(s) of the increase in C. The clear-cut was carried out some years before site preparation and planting (2005 for Gibrelle and 2007 for Gouverneurs, the two subsites of the Gedinne site), which implies that these processes were already taking place a few years before the first sampling (2011). The results described above may additionally be attributed to the transformation of coniferous forest into a mixed plantation (for example, Cremer and others 2016; Cremer and Prietzel 2017).

Afforestation of Arable Field on Sandy Soil: Zedelgem

Our third site, Zedelgem, is situated on former cultivated land. This largely explains the low C concentration and C:N ratio, and high available P concentration, pH and base concentration at the time of planting. These contrasting starting conditions compared to the other two sites explain the difference in the directions of the changes in nutrient composition. Previous studies have demonstrated an increase in total C and soil organic C after afforestation of agricultural land (Laganière and others 2010; Li and others 2012), similar to the effect we saw at this site. The non-significant change in C:N indicates an equal relative increase in N at the site. In contrast to our findings, Deng and others (2017) found in a meta-analysis that afforestation on former agricultural land tended to decrease available P. Compared to transition to other vegetation types, Deng and others (2017) reported, however, that afforestation leads to a lesser decrease in available P and attributed this to accelerated P cycling, which could have possibly lead to an increase at our site. Another explanation for the increase in Olsen P in our study can be a decrease in pH. This causes a smaller availability of Ca (Supplementary 3, Fig. 5) and hence a decreased precipitation of calcium phosphates (Sorn-Srivichai and others 1984), leading to higher P availability in the soil. A decrease in BS and pH was described by Berthrong and others (2009) in a meta-analysis, comparable to what we observed. The drop in BS is caused by a decrease in Ca and Mg (Supplementary 3, Fig. 5). K, however, increases in concentration. This can be attributed to its high mobility and hence rapid release from litter during decomposition. The change in BS does not follow the direction of C, in contrast to the other two sites, which suggests that unlike in Gedinne and Hechtel-Eksel, the part of CEC related to the SOM is relatively limited. The higher initial concentrations of Ca, Mg, and K are most probably related to previous liming and fertilization. Here, we can explain the decrease in Ca and Mg, and consequently BS, by net leaching of those nutrients under soil acidification. A reduction in pH may be explained by several mechanisms (De Schrijver and others 2012), including an elevated production of organic acids, creation of carbonic acid due to higher rates of autotrophic respiration (Andrews and Schlesinger 2001), vertical redistribution of cations in the soil profile due to root uptake and litterfall (Jobbágy and Jackson 2003), and increased input of acidifying depositions due to increase canopy interception (Rasmussen 1998).

First Signs of Tree Species Composition Effects

Overall, we did not observe many significant effects of species composition in this early stage of forest development, especially in Hechtel–Eksel (clear-cut on sandy soil) and Zedelgem (arable land on sandy soil). In other words, within a site the concentrations and ratios generally shift in the same direction at a similar rate and only a few specific species combinations deviate from this overall trend. This is not unexpected, since in mature forests that have grown over multiple decennia, the differences are subtle as well (Guckland and others 2009; Schleuß and others 2014; Schmidt and others 2015; Dawud and others 2016).

Comparing the degree to which composition effects play out in different sites, we see that the Gedinne site (clear-cut on loamy soil) shows the most composition-dependent changes (Figure 2). Here we discuss four possible reasons for this (site preparation, soil texture, climate, and species pool), but note that it is not possible to distinguish the most important factor that is causing the difference in strength at the three sites because these context variables are confounded. Forest soil development and site preparation could offer a first explanation. Both the Hechtel–Eksel and Zedelgem sites bear the strong imprint of previous land use, due to the intensive pre-planting site preparation and due to past agricultural practices, respectively. The impact of the disturbance, however, differs between Hechtel-Eksel and Zedelgem. In Hechtel-Eksel it leads to a loss of SOM and in Zedelgem to high concentrations of base cations, a high pH, and low C concentration and C:N ratio. In both sites, a forest soil and floor has not vet developed. Any composition effects are masked by the corresponding disturbance. Unlike the compositions in Gedinne, where existing forest soil was left relatively undisturbed prior to planting. Similar to our results in Zedelgem, Ritter and others (2003) only found an effect of time and no species effects in the topsoil after afforestation of cultivated land. Compton and others (1998) also detected no species effect for the N content of the soil after afforestation, but found it influenced the C content. In contrast, De Schrijver and others (2012) did find significant species effects during post-agricultural forest development in well drained loamy soils. These finding were, however, after almost four decades of forest development.

Soil texture and climate can influence the effects of species composition on soil via their effects on tree productivity. Toïgo and others (2015) found that a low soil water holding capacity, which is greatly linked to soil texture, is a stressing factor that increased diversity effects on productivity. We can expect that productivity affects the intensity of the impact that trees have on the soil chemical composition. A similar impact of increasing soil sand content was observed by Ratcliffe and others (2017) on other ecosystem functions. These observations are not supported by our study in which we would expect, but could not detect, stronger composition effects in Hechtel-Eksel (situated on coarse sandy soil) compared to reforestations on soil types with finer soil texture, which can possibly be explained by the fact that the soil was strongly disturbed before planting. Hechtel-Eksel is also the most recent site of the three and trees have a smaller biomass compared to the other two sites. Possibly stronger composition effects will be observed in later stages of forest development.

Third, the climate is more continental at the Gedinne site. Evidence has been shown for a stronger positive relationship between tree species diversity and productivity in colder climates (Paquette and Messier 2011; Jucker and others 2016). However, de Peer and others (2018) found overyielding in both the Gedinne and Zedelgem sites, that is, higher productivity in mixed stands than expected based on the productivitly in the respective monocultures of the constituent species. Hence, diversity effects on productivity are not limited to the Gedinne site. This suggests that the observed stronger composition effects on the soil are not caused by potential stronger diversity effects on the productivity, caused by colder climatic conditions. The climatic gradient is also small and less likely to be the reason for the difference in strength of composition effects.

Fourth, the three sites are planted with a different species pool. However, all sites have at least two genera in common and consist of a comparable pool of traits, including leaf phenology, root system, mean annual increment, and litter C:N (Verheyen and others 2013).

Tree Species Identity Matters

When we look at the effects of individual tree species, we can see some patterns that are recurring across multiple elements. Our results show opposing effects of *Larix* in monocultures and mixtures of

this genus with *Acer* or *Pseudotsuga* in Gedinne. Plots consisting of monocultures of *Larix* in Gedinne have a larger biomass than their mixtures (Figure 2), because *Larix* is a fast growing pioneer and both *Pseudotsuga* and especially *Acer* do not grow well in Gedinne. A larger biomass is accompanied by higher production of litter, that may lead to a faster increase in total C and C:N. In addition, mixing litter leads to faster decomposition (Gartner and Cardon 2004), which can explain the smaller C:N ratio in the mixtures with *Larix*. Chapman and Koch (2007) found strong non-additive effects for mixtures of conifers, similar to our mixture of *Larix* and *Pseudotsuga*.

In Hechtel-Eksel, we detected a relative increase in pH accompanied by an increase in BS for twospecies mixtures containing Larix and Pinus, despite their low-quality litter with a low C:N and basecation concentration. Both species are fast growing pioneers and could have built up a higher SOM compared to most other compositions. It is likely that litter quantity plays a more important role than its quality in this early stage in this site. The smaller increase in C:N and Olsen P for monocultures of Tilia in Zedelgem can be explained by the same mechanism of limited litter inputs. Tilia is a slow growing late succession species and hence produces less litter in early stages of forest development. Its good quality litter will also lead to a smaller soil C:N ratio than other species at that site (Vesterdal and others 2008); however, other studies did not find this effect (Hagen-Thorn and others 2004; Langenbruch and others 2012).

Non-tree vegetation can also have a relatively strong impact on nutrient concentration in the soil (Landuyt and others 2019), especially in the early stages of forest development, when trees are relatively small. All three sites have a understorey vegetation ranging from zero to (almost) fully covered, depending on the plot (Table 1). This vegetation is largely dependent on several mechanisms, including microclimate and litter layer thickness (Barbier and others 2008), which differs depending on tree growth and canopy shading, which in turn is affected by tree species identity and diversity (Sercu and others 2017). Previous studies have shown that the composition of the understory vegetation is dependent on the tree species (Barbier and others 2008), which has also been demonstrated in the Zedelgem site (Van Lysebettens, 2019). In this way, tree species identity and composition can affect the chemical composition of the soil indirectly.

CONCLUSION

Our results showed a strong change in most of the considered nutrient concentrations in the three experimental forest plantation sites only 6-8 years after plantation. We found the expected increase in total C and decrease in BS and pH in the afforested site on an arable field (Zedelgem). Our results also showed the opposing effects on the BS and C and Olsen P concentrations between the two reforested sites, of which one is on sandy soil and preceded by soil tillage (Hechtel–Eksel) and the other on loamy soil and preceded by mulching of logging debris (Gedinne). The effect of species identity and composition was largely lacking at both sites on sandy soil (Zedelgem and Hechtel-Eksel). Both of these sites were also disturbed to a larger degree than the loamy site (Gedinne). Because the site-specific variables (soil texture, land-use history, and site preparation) are confounded in this study, we cannot distinguish the relative importance of different factors. Fast growing pioneers, like Larix in Gedinne, caused stronger increases relative to the average change of its site in total C and Olsen P, respectively, whereas slow growing climax species, like *Tilia* in Zedelgem, had the opposite effect, that is, weaker increase in Olsen P. These results highlight the importance of the context, including soil texture, land-use history, and site preparation, to predict the direction and strength of the change in the chemical composition of the soil; consequently, additional studies are necessary to determine the relative importance of different factors. Our findings also indicate that depending on the context, species identity and composition effects can already be found after six to eight years following afforestation or reforestation. This stresses the importance of species choice, even in the early stages of forest development.

ACKNOWLEDGEMENTS

E.D. holds a doctoral fellowship and P.D.S. a postdoctoral fellowship of the Research Foundation Flanders (FWO). We would like to thank the following people for the technical support. Robbe De Beelde, Kris Ceunen, Geydis Green Renoso, Shengmin Zhang, Margot Vanhellemont carried out the soil sampling. Tree measurements were performed by Kris Ceunen, Robbe De Beelde, Luc Willems, Eric Van Beek, and Olivier Boucher. Chemical analysis was executed by Luc Willems and Greet De Bruyn. We also want to thank the two anonymous reviewers for their insightful and constructive comments.

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