Supervisors: Prof. dr. ir. Kris Verheyen
Department of Environment
Ghent University

Prof. dr. ir. Dirk Reheul
Department of Plants and Crops
Ghent University

Prof. dr. ir. Jan Mertens
Department of Environment
Ghent University

Dr. ir. Bert Reubens
Crop Husbandry and Environment
Flanders Research Insitute for Agriculture, Fisheries and Food (ILVO)

Dean: Prof. dr. ir. Marc Van Meirvenne

Rector: Prof. dr. ir. Rik Van de Walle

GHENT
UNIVERSITY

Pardon Paul

Silvoarable agroforestry systems in temperate regions: impact of tree rows on crops, soil and biodiversity

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Doctor (PhD) in Applied Biological Sciences

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Agroforestry in de gematigde streken: impact van bomenrijen op gewassen, bodem en biodiversiteit

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Summary

Agroforestry is defined as a land use system in which trees are grown in combination with agricultural crops or livestock on the same land, and where both ecological and economic interactions occur between the tree and non-tree components of the system. In temperate regions, interest in agroforestry has been growing for 20 years because it is considered as a sustainable agricultural practice that combines primary production with other ecosystem services. Much of the past agroforestry-research has focused on tropical and subtropical regions where positive effects such as increased soil fertility and biodiversity have been demonstrated. However, also for temperate regions, several recent reviews have indicated the potential beneficial effects of agroforestry such as carbon sequestration, protection of (ground)water quality through reduction of nitrogen leaching, mitigation of soil erosion, enhanced biomass production and biodiversity conservation. In particular the practice of alley cropping may offer a promising land use alternative. In this type of agroforestry system, trees are planted in rows across the field. As such, the trees can efficiently be combined with the use of modern farming techniques and machinery for the cultivation of agricultural crops in the intercropping zone between the tree strips.

Implementation of agroforestry remains, however, rather limited in large parts of temperate Europe. Besides uncertainties on the legislative and economic level, this is assumed to result from a lack of actual quantification of the potential effects on ecosystem services and biodiversity. Therefore, the main goal of this PhD research is to analyze and quantify the effect of tree row presence on a subset of provisioning, regulating and supporting ecosystem services and biodiversity aspects in a set of silvoarable fields in Belgium. For the regulating ecosystem services, soil organic carbon (SOC) and soil nutrient conditions were assessed, as well as the potential for biological pest control. For the latter ecosystem services (biological pest control), the abundance and diversity of predatory arthropods were analyzed. The abundance and diversity of macro-detritivorous arthropods was quantified to assess the potential enhancement of decomposition processes and/or nutrient cycling, which are important supporting ecosystem services. Finally, the production of (arable) crops and woody biomass was retained as the provisioning ecosystem service.

Two types of systems were used for the simultaneous assessment of the abovementioned topics. A set of young alley cropping fields was selected to assess the effect of recently-established tree rows. Due to a lack of mature alley cropping systems in Belgium, a set of arable fields bordered by a row of high-pruned poplar or walnut trees (“boundary planted tree rows”) was selected as a proxy for older alley cropping systems. The effect of tree row presence on abovementioned variables was monitored at varying distances from the trees, up to 30m into the arable zone.

We assessed the effect of tree row presence on SOC, total N, P, K, Mg, Na, Ca and pH in the plough layer of the experimental fields. Although no effects were observed near the young tree rows, significantly increased SOC and soil nutrient concentrations were observed near the boundary planted tree rows. 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 magnitude of the observed effects differed according to tree species and the increase in SOC, total N, K, and Na near the poplar rows was related to the size of the trees, indicating a continuous evolution in SOC and soil nutrient status of the agroforestry system as trees mature. The main causal factor was 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 and a potentially reduced nutrient uptake of the arable crops.

Next, the effect of tree row presence on the activity-density and diversity of two types of macro-detrivorous arthropods (woodlice and millipedes) and two types of carnivorous arthropods (carabids and rove beetles) was assessed. Strongly increased activity-density values and diversity of the macro-detritivoreous arthropods were detected in silvoarable fields. Near the (larger) boundary planted trees, these effects extended into the neighboring arable zone. Contrasting gradients in abundance were observed for carabids and rove beetles, with increased activity-density values in the arable zone.

Finally, the influence of tree rows on yield and quality of key western European arable crops was quantified. Tree size, crop type and distance to the trees were main determinants of the crop yield and quality in the silvoarable fields. While effects on crop yield were limited for all crops near young tree rows, substantial yield reductions were observed near mature trees, in particular for maize and potato. Effects on crop quality were limited for all crops under study, with substantial effects only arising near the oldest tree rows. To optimize the provisioning service of agroforestry systems, the cultivation of winter cereals may be advisable over maize and potato towards the end of the lifecycle of the tree component. In addition, poplar trees should be harvested when they reach their target diameter for industrial processing. If tree rows are preserved for the delivery of other ecosystem services, however, substantial impacts on crop yield and quality should be taken into account.

Samenvatting

Agroforestry wordt gedefinieerd als een landgebruikssysteem waarbij bomen in combinatie met vee of landbouwgewassen worden geteeld op hetzelfde perceel, en waar ecologische en economische interacties aanwezig zijn tussen de bomen en de niet-houtige componenten van het systeem. In de gematigde streken is er sedert 20 jaar een groeiende interesse in agroforestry omdat het wordt beschouwd als een duurzame landbouwpraktijk waarbij primaire productie gecombineerd wordt met andere ecosysteemdiensten. Bij een groot deel van het reeds bestaande onderzoek naar agroforestry lag de focus op tropische en subtropische regio’s, waar positieve effecten zoals een gestegen bodemvruchtbaarheid en biodiversiteit werden aangetoond. Ook met betrekking tot de gematigde streken zijn er echter meerdere recente studies die wijzen op de mogelijke gunstige effecten van agroforestry zoals koolstofsequestratie, het verbeteren van de (grond)water kwaliteit door de reductie van stikstofuitloging, het tegengaan van bodemerosie, een verbeterde productie van biomassa en het behoud van biodiversiteit. In het bijzonder de toepassing van “*alley cropping*” kan hier een veelbelovend alternatief bieden. In dit type agroforestry systeem worden bomen in rijen aangeplant op het perceel. Bijgevolg kan de aanwezige boomcomponent efficiënt gecombineerd worden met de huidige landbouwtechnieken en –machines voor de teelt van landbouwgewassen in de akkerbouwzone tussen de bomenrijen.

De aanleg van agroforestry systemen is tot op heden echter eerder beperkt in grote delen van gematigd Europa. Naast onzekerheden op wettelijk en economisch vlak, wordt dit geweten aan een gebrek aan kwantificatie van de mogelijke effecten op de geleverde ecosysteemdiensten en de aanwezige biodiversiteit. Dit doctoraatsonderzoek heeft dan ook als doel om het effect te analyseren en te kwantificeren van de aanwezigheid van bomen op een subset van productie-, regulerende en ondersteunende ecosysteemdiensten en biodiversiteitsaspecten op een set silviculturele percelen in België. In het kader van regulerende ecosysteemdiensten werden het gehalte organische bodemkoolstof (SOC) en bodemnutriënten nagegaan alsook het potentieel voor natuurlijke plaagbestrijding. Voor deze laatste werd de aanwezigheid en diversiteit van predatore arthropoden bestudeerd. De aanwezigheid en diversiteit van detrivore arthropoden werd geëvalueerd om de potentiele gunstige effecten in te schatten op de aanwezige decompositieprocessen, een belangrijke ondersteunende ecosysteemdienst. Ten slotte werd de productie van (akkerbouw)gewassen en houtige biomassa geanalyseerd om het effect op productiediensten na te gaan.

Voor de simultane studie van bovenvermelde thema’s werden twee sets van combinaties tussen bomen en gewassen gebruikt: een set jonge alley cropping percelen werd gebruikt om het effect van recent aangeplante bomenrijen te bestuderen. Door een gebrek aan mature alley cropping percelen in België, werden daarnaast een set akkerbouwpercelen geselecteerd

die geflankeerd worden door een rij opgesnoeide populieren of walnotelaars (“bomenrijen op perceelsranden”) als een proxy voor oudere alley cropping systemen. Het effect van de bovenvermelde variabelen werd op verschillende afstanden van de bomenrijen gemeten, dit tot een afstand van ca 30 m in het akkerbouwperceel.

Het effect van de aanwezigheid van bomenrijen op SOC, totale N, P, K, Mg, Na, Ca en pH werd nagegaan in de bouwvoor van de proefpercelen. Hoewel er geen effecten werden vastgesteld op de jonge alley cropping percelen, werden significant hogere concentraties aan SOC en bodemnutriënten waargenomen naast de bomenrijen op de perceelsranden. Deze verhogingen waren sterk afhankelijk van de afstand tot de bomenrijen, wat resulteerde in aanzienlijke ruimtelijke gradiënten. Bovendien varieerde de grootte van de waargenomen effecten sterk in functie van boomsoort en de stijging van SOC, totale N, K en Na nabij de populieren was afhankelijk van de omvang van de bomen, wat wijst op een continue evolutie in concentratie aan SOC en bodemnutriënten in agroforestry systemen naarmate de bomen in omvang toenemen. De input van koolstof en nutriënten afkomstig van strooisel, in bijzonder bladval, werd als voornaamste verklarende factor gezien, en in minder mate de input via met nutriënten verrijkt doorvalwater en een potentieel gereduceerde gewasopname van nutriënten.

Vervolgens werd het effect van de aanwezigheid van bomenrijen op de activiteit-densiteit en diversiteit van twee types macro-detrivore arthropoden (pissebedden en miljoenpoten) en twee types predatore arthropoden (loopkevers en kortschildkevers) geëvalueerd. Sterk gestegen waarden van activiteit-densiteit en diversiteit van de macro-detrivore arthropoden werden waargenomen in de silviculturele percelen. Bij de (grotere) bomen op de perceelsranden reikten deze effecten tot in de nabije akkerbouwzone. Contrasterende trends werden vastgesteld voor wat betreft aanwezigheid van loopkevers en kortschildkevers, waarbij grotere waarden van activiteit-densiteit in de akkerbouwzone werden waargenomen.

Ten slotte werd het effect van bomenrijen op de opbrengst en kwaliteit van een set in West-Europa frequent geteelde gewassen gekwantificeerd. De omvang van de bomen, het gewastype, en de afstand tot de bomen bleken belangrijke bepalende factoren voor de opbrengst en kwaliteit van de landbouwgewassen in de silviculturele percelen. Hoewel effecten op gewasopbrengst beperkt waren naast de jonge bomen op de alley cropping percelen, werden aanzienlijke opbrengstverliezen waargenomen naast de mature bomenrijen op de perceelsranden, in het bijzonder voor maïs en aardappel. Effecten op gewaskwaliteit waren beperkt voor alle beschouwde kwaliteitsparameters, waarbij substantiële effecten enkel naast de oudste bomenrijen werden waargenomen. Ter optimalisatie van de productiedienst van agroforestry systemen is het wellicht aangeraden om naar het einde van de levenscyclus van de bomen de teelt van wintergranen de voorkeur te geven ten opzichte van maïs en aardappel. In dat opzicht is het tevens aangeraden de bomen ook effectief te kappen eens de doeldiameter bereikt is. Wanneer, met het oog op de levering van andere ecosysteemdiensten, de bomen langer op stam gehouden worden, dient met een substantiële impact op opbrengst en kwaliteit van de landbouwgewassen rekening gehouden te worden.

List of abbreviations

AFS: agroforestry system
a.o.: among others
CAP: common agricultural policy
CEC: cation exchange capacity
Cf.: compare
Conc.: concentration
CP: crude protein
DBH: diameter at breast height
DM: dry matter
EFA: ecological focus area
e.g.: for example
ES: ecosystem services
Etc.: etcetera
EU: European Union
GHG: greenhouse gas
i.e.: that is
LAI: leaf area index
LER: land equivalent ratio
LMM: lineair mixed model
MBD: mineral bulk density
NIRS: near infrared spectroscopy
NMDS: nonmetric multidimensional scaling
OMD: organic matter digestibility
PAR: photosynthetically active radiation
SOM: soil organic matter
RQ: research question
SAF: silvoarable field
S.E.: standard error
SOC: soil organic carbon
TKW: thousand kernel weight
UK: United Kingdom
UWW: underwater weight
vs.: versus
yr.: year

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1. Introduction

1.1 Intensification of agriculture in Europe: past evolution and future challenges

1.1.1 Historical presence of agroforestry

Mixed agricultural production systems in which trees and shrubs are deliberately incorporated in crop or livestock production areas, were widely present in the agricultural landscape of north-western Europe throughout historical times (Borremans et al., 2018; den Herder et al., 2017; Mosquera-Losada et al., 2012; Nerlich et al., 2013; Santiago-Freijanes et al., 2018). Thereby, the three main purposes of trees in the agrarian economy were the production of wood (for fuel, litter or timber), fodder and fruits. In addition, they provided shade and shelter for laborers and livestock, acted as fences and combatted erosion by wind and water (Eichhorn et al., 2006; Mosquera-Losada et al., 2012). Such traditional systems comprise for example *pré-vergers* and *streuobst*, where fruit trees are grown on agricultural land and undersown with crops (*streuobstäcker*) or managed grassland (*streuobstwiesen*) (Eichhorn et al., 2006; Herzog, 1998; Nerlich et al., 2013; Smith, 2010a). Other examples include the use of *pollard trees* in or alongside meadows and arable land to obtain leaf fodder for feeding livestock and/or wood for primarily fuel, or *pannage* wherein pigs are released into beech and oak woodlands to feed on the acorn and beech mast, and into fruit orchards to eat fallen fruit (Eichhorn et al., 2006; Smith, 2010a).

At present, the intentional inclusion of trees and shrubs into crop and/or animal production systems on the same land is referred to as “agroforestry”, a term first used by Bene et al. (1977) (Dupraz and Liagre, 2008; Nair et al., 2010; Smith et al., 2012a). Hence, “agroforestry” is a new name for a rather old practice (Mosquera-Losada et al., 2012; Nerlich et al., 2013). Given the high number of potential tree-crop-animal combinations, currently, a wide range of terminologies exists to typify the various forms of agroforestry systems (AFS). Silvopastoral agroforestry comprises systems whereby trees are combined with grazing. In silvoarable agroforestry (SAF), trees and arable crops are cultivated on the same land area. Further differentiation of AFS can be made based on e.g. their components (crops, animals, trees, shrubs) or their spatial (Figure 1.1) and temporal arrangement (coincident to sequential) (Graves et al., 2007; Sinclair, 1999).

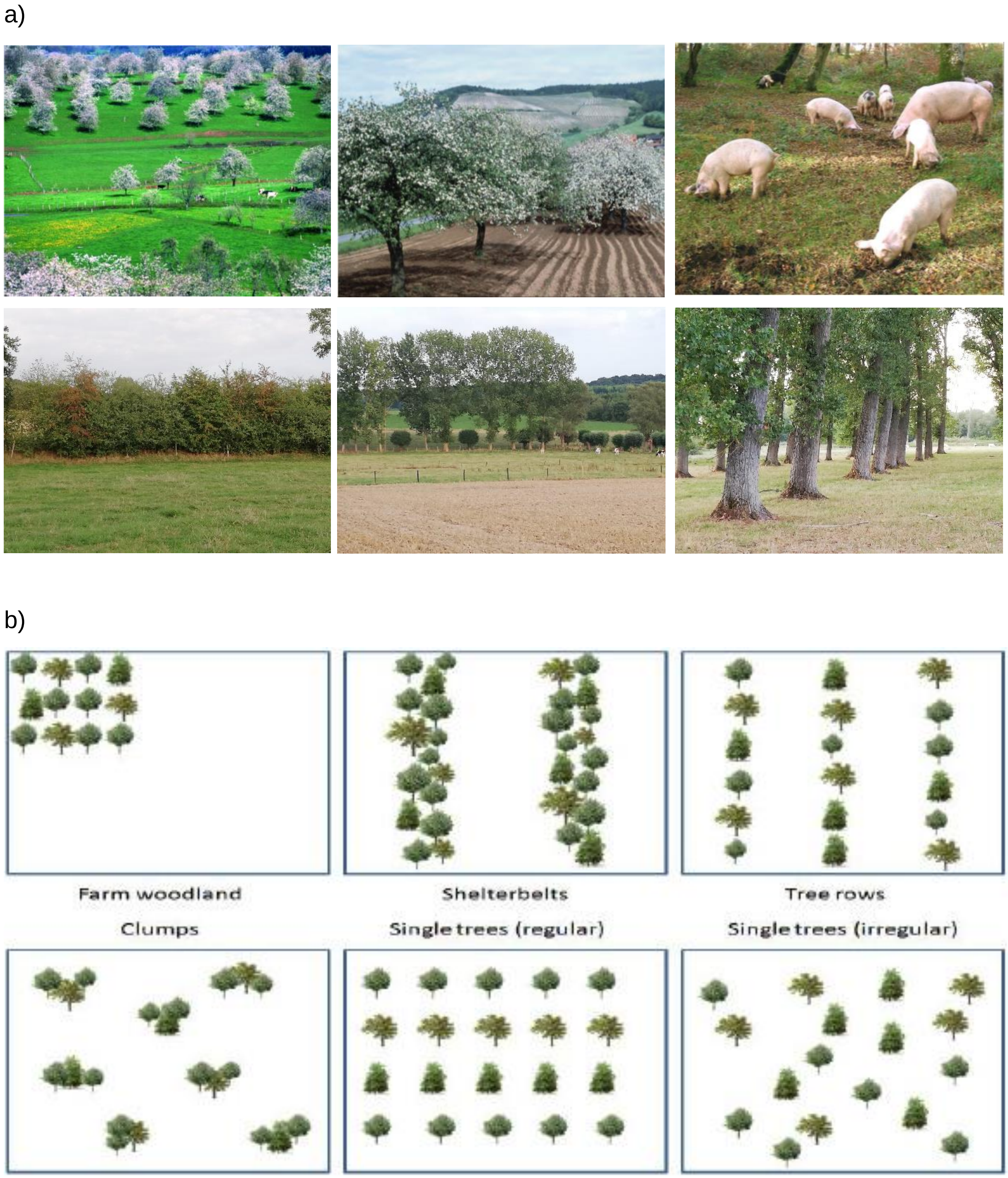


Figure 1.1: a) Examples of traditional agroforestry practices in Europe. Upper panels: left: pré-vergers (France) (OSAE, 2018); middle: Streuobstäcker (Germany) (BLfL, 2013); right: pannage (UK) (Smith, 2010a). Lower panels: left: hedgerows alongside meadow (Belgium); middle: rows of poplar and willow on field boundaries (Belgium); right: meadow with poplar trees (Belgium). b) Different types of agroforestry based on the spatial arrangement of the woody component (non-exhaustive) (Smith, 2010b).

1.1.2 Intensification: increased productivity and future challenges

During the past decades, woody features in the north-western European landscape have increasingly disappeared with the intensification of agriculture (Borremans et al., 2018; Nerlich et al., 2013; Tscharntke et al., 2005). This process started mid-20th century and was characterized by amongst others an increased use of high-yielding crop varieties, inorganic fertilizers and pesticides. This intensification furthermore came along with a strong mechanization and corresponding field enlargement (Binswanger, 1986; Bos et al., 2013; Jepsen et al., 2015; Matson et al., 1997; Palma et al., 2007). This led to substantial increases in crop yield, with current yield levels of several crops equaling multiple times the levels obtained at the start of this intensification process (Figure 1.2) (Binswanger, 1986; Donald et al., 2001; Moore and Lobell, 2015; Mosquera-Losada et al., 2016; Niedertscheider et al., 2014). The simultaneous gains in use efficiency and labor productivity allowed a decrease of labor forces active in agriculture, with e.g. Robinson and Sutherland (2002) indicating a 77% decrease in farm labor between 1945 and 2000 in the UK. Hence, the intensification of agriculture has contributed to provide the necessary agricultural goods for a growing human population while reducing the number of required labor units (Niedertscheider et al., 2014).

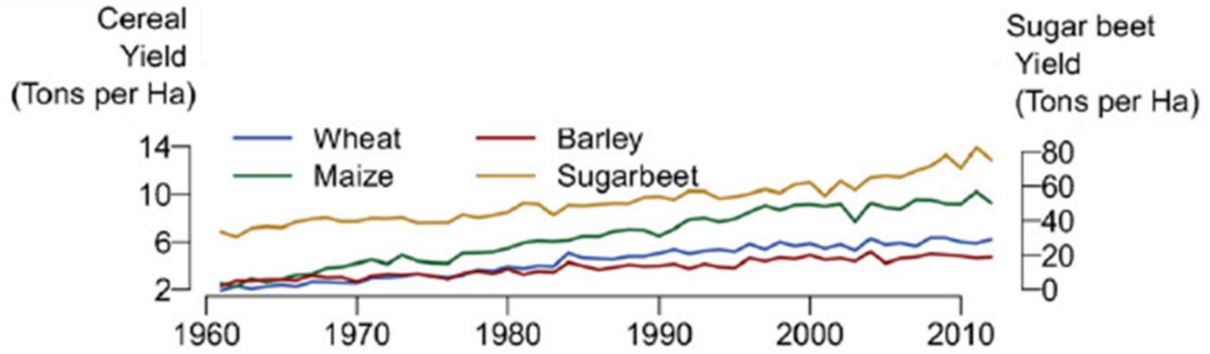


Figure 1.2: Yield increase (1960-2010) of four main arable crops in Europe (Appendix 1.1) (Moore and Lobell, 2015).

In recent years, however, rates of yield increase are becoming smaller (Brisson et al., 2010; Finger, 2008). For example, the average productivity increase of wheat equaled 0.9% year^{-1} between 1993 and 2007, which dropped to an average of 0.5% between 2008 and 2015. Between 2017 and 2025 an average annual growth of 0.4% is predicted (European Union, 2017; Van Vooren, 2018). Primary factors for this stagnation are considered to be the proximity to biophysically possible yields, climatic trends and changes in environmental policies (e.g. restrictions in fertilizer use) and agricultural subsidies (e.g. greening requirements) (Brisson et al., 2010; Finger, 2007; Moore and Lobell, 2015).

The intensified production process has been linked to several negative environmental side-effects. One such issue is the agricultural contribution to greenhouse gas emissions. In the EU, agriculture is responsible for 10% of total greenhouse gas (GHG) emissions (EEA, 2015a).

These primarily result from methane emissions of ruminants, production and application of (synthetic) fertilizers and to a lesser extent from fossil fuel-use for machinery (EEA, 2015a; MEA, 2005). For example, in Flanders, a region with highly intensified agriculture (responsible for 9% of total Flemish GHG emissions), agriculture accounted for 70% of the total methane emission and 53% of total N_2O emission in 2015 (VMM, 2018). Historical reductions in sequestered carbon (above- and belowground) have been caused by the strongly diminished number of trees, hedges (e.g. 50% decrease in the UK between 1945 and 2000 (Robinson and Sutherland, 2002)) and other (semi)-natural features in the agricultural matrix, as a result of land conversions and increasing field sizes throughout past decades (Bianchi et al., 2005).

As indicated by the European Environment Agency (EEA), in 2015, only 53% of all freshwater bodies were in good ecological condition. Thereby, agriculture is considered a main responsible for the pollution of freshwaters, mainly due to the loss of excessive nutrients and pesticides (EEA, 2015b). Water and wind erosion may be increased on agricultural land as a result of amongst others tillage practices, presence of machinery tracks and absence of permanent vegetation that may provide shelter from the wind or capture run-off water (Stoate et al., 2001). This leads to direct losses of topsoil at the field-level (thereby negatively affecting soil fertility), but can also lead to sedimentation in reservoirs and lakes where it reduces the lifetime of water systems and negatively affects feeding and reproduction of fish and aquatic invertebrates (Matson et al., 1997; Ruttan, 2002). During the second half of the twentieth century, soil nutrient availability was generally maintained by increasing additions of fertilizers. Besides contributing to greenhouse gas emissions (see higher), these increased inputs may further negatively impact water quality, as a result of losses via leaching to the groundwater as nitrate, whereby eutrophication of surface waters and pollution of drinking water may occur (Matson et al., 1997; Tilman et al., 2001).

A key feature of intensification has been the increasing specialization in the agricultural production processes. Although in certain cases increased (genetic) crop diversity was observed (e.g. in case of vegetables (Meul et al., 2005)), this often resulted in a reduction in the number of crop or livestock species (Gurr et al., 2003; Matson et al., 1997). Together with above-mentioned increases in field sizes and removal of (semi-)natural features, this has led to monocultures and homogenization of the agricultural landscape. The associated losses in biodiversity have been described by various authors for a.o. endangered farmland birds (Donald et al., 2001), arthropods (Aviron et al., 2005; Holland and Fahrig, 2000), micro-organisms (Wardle et al., 1999) and plants (Batáry et al., 2012; Kleijn et al., 2009). At present, more than 80% of the amphibians, 42% of the birds and 25% of the mammals of European interest linked to agricultural landscapes are threatened and 76% of the habitats linked to agro-ecosystems have an unfavorable conservation status (EEA, 2015c).

1.2 Agroforestry: a sustainable and resilient agricultural system?

1.2.1 Ecosystem services

Human wellbeing is dependent on and in strong interaction with the ecosystem. ‘Ecosystem services’ (ES) are defined as the ecological characteristics, processes, or functions that directly or indirectly contribute to human wellbeing, i.e. the benefits that people and society derive from functioning ecosystems (Costanza et al., 2017, 1997; MEA, 2005). The following categorization of ES into four broad types was proposed by the Millennium Ecosystem Assessment (2005) and also used in The Economics of Ecosystems and Biodiversity (TEEB, 2010) (Costanza et al., 2017):

Provisioning ES: the material output of ecosystems. E.g. food, fodder, fibre, water, timber, medicines.

Regulating ES: the regulating processes of ecosystems. E.g. the regulation of local climate, air quality maintenance, carbon sequestration, maintenance of soil fertility, erosion prevention, pollination and pest control.

Supporting or Habitat ES: the basis of all other ES. E.g. soil formation, nutrient cycling, habitats for species and the maintenance of genetic diversity.

Cultural ES: the non-material benefits that can be obtained from ecosystems. E.g. recreation, spiritual and aesthetic values, education.

1.2.2 Ecosystem services and agriculture: tradeoffs and synergies

Humans value agricultural systems especially for their provisioning services, and intensively managed agro-ecosystems are designed to provide food, fiber, forage, pharmaceuticals and bioenergy (Gaba et al., 2015). As described higher, this contributed to the provision of the necessary agricultural goods for a growing human population while reducing the number of required labor units (Niedertscheider et al., 2014). In turn, agricultural systems strongly depend on an extended set of ES (Power, 2010). Pollination and the reduction of pest insects in agriculture through biological pest control, thereby reducing the need for pesticides, is an important ES that is often supported by neighboring natural ecosystems (Landis et al., 2000; Pumariño et al., 2015). Perennial vegetation may partly regulate the capture, infiltration, retention and flow of water across the landscape, thereby contributing to the provision of sufficient quantities of clean water provided to agricultural systems. Soil structure and fertility provide essential ES, with well-aerated soils with abundant organic matter being fundamental to nutrient acquisition by crops, as well as water retention (Power, 2010; Zhang et al., 2007).

Soil pore structure, soil aggregation, decomposition of organic matter and nutrient availability are substantially regulated by the activity of a diverse soil community of invertebrate animals and microbes (Chander et al., 1998; Delgado-Baquerizo et al., 2015; Matson et al., 1997).

As described before, intensified agriculture can, however, also be a source of several disservices (including greenhouse gas emissions, loss of habitat for conserving biodiversity, nutrient runoff, soil compaction, etc.) (Billeter et al., 2008; Donald et al., 2001; Stoate et al., 2001; Zhang et al., 2007). Besides the negative effects for environment and society, one major concern is the potential feedback of these environmental impacts on agricultural production itself (Ruttan, 2002). Whereas the main goal of the agricultural intensification process has been to maximize the delivery of provisioning services, the sustained delivery of these provisioning ES may be negatively affected by the compromising of supporting and regulating ES. As such, agriculture is currently partly undermining its own production potential, while the combination of stagnating yield increases and ongoing population growth will most likely raise the pressure on the agricultural sector even more.

However, agricultural landscapes can be designed and managed in such a way that an extensive range of ES can be delivered, such as habitat, carbon sequestration, flood control, scenic beauty, recreation and tourism (Assandri et al., 2018; Bennett et al., 2009; Junge et al., 2015; Van Vooren, 2018). At the same time, this can ameliorate many of the negative impacts of agriculture, while largely maintaining provisioning services (Power, 2010; Rey Benayas and Bullock, 2012; Van Vooren, 2018). Hence, developing strategies to simultaneously protect and optimize provisioning, supporting and regulating ES is crucial to continue high-yielding agriculture in the future (Matson et al., 1997). Among these strategies, a transition to more sustainable production methods has been suggested by multiple authors (Matson et al., 1997; Oelbermann et al., 2006; Palma et al., 2007; Tilman et al., 2001). Due to its multifunctional properties, one such alternative may be the renewed implementation of agroforestry, which at present is again receiving attention (Nerlich et al., 2013; Reisner et al., 2007; Smith et al., 2012a; Wolz et al., 2017). Considering the highly mechanized nature of European arable crop production, particularly configurations whereby the tree component is organized in rows across or alongside the fields may be of primary interest. These forms of AFS can efficiently be combined with the use of modern farming techniques and machinery in the intercropping zone between the tree rows (Nerlich et al., 2013; Quinkenstein et al., 2009; Tsonkova et al., 2012).

1.2.3 Current presence of agroforestry in Europe and Flanders

The total agricultural area of Europe (EU-28) amounted to 178.5 million hectare in 2015, equaling 40.7% of the European territory. Permanent grassland and meadows occupied 33.2% of the agricultural area (Eurostat, 2017a, 2016). Arable land amounted to 59.8% of the agricultural area, whereby the main arable crops are wheat (*Triticum aestivum* L.), barley (*Hordeum vulgare* L.), maize (*Zea mays* L.), and to a lesser extent potato (*Solanum tuberosum* L.) and sugar beet (*Beta vulgaris* L.) (Appendix 1.2) (Eurostat, 2017b; FAOstat, 2018).

Although values may vary according to the selection criteria used, currently, 8.8% of the utilized agricultural area in Europe is under agroforestry, according to the estimates of den Herder et al. (2017). However, its geographical distribution over Europe is strongly unbalanced with the majority of AFS occurring in the southern regions (Figure 1.3). The largest area of agroforestry is found in Spain (5.6 million ha), France (1.6 million ha, mainly southern part), Greece (1.6 million ha), Italy (1.4 million ha) and Portugal (1.2 million ha). When expressed as a proportion of total agricultural area, the highest relative shares of agroforestry are observed in Cyprus (40%), Portugal (32%), Greece (31%) and Spain (23.5%). In northwestern Europe, the presence of agroforestry is considerably smaller. For example, according to the estimates of den Herder et al. (2017), the relative share of agroforestry in the total agricultural area equals 5.5%, 3.3%, 3.2%, 1.6%, 1.5% and 0.6% for Luxembourg, the United Kingdom, Belgium, Germany, the Netherlands and Denmark, respectively. In addition, strong differences can be observed according to the type of agroforestry. For example, the total area of livestock agroforestry (i.e. livestock production is combined with permanent woody crops; woodlands; arable lands with sparse trees; or grasslands with sparse trees.) equals 15.1 million hectare, whereas SAF amounts to merely 0.36 million ha (Figure 1.3).

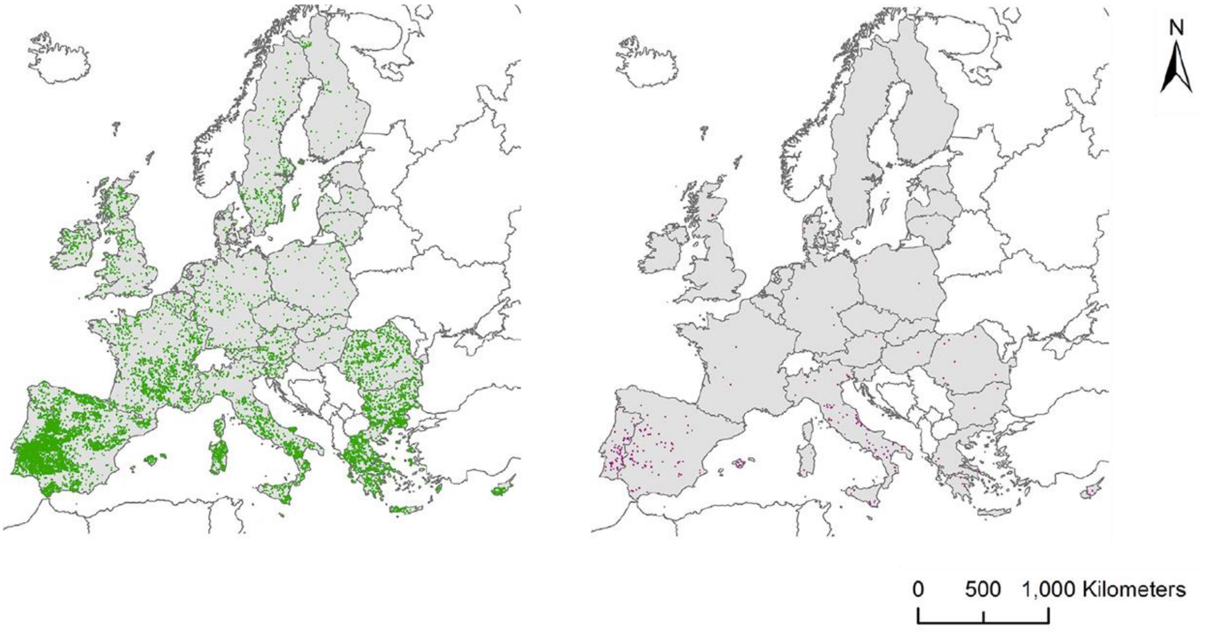


Figure 1.3: Geographical distribution of agroforestry in Europe. Left: total agroforestry, right: silvoarable agroforestry (den Herder et al., 2017).

In recent years, incentives were launched in several of these northwestern European countries and/or regions to increase the potential for implementation of AFS (Mosquera-Losada et al., 2016; Santiago-Freijanes et al., 2018). For example, in Flanders (total agricultural area of 0.6

million hectare or 45% of the Flemish territory (L&V, 2016)), agroforestry implementation currently is supported through the regional implementation of both pillars of the European Common Agricultural Policy (i.e., CAP 2020) (Borremans et al., 2018, 2016). In the second pillar, this is realised through the implementation of submeasure 8.2 (previously measure 222). The latter means that from 2011 onwards, farmers can apply for subsidies for the establishment of new agroforestry. An initial subsidy program for the installation of agroforestry plots was set up in 2011 and renewed in 2014. In the current program, 80% of the establishment costs are reimbursed (L&V, 2018). To benefit from this subsidy, the following requirements need to be fulfilled: number of trees ha^{-1} between 30 and 200; minimal field size of 0.5 ha; fields are in agricultural use; trees are not cut for at least 10 years; coniferous trees and invasive exotic species are excluded; the trees should be homogeneously distributed over the field (focus on alley cropping). In addition, agroforestry is considered as an official measure to fulfil the greening requirements regarding ecological focus area (EFA) as defined in the first pillar of the CAP (a weighing factor of one was attributed to this land-use practice).

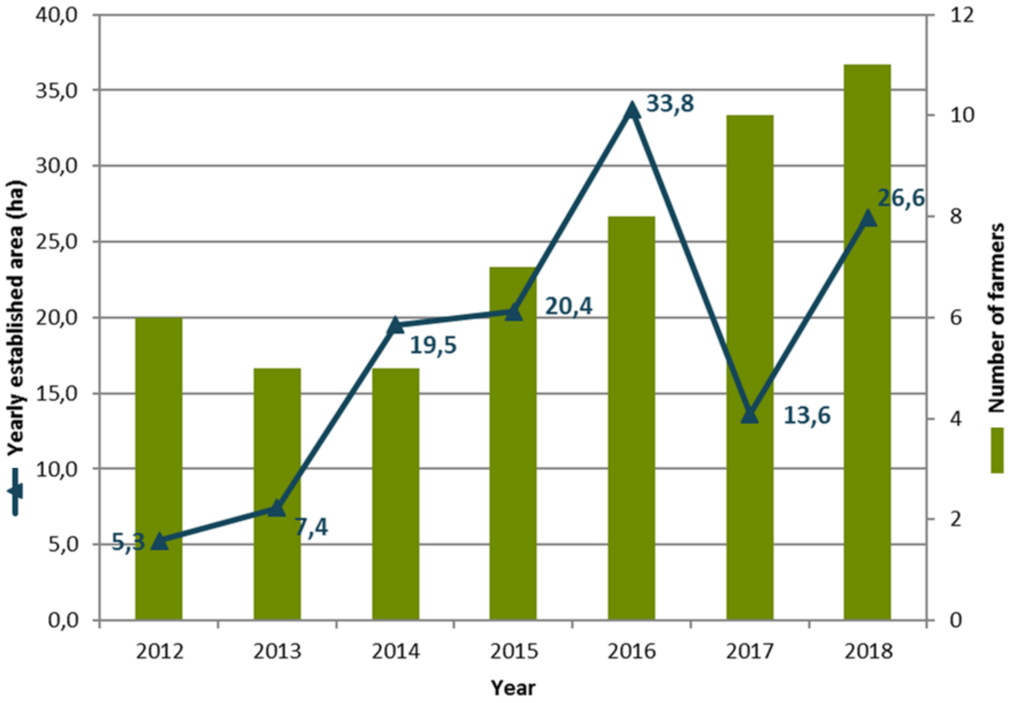


Figure 1.4: Evolution (2012-2018) in area of (newly-established) agroforestry fields and number of farmers receiving the Flemish subsidy for establishment of agroforestry.

These changes in policies and subsidies are assumed to have contributed to the recent increase in the number of newly-established fields per year, as well as the number of adopting farmers (Figure 1.4). Between 2011 and 2018, a total area of 127 ha agroforestry was established through this measure. However, despite the increasing interest for this cropping system, the total area of newly established AFS remains extremely limited when compared to the total area of agricultural land. Besides remaining legal issues and/or uncertainties, the main drawbacks to further the adoption of agroforestry among Flemish farmers are considered to be negative perceptions and lack of knowledge regarding tree-crop compatibility and profitability (Borremans et al., 2016). Therefore, in order to uncover and fully make use of the opportunities of AFS in the context of northwestern European agricultural systems, several steps are needed. This includes, probably first of all, aiming at a full understanding of the functioning and impact of these systems. This starts with a thorough assessment of the impact of introducing trees in agricultural systems as they are present now, both by studying the specific influence of individual aspects (such as competition for light, impact on biodiversity, etc.) and by evaluating the functioning of the system as a whole (including interaction between these individual aspects). From there, also social and economic impacts in currently existing systems can be assessed. Subsequently, next steps might aim on the one hand at enhancing the current systems (e.g. through research and experimentation aimed at strengthening potential synergies and limiting negative effects) and on the other hand at smoothening implementation (e.g. through the development of (new) pathways for economical valorization of AFS outputs, as well as the further development of institutional incentives). In our research, we focus on the first step mentioned in the abovementioned process, through the simultaneous assessment of several biophysical interactions in AFS.

1.2.4 Impact of tree presence on ES in AF: current knowledge and research gaps

Much of the past agroforestry-research has focused on tropical and subtropical regions (Fagerholm et al., 2016; Torralba et al., 2016) where positive effects such as increased soil fertility (Chander et al., 1998; Haggar et al., 1993) and biodiversity (Schulze et al., 2004) have been demonstrated. In temperate regions, integrating trees in arable systems is often associated with technical difficulties related to for example the management of the grass strips, weed infestation of the nearby arable zone, or the contamination of agricultural products with tree litter and fallen branches. In addition, competition for resources is often supposed to be severe, resulting in reduced crop yields. However, also for temperate regions, several recent reviews have indicated the potential enhancement of ES delivery in AFS in general (Jose, 2009; Smith et al., 2012a; Torralba et al., 2016) and alley cropping systems in particular (Quinkenstein et al., 2009; Tsonkova et al., 2014, 2012). For example, Thevathasan and Gordon (2004) observed 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. Increased soil nutrient availability in alley cropping systems has been described by Cardinael et al. (2017) and Jose et al. (2000), which was attributed to tree (leaf) litter input and fine tree root decomposition. Furthermore, the tree component of AFS contributes to a heterogeneous agricultural landscape with an increased variety of habitats and structural diversity of vegetation. As such it may support biodiversity by enhancing the provision of food, nesting and overwintering resources for multiple species of mammals, arthropods, etc. (Jose, 2012; Quinkenstein et al., 2009; Tscharntke et al., 2005; Tsonkova et al., 2012). In addition, these (semi-)permanent features can allow the movement of species between isolated patches of natural habitats in otherwise open landscapes, as well as buffer protected areas from the impacts of more intensive systems (Smith et al., 2012a). A primary characteristic of agroforestry is that the abovementioned delivery of ES and enhancement of biodiversity are combined with the continued provision of (agricultural) goods. The land equivalent ratio (LER) is typically defined as the ratio of the area under sole cropping to the area under the AFS, at the same level of management, that gives an equal yield (Mead and Willey, 1980). Although results are inconsistent and mainly based on modeling, several authors have indicated a land equivalent ratio of temperate AFS larger than one (Graves et al., 2010; Rivest et al., 2010; Tallieu, 2011). This may indicate the potential of agroforestry, not only to maintain, but also to further increase agricultural biomass production (i.e. both arable crops and woody biomass) per area of land.

Existing research of tree-impacts in temperate alley cropping systems has, however, mainly been conducted in fields with tree rows of only limited age (e.g. Dufour et al., 2013; Gillespie et al., 2000; Peng et al., 2009; Thevathasan and Gordon, 1997), with several studies even being conducted on the same site (e.g. Bambrick et al., 2010; Oelbermann et al., 2006, 2004; Oelbermann and Voroney, 2007; Peichl et al., 2006; Thevathasan and Gordon, 2004). In addition, most studies focus on one aspect only (i.e. either impact on crop productivity, soil quality, biodiversity or another parameter), but rarely on the combination of those issues (Jose, 2009; Torralba et al., 2016). Furthermore, at present, actual quantification of several aspects remains limited, in particular regarding crop yield and quality (Gillespie et al., 2000; Jose et al., 2008; Tsonkova et al., 2012). Finally, research often concerns the field-level or landscape scale, whereas potential gradients in alley cropping fields have only been assessed to a limited extent. The latter is, nonetheless, of primary importance for farmers, because of the potential impact on agricultural management. This lack of quantitative and integrated knowledge is considered to be one of the main stumbling blocks to further the adoption of agroforestry in temperate regions (Artru et al., 2016; Borremans et al., 2016; Smith et al., 2012b; Tsonkova et al., 2012).

1.3 General objectives, hypothesis and research questions

The main goal of this PhD research is to analyze and quantify the effect of tree row presence in SAF on a subset of provisioning, regulating and supporting ES and biodiversity aspects. As described higher, at present, quantification of effects on crop yield remains limited although this is considered to be of key importance by farmers who are considering the implementation of AFS. Therefore, arable crop production was retained as the provisioning ES. Two major assets of AFS, which may in turn affect crop yield, are considered to be the beneficial effects on soil fertility and biodiversity. Therefore, for the regulating ES, soil organic carbon (SOC) and soil nutrient conditions were assessed, as well as the potential for enhancing biological pest control. For the latter ES (biological pest control), the abundance and diversity of predatory arthropods was analyzed. Finally, the abundance and diversity of macro-detritivorous arthropods was quantified to assess the potential enhancement of decomposition processes and/or nutrient cycling, which are important supporting ES. These topics are simultaneously assessed on an extended set of experimental arable fields with tree rows of varying age (young, middle-aged and old, see further).

Hypotheses and research questions (RQ) are listed below and embedded in the general structure of the thesis (Figure 1.5). The selection process of the experimental fields and the methods and materials used in the following chapters (2-5) are summarized.

In chapter 2, the effect of tree rows on soil nutrient conditions is quantified. A set of key soil nutrients (P, K, total N, Mg, Na, Ca) and pH-KCl are assessed in the plough layer (0-23) cm of arable fields, as well as soil organic carbon (SOC). Besides contributing to soil structure and fertility and soil water retention, the potential of AFS to increase SOC levels is considered a major asset in the context of climate change mitigation (Lorenz and Lal, 2014).

> ***Hypothesis 1:*** *Tree row presence significantly affects soil characteristics in arable fields. The magnitude of these effects is dependent on both distance to the trees and their size.*
>
> ***RQ1.1:*** *How large is the increase of SOC and soil nutrient concentrations near tree rows?*
>
> ***RQ1.2:*** *To what extent does the magnitude of the observed effects vary with decreasing distance to the field edge and increasing size of the trees?*

In chapter 3 the effect of tree rows on the abundance and diversity of potentially beneficial arthropods is assessed. Two functional groups were studied, namely macro-detritivores (woodlice and millipedes, which may contribute to organic matter decomposition and enhanced nutrient cycling), and pest predatory taxa (rove beetles and carabids, which may contribute to natural pest control). The choice for abovementioned taxa was based on their potential to contribute to the considered ES. Woodlice and millipedes may substantially enhance decomposition processes and carabids and rove beetles are considered to be major natural enemies for pests. Moreover, they all are relatively common in temperate regions, are easily identifiable, and are often used in other research assessing the above-mentioned ES which increases comparability between different studies.

> ***Hypothesis 2:*** *Tree row presence significantly increases the abundance and diversity of potentially beneficial arthropods in arable AFS.*
>
> ***RQ2.1:*** *How large are the increases in abundance and diversity of arthropods in and near the tree rows when compared to treeless field edges and further locations (30 m) in arable fields? Are the observed trends similar for macro-detritivorous and carnivorous arthropods?*
>
> ***RQ2.2:*** *How strongly does the crop type affect the observed effects?*

In chapter 4, the effect of tree row presence on crop yield and quality is assessed for five main arable crops: silage maize, grain maize, potato, winter wheat and winter barley.

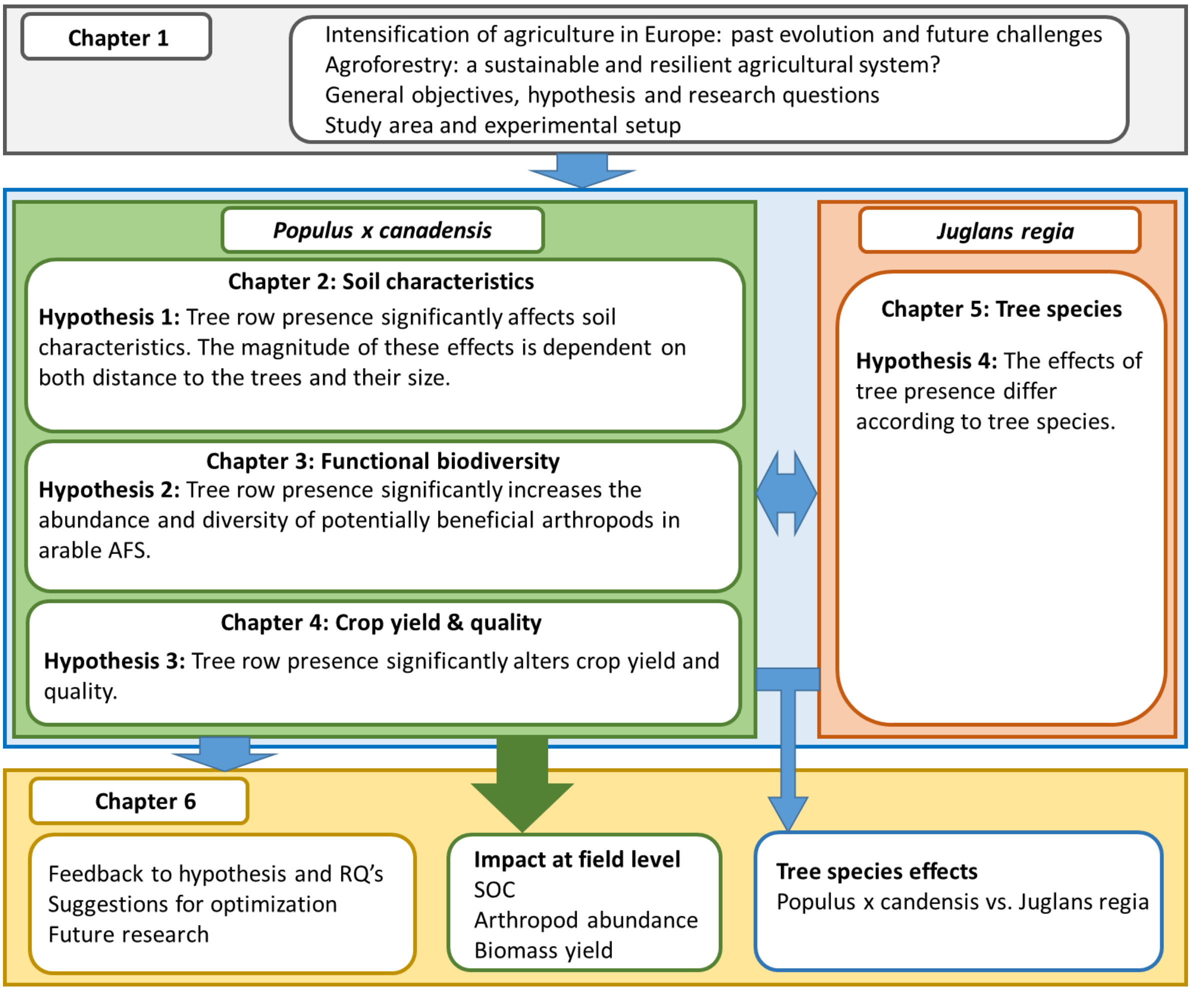
> ***Hypothesis 3:*** *Tree row presence significantly alters crop yield and quality.*
>
> ***RQ3.1:*** *How much is the yield of arable crops enhanced or deteriorated as a result of tree row presence and to what extent do the effects differ according to crop type and tree size?*
>
> ***RQ3.2:*** *How much is the quality of arable crops enhanced or deteriorated as a result of tree row presence?*
>
> ***RQ3.3:*** *How strongly does the magnitude of the observed effects increase with decreasing distance to the field edge?*

In chapters 2 to 4, the middle-aged and mature tree components consist of poplar (*Populus x canadensis* Moench.). Effects of tree row presence may, however, vary according to tree species. Therefore, in chapter 5, the abovementioned research topics are studied near a mature alley of walnut trees (*Juglans regia* L.) to quantify potential effects of tree species.

> ***Hypothesis 4:*** *The effects of tree presence differ according to tree species.*
>
> ***RQ4.1:*** *To what extent are the observed effects of tree row presence on soil characteristics in the arable zone different near tree rows of walnut when compared to tree rows of poplar?*
>
> ***RQ4.2:*** *To what extent are the observed effects of tree row presence on the abundance and diversity of potentially beneficial arthropods different near tree rows of walnut when compared to tree rows of poplar?*

RQ4.3: *To what extent are the observed effects of tree row presence on the yield and quality of arable crops different near tree rows of walnut when compared to tree rows of poplar?*

Finally, in chapter 6, the results obtained in the previous chapters for an individual crop and year are extrapolated by calculating the effect of tree row presence on SOC, arthropod abundance and crop yield during an entire tree growth cycle with poplar. Next, all research questions are taken up again, discussed, and the hypotheses are validated or countered. A general discussion in a broader perspective and recommendations for further research are given at the end.



Intensification of agriculture in Europe: past evolution and future challenges
Agroforestry: a sustainable and resilient agricultural system?
General objectives, hypothesis and research questions
Study area and experimental setup

Chapter 2: Soil characteristics

Hypothesis 1: Tree row presence significantly affects soil characteristics. The magnitude of these effects is dependent on both distance to the trees and their size.

Chapter 3: Functional biodiversity

Hypothesis 2: Tree row presence significantly increases the abundance and diversity of potentially beneficial arthropods in arable AFS.

Chapter 4: Crop yield & quality

Hypothesis 3: Tree row presence significantly alters crop yield and quality.

Chapter 5: Tree species

Hypothesis 4: The effects of tree presence differ according to tree species.

Feedback to hypothesis and RQ's
Suggestions for optimization
Future research

Impact at field level
SOC
Arthropod abundance
Biomass yield

Tree species effects
Populus x candensis vs. Juglans regia

Figure 1.5: Thesis outline.

1.4 Study area and experimental setup

All fields are located in Belgium (16 in Flanders and three in the Walloon region). Actual arable alley cropping systems in these regions are, however, scarce and almost exclusively of young age. As a proxy, a set of conventional arable fields was selected that are bordered by a tree row (further referred to as "boundary planted fields") to estimate the effect of middle-aged and mature trees. Following criteria were set for the selection of these boundary planted fields:

- **Orientation of the tree row** was approximately North-South, which is generally considered to be the most favorable orientation in actual temperate alley cropping fields since this orientation results in the lowest quantity of shade in the arable zone because the tree shadows fall in the tree rows when the sun is at its apex. Furthermore, this results in the most equal distribution of sunlight between the arable zones on both sides of the tree rows (Artru, 2017; Smith et al., 2012b).

- **Tree species** was either poplar or walnut. Poplar is a tree species often used in temperate agroforestry fields since it is characterized by a fast growth, which limits the duration of the agroforestry-rotation (i.e. period from planting of the trees until cutting) and hence the delay of associated revenues. Whereas walnut trees necessitate a longer growing period due to their slower growth, they may produce wood of high quality with generally a high market value up to 676 € m^{-3} stemwood, versus 45 € m^{-3} for poplar (Bosgroepen, 2018; kbbm, 2018). Moreover, early returns can be realized if the trees are grown for the production of walnuts. Walnut trees are furthermore characterized by a late budburst and both poplar and walnut trees are often characterized by a moderately dense crown with a relatively low number of interior leaves, which limits competition for light with (arable) intercrops (Peng et al., 2009; Reynolds et al., 2007). Finally, as shown by Reisner et al. (2007), large parts of temperate Europe, as well as the region of study of this PhD research, are considered to have optimal growth conditions for both poplar and walnut trees (Figure 1.6).

- **No headland** is present next to the tree row and all selected fields were cultivated in a direction parallel to the tree row to reflect actual alley cropping conditions in the arable zone as close as possible.

- Tree rows are of **homogenous size** at field level but with varying size among the different fields to allow the assessment of effects according to tree growth stage. Intra-row tree distance of the tree rows was always circa 8 m in case of poplar and 9 m in case of walnut.

- **Part of the field is not bordered by the tree row**. The treeless parts of these fields hereby act as a reference situation to isolate tree effects from slight differences in e.g. fertilization.

- **Soil texture** is loam or sandy loam (Table 1.1). In Flanders, these soil types constitute the main regions for arable farming with generally high crop yields and high potential for cultivation of different crop types. These regions coincide with the *target regions* in Flanders as defined by Reisner et al. (2007), which are based on the occurrence of one or more environmental issues that may be mitigated through the implementation of agroforestry (Figure 1.6). Furthermore, the cultivated intercrops were assumed to be potentially less susceptible to stress caused by tree-crop competition on these soil types, given the generally high nutrient availability and the relatively high moisture retention.

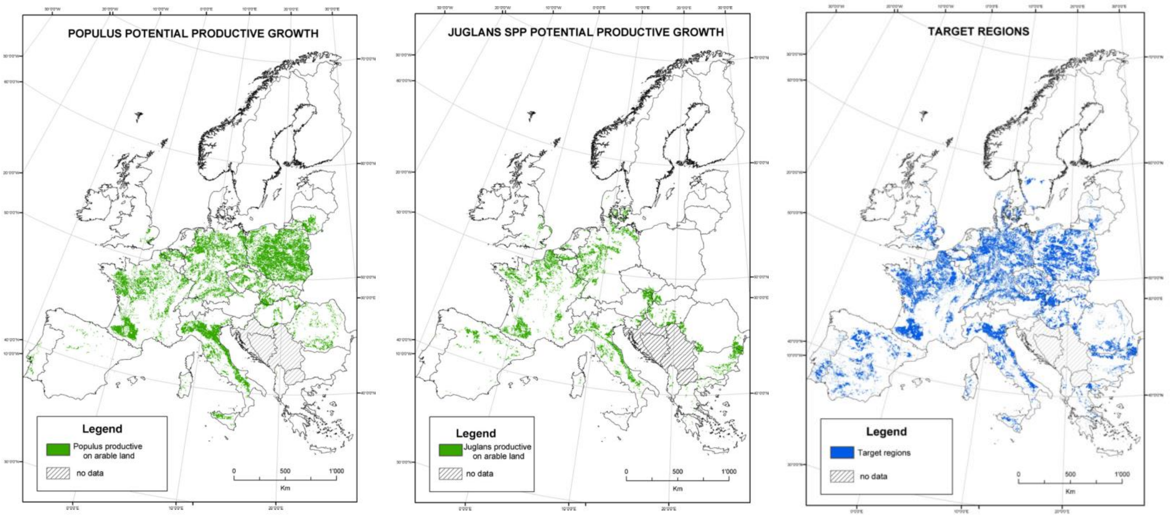


Figure 1.6: Potentially productive area for poplar (left) and walnut (middle) on arable land in Europe, and European target regions for silvoarable agroforestry (right) (Reisner et al., 2007).

For selection of the fields in Flanders, an overlay of the Soil map of Flanders (OC GIS-Flanders, 2001), the Biological Valuation Map (BVM) (INBO, 2010) and the Single application data of 2013 (L&V, 2014) was made using Qgis version 2.4 (QGIS Development Team, 2014). All fields where an arable crop was grown and that were characterized by a loam or sandy loam soil texture were selected. All tree lines with poplar or walnut were selected from the BVM. Subsequently, all combinations of selected fields and tree rows were evaluated for their potential suitability as experimental fields using Google earth aerial photography (Google Earth, 2015). Finally, the suitability of the best fields was evaluated by field visits. In addition, all agricultural fields in the northern part of the of the Walloon region were evaluated using Google earth. Thereby, suitability was checked based on arable land use, tree row presence and abovementioned conditions (e.g. North-South orientation, soil type), after which a field-visit was conducted to assess the tree row species and evaluate actual suitability. The resulting set of experimental fields comprised eleven conventional arable fields bordered with poplar and two fields bordered with walnut (Figure 1.7).

In addition, a set of six young alley cropping fields (2-5 years in 2015) was selected to assess the abovementioned effects near a newly established tree component (Figure 1.7). Fields were primarily selected based on previous contacts with farmers and their willingness to collaborate. Given the very limited number of existing fields at the start of the PhD-research, no restrictions regarding soil texture were made for these young alley cropping fields and the soil texture in these fields ranged from silt to sandy. 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 x canadensis*, *Juglans regia* L., *Prunus avium* L. and *Sorbus torminalis* L. Crantz (Table 1.1b). 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.). 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. 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.

Fields were conventionally farmed and at all field sites, mainly the following crops were grown: maize (*Zea mays* L.), winter wheat (*Triticum aestivum* L.), winter barley (*Hordeum vulgare* L.), sugar beet (*Beta vulgaris* L.) and potato (*Solanum tuberosum* L.). Straw of winter cereals was removed after harvest. Soils were tilled and remaining crop residues were incorporated into the soil. During winter, cover crops (mainly yellow mustard (*Sinapis alba* L.) and perennial and Italian ryegrass (*Lolium perenne* L. and *Lolium multiflorum* Lam.)) were applied. Crops were fertilized according to their nutrient requirements (Vandendriessche et al., 1996; VLM, 2014) with animal manure and mineral fertilizers and in accordance with governmental regulations (SPW, 2014; VLM, 2014). Chemical crop protection agents were applied according to common agricultural practice, i.e., generally a single herbicide application in case of maize after crop emergence in spring and according to governmental recommendations in case of winter cereals (Lamont and Lambrechts, 2009). During the period of monitoring, no pesticides were applied in the tree rows or (treeless) grass strips.

On the selected boundary planted fields, transects were installed perpendicularly to the present tree rows to study the effect of tree presence as a function of distance into the arable zone (Figure 1.8). At each experimental site and perpendicular to the tree row and to the treeless border, 3 and 2 transects were installed, respectively, for the assessment of soil characteristics and crop yield measurements. Each transect consisted of 5 rectangular sampling plots, the center of which was located at distances 2, 5, 10, 20 and 30 m away from the tree row/treeless field edge. For the arthropod sampling, two transects were installed perpendicular to the tree row and to the treeless border. Each transect consisted of four sampling points located in the field border and at distances 1, 5 and 30 m away from the field edge.

On the selected alley cropping fields, 3 transects were installed between and perpendicular to both selected tree rows for the assessment of soil characteristics and crop yield measurements. Thereby, each transect consisted of 6 sampling plots, the center of which was located at distances 2, 5 and 12 m from the closest tree row. For the arthropod sampling, two transects were installed. Each of these transects had seven sampling points, two of which were located within the tree strips. The others were located at distances 1 and 5 m away from the field edge near both tree rows, with one in the center of the intercropping zone. Where possible, additional control points were marked in the transects, located between 18 to 55 m away from the tree rows.

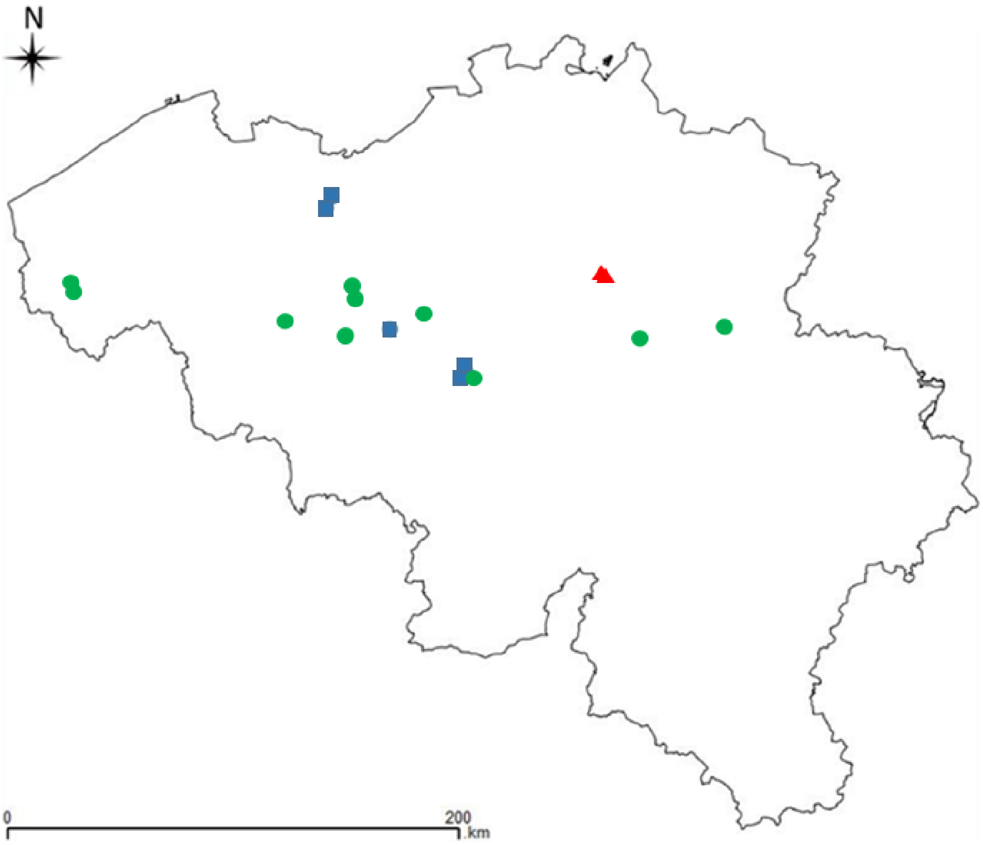


Figure 1.7: Location of experimental fields. Green dots: poplar, Red triangles: walnut, Blue rectangles: young alley cropping.

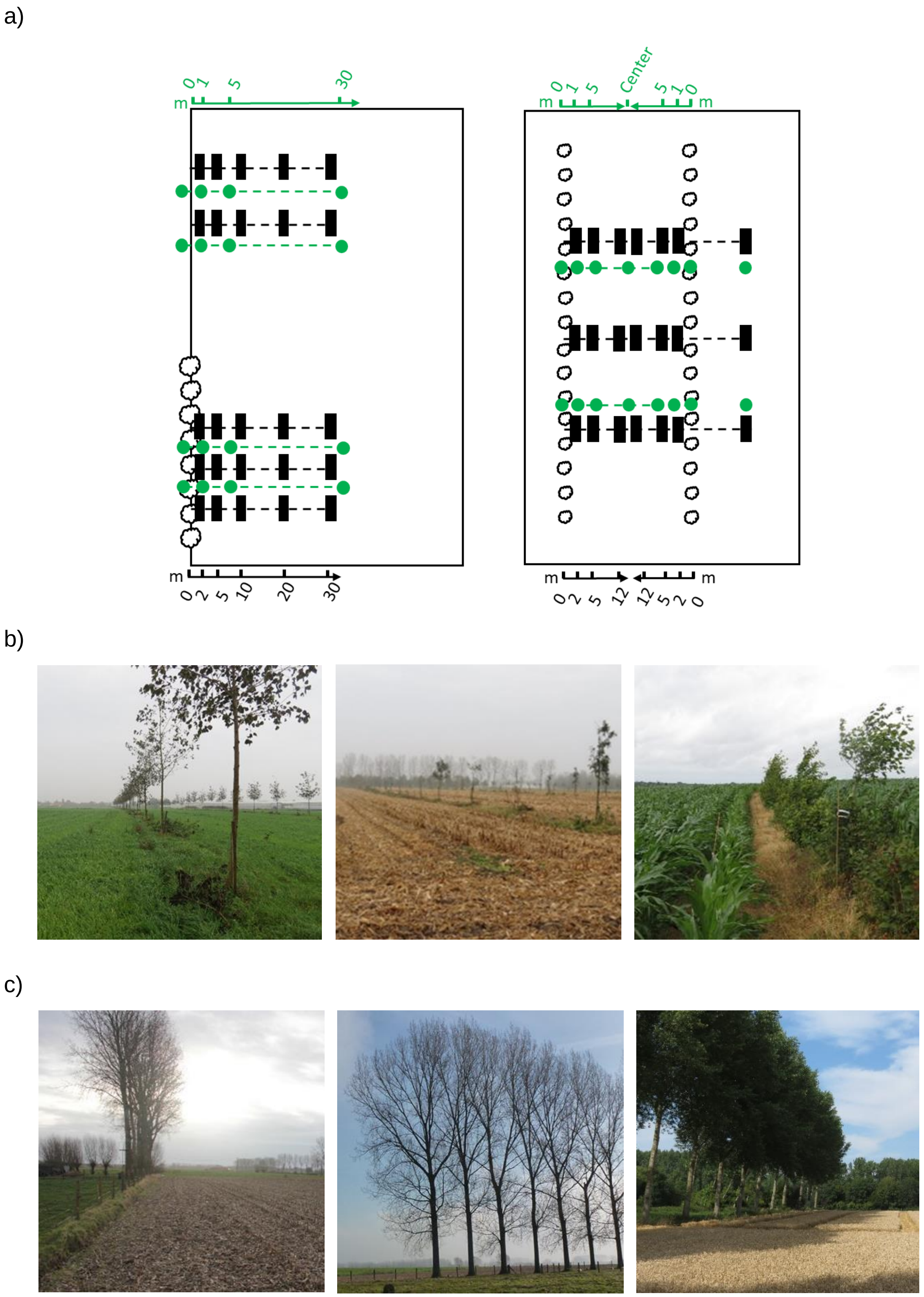


Figure 1.8: a) General experimental setup on boundary planted fields (middle) and alley cropping fields (right). Black rectangles denote sampling locations for soil characterization and experimental harvests. Green dots denote sampling locations for monitoring of functional (arthropod) biodiversity. b) Example of young alley cropping fields and c) boundary planted fields.

Table 1.1: Characteristics of a) boundary planted fields with tree species Populus x canadensis or Juglans regia and b) young alley cropping fields with varying tree species. Climatic data ("Temp.": annual mean air temperature in °C near surface, "Precip.": annual mean precipitation in mm yr^{-1}) for the period 1990-2015 (Grechka et al., 2016). Soil type according to soil map of Belgium (OC GIS-Flanders, 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. "DBH": diameter at breast height. "x": field included in at least one of the sampling years for the corresponding research topic. c) Research topics studied on each field and crop rotation. "NA": no measurements conducted.

a)

Location	Coordinates	Annual mean temp. C°	Annual mean precip. mm yr^{-1}	Soil type	WRB Soil group	Estimated year of plantation	Height (m)	DBH (m)	Aspect	Distance from tree stem to first sowing line (m)
Populus x Canadensis										
Sint Pieters-Leeuw 1	50°47'74"N 4°12'41"O	10.3	787.9	Acp	Luvisol	2001	16.7	0.29	W	1.7
Sint Pieters-Leeuw 2	50°47'45"N 4°12'37"O	10.3	787.9	Acp	Luvisol, Cambisol	2001	17.4	0.34	NW	2
Haut-Ittre 1	50°38'19"N 4°17'51"O	9.8	836.0	Aba, Abp	Luvisol, Cambisol	2000	21.5	0.45	E	2.5
Maarkedal	50°49'14"N 3°40'15"O	10.1	752.1	Abp, Adp	Cambisol	1998	26.3	0.59	W	1.7
Tongeren	50°45'14"N 5°26'15"O	9.5	842.3	Aba, Abp	Luvisol, Cambisol	1998	26.7	0.60	E	2.5
Landen	50°43'50"N 5°05'40"O	9.8	814.1	Abp, Ahp	Cambisol, Gleysol	1994	32.3	0.60	NW	1.7
Ieper 1	50°52'47"N 2°47'58"O	10.1	679.4	Lca	Luvisol	1985	27.0	0.73	W	1.7
Geraardsbergen	50°44'11"N 3°56'56"O	10.2	775.5	Aba	Luvisol	1988	33.1	0.70	W	2.5
Herzele	50°52'1"N 3°54'20"O	10.0	784.9	Aba, Aca	Luvisol	1977	33.4	0.69	E	1.7
Steenhuize	50°49'51"N 3°55'2"O	10.1	781.0	Aba	Luvisol, Cambisol	1985	29.9	0.76	NE	2.7
Ieper 2	50°52'37"N 2°47'38"O	10.1	679.4	Lca, Ldc	Luvisol	1969	31.2	0.88	E	3
Juglans regia										
Tielt Winge 1	50°55'01"N 4°53'52"O	9.7	828.1	Lca	Luvisol	1947	12.65	0.47	W	2.7
Tielt Winge 2	50°55'01"N 4°54'00"O	9.7	828.1	Lca	Luvisol	1947	12.85	0.41	E	2.7

b)

Location	**Coordinates**	**Annual mean temp. C°**	**Annual mean precip. mm yr^{-1}**	**Soil type**	**WRB Soil group**	**Tree species**	**Year of plantation**	**Orientation**	**Interrow Distance (m)**	**Intra-row distance (m)**	**Tree row width (m)**
Vollezele	50°45’43”N 4°3’13”O	10.0	802.5	Aba	Luvisol	*Prunus avium*	03/2010	NS	54	8	2
Lochristi 1	51°6’32”N 3°49’49”O	10.2	755.8	Sdb, Zdb	Cambisol, Arenosol	*Populus* sp.	03/2011	EW	26	8	2
Lochristi 2	51°6’41”N 3°49’47”O	10.2	755.8	Zdh	Anthrosol	*Prunus avium*	03/2011	EW	26	8	2
Haut-Ittre 2	50°38’54”N 4°17’48”O	9.8	836.0	Aba	Luvisol	*Juglans regia &* *Sorbus torminalis*	11/2011	NS	28	8	2
Haut-Ittre 3	50°38’37”N 4°17’40”O	9.8	836.0	Aba, Lba	Luvisol	*Juglans regia &* *Sorbus torminalis*	11/2011	NS	28	8	2
Lochristi 3	51°5’35”N 3°48’13”O	10.2	755.8	Zdh	Anthrosol	*Juglans regia*	12/2012	EW	26	8	2

c)

Location	Soil characteristics	Arthropod presence	Crop Yield & Quality	Crop 2015	Cover crop	Crop 2016	Cover crop	Crop 2017	Tree strip management
Populus x Canadensis									
Sint Pieters-Leeuw 1	x	x	x	Maize	fallow	NA	NA	NA	extensive
Sint Pieters- Leeuw 2	x	-	x	Winter wheat	Yellow mustard	Maize	Winter wheat	Winter wheat	extensive
Haut-Ittre 1	x	x	x	Winter wheat	Yellow mustard	Cichorei	Winter wheat	Winter wheat	extensive
Maarkedal	x	x	x	Maize	Ryegrass	Maize	Ryegrass	Potato	extensive
Tongeren	x	x	x	Winter wheat	Yellow mustard	Maize	Winter wheat	Winter wheat	extensive
Landen	x	-	-	Winter wheat	Yellow mustard	NA	NA	NA	extensive
Ieper 1	x	x	x	Maize	Mixture	Maize	Fallow	Bean	grazing
Geraardsbergen	x	x	x	Winter barley	Yellow mustard	NA	NA	NA	extensive
Herzele	x	x	x	Maize	Winter wheat	Winter wheat	Yellow mustard	Maize	grazing
Steenhuize	x	x	x	Maize	Winter wheat	Winter wheat	Ryegrass	Maize	extensive
Ieper 2	x	-	x	Winter barley	Ryegrass	Maize	Fallow	Potato	extensive
Juglans regia									
Tielt Winge 1	x	x	x	Winter wheat	Winter triticale	Winter triticale	Yellow mustard	Sugar beet	mowing
Tielt Winge 2	x	x	x	Winter wheat	Winter barley	Winter barley	Yellow mustard	Maize	mowing
Young alley cropping									
Vollezele	x	x	x	Winter barley	Yellow mustard	Potato	Winter wheat	Winter wheat	extensive
Lochristi 1	x	x	x	Maize	Winter wheat	Winter wheat	Yellow mustard	Maize	extensive
Lochristi 2	x	x	x	Maize	Fallow	Maize	Fallow	Potato	extensive
Haut-Ittre 2	x	x	x	Winter wheat	Winter barley	Winter barley	Yellow mustard	Potato	extensive
Haut-Ittre 3	x	x	x	Maize	Winter wheat	Winter wheat	Winter wheat	Winter wheat	extensive
Lochristi 3	x	x	x	Winter wheat	Yellow mustard	Maize	Fallow	Maize	extensive

1.5 Appendix

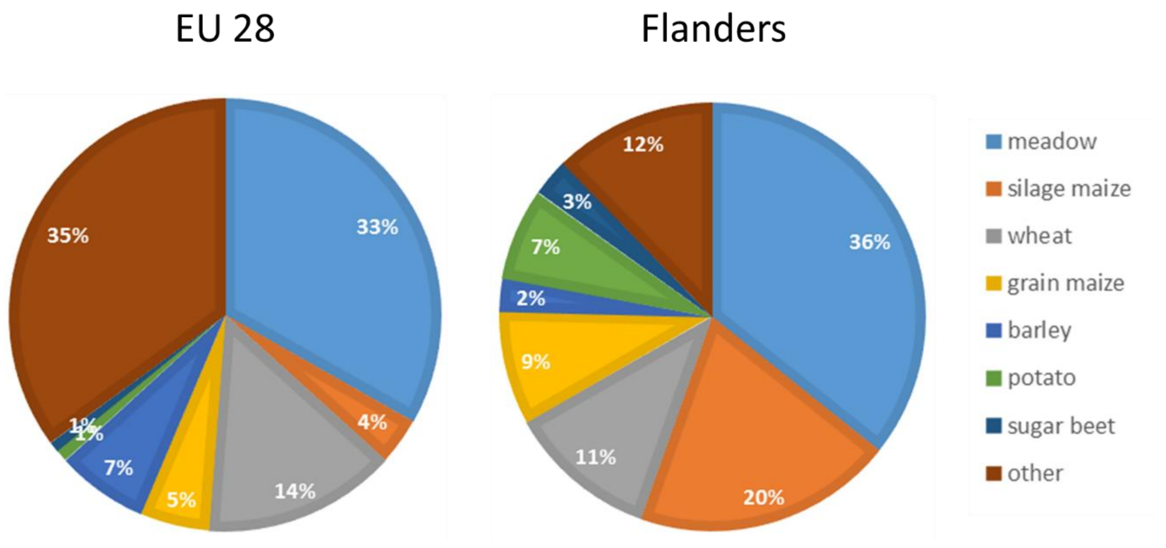
1.5.1 Appendix 1.1

Countries with regions included in the study of evolutions in crop yield by Moore and Lobell (2015).

Crop	Countries included
Wheat	Belgium, France, Germany, Greece, Ireland, Italy, Luxembourg, Netherlands, Portugal, Spain, UK.
Maize	Belgium, France, Germany, Greece, Italy, Netherlands, Portugal, Spain.
Barley	Belgium, France, Germany, Greece, Ireland, Italy, Luxembourg, Netherlands, Portugal, Spain, UK.
Sugar beet	Belgium, France, Germany, Greece, Italy, Netherlands, Spain, UK.

1.5.2 Appendix 1.2

Share of main (arable) crops relative to the total agricultural land use area for the EU-28 (left) and Flanders (right) (Eurostat, 2017b; FAOstat, 2018; L&V, 2016).



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

After: Pardon P., Reubens B., Reheul D., Mertens J., De Frenne P., Coussement T., Janssens P., Verheyen, K. 2017. Trees increase soil organic carbon and nutrient availability in temperate agroforestry system. Agric. Ecosyst. Environ. 247, 98-111.

2.1 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.

2.2 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 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., 2000a). 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 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., 2012b) 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., 2016; 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., 2000a; 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.

2.3 Material and methods

As described in 1.4, 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 11 arable fields (partially) bordered by a row of high-pruned trees of moderate to older age (15-47 years) was selected as a proxy ("boundary planted fields") (cf. Nair et al., 2009; Torquebiau, 2000; Young, 1989). 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), as described in Table 1.1. The prevailing wind direction (1981-2010) is South-Southwest (KMI, 2016). Fields were managed as described higher (1.4).

2.3.1 Soil sampling

Boundary planted fields

At each experimental site and perpendicular to the tree row and to the treeless border, 3 and 2 transects were installed, respectively (Figure 2.1). Each transect consisted of 5 rectangular sampling plots (1.5 m x 6 m), the centre of which was located at distances 2 ("A"), 5 ("B"), 10 ("C"), 20 ("D") and 30 ("E") m away from the tree row/treeless 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 abovementioned plots were omitted for further analyses.

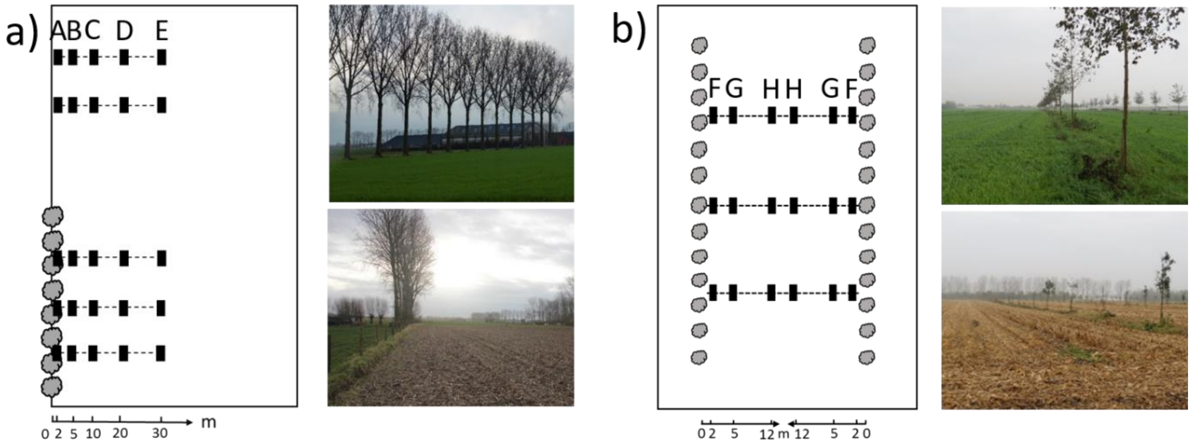


Figure 2.1: Location of soil sampling points in the boundary planted (left) and alley cropping (right) fields. The black rectangles denote locations where samples were collected.

Alley cropping fields

In each field, 3 transects were laid out between and perpendicular to both selected tree rows (Figure 2.1). At each location and along each transect, soil samples were collected once between December 2015 and January 2016 in rectangular sampling plots (1.5 x 6 m) up to 23 cm depth. Each transect consisted of 6 sampling plots, the centre of which was located at distances 2 (“F”), 5 (“G”) and 12 (“H”) 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.

2.3.2 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).

Equation 1:

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

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).

2.4 Results

2.4.1 Boundary planted fields

Table 2.1: 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=alog_{10}(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*

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 2.1, Figure 2.2). 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, although this effect was not consistently observed on all fields (Table 2.2, Appendix 2.1). 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 11.8 g (kg dm)$^{-1}$ 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 13.5 g (kg dm)$^{-1}$, 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 2.2).

Table 2.2: 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- (ton ha^{-1}) and soil nutrients stocks (kg ha^{-1}) along the evaluated transects (i.e. between a distance of 2 and 30m 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 (0-23cm) 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	45.1	39.8
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

Significant values of $r_s$intercept were found for SOC, N, Na, and K (Table 2.3). Differences in soil concentration of these variables between the AFS and control situation increase as tree-size increases (Appendix 2.2). 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 30m to the tree row as tree size increases. Neither $r_s$slope nor $r_s$intercept were significant for Mg.

Table 2.3: 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 30m to the tree row as tree-size increases. Bold characters indicate significant effect (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**

2.4.2 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 2.4, Appendix 2.2).

*Table 2.4: 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*log$_{10}$(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*

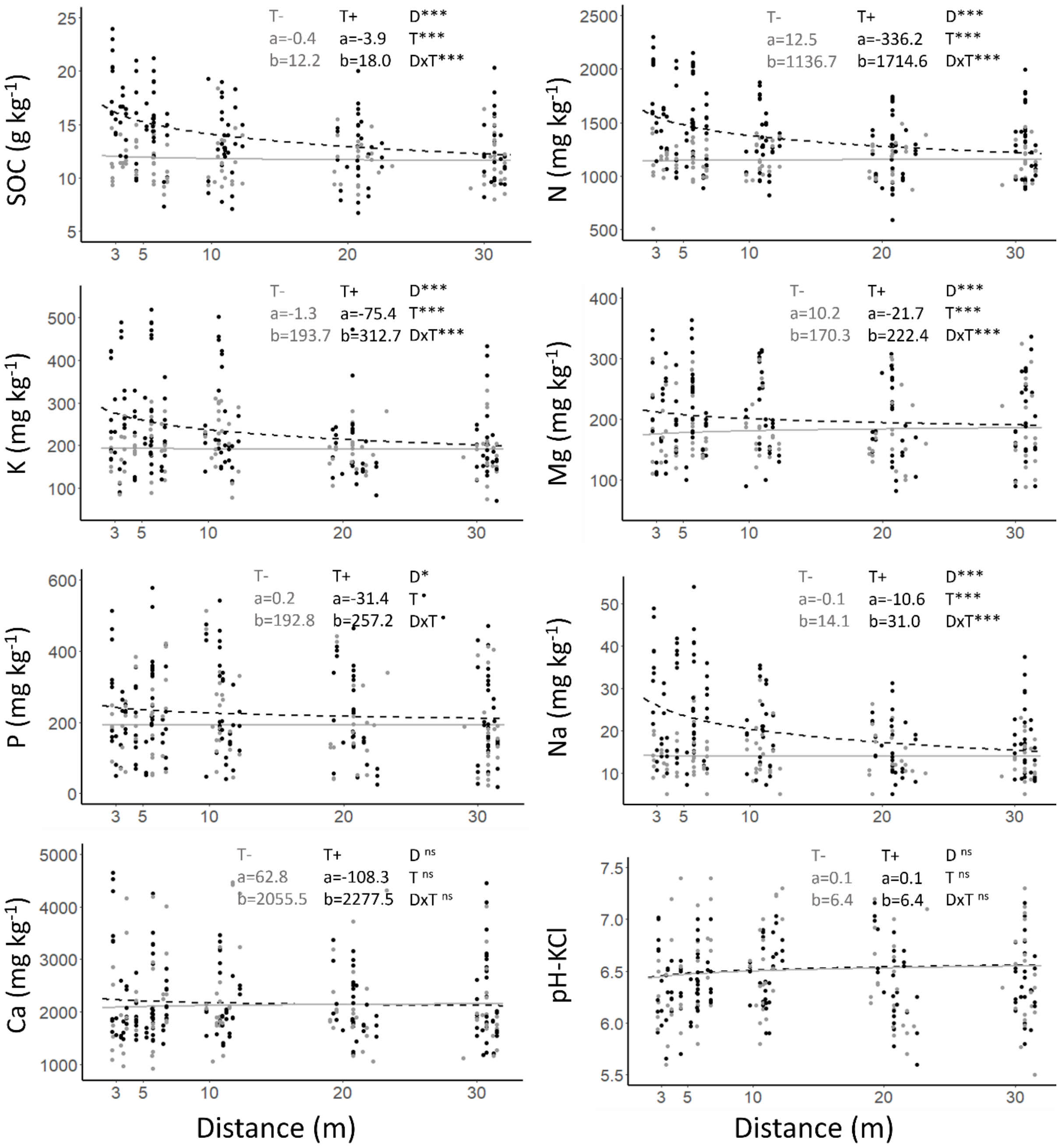


*Figure 2.2: Soil characteristics as function of distance (m) to tree row and/or treeless field edge. Lines according to linear mixed modeling results, black (dashed): tree row, grey: control zone. Model formula: Y= a*log (distance in m) +b. Significance of fixed effects: ˙P <0.1,*P <0.05,**P <0.01 and ***P <0.001, "D": distance, "T": Tree row presence, "DxT": interaction.*

2.5 Discussion

Based on the experimental design and the significance of the interaction 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.

2.5.1 Soil organic carbon and nutrient availability in AFS

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 equaled 10.2 ± 0.12 (S.E.) close to the tree row and 10.2 ± 0.17 in the control transects (Appendix 2.1), 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 2.3).

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 & 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 SAF.

2.5.2 Processes affecting carbon input in AFS

As often argued in studies investigating SOC in AFS (Bambrick et al., 2010; Cardinael et al., 2016; 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 2.3, a yearly leaf litterfall of 214 g m^{-2}, which seems consistent with literature (e.g. Wotherspoon et al., 2014; 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 1.1a), this would result in the observed total increase of 5.3 tons. 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.

2.5.3 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, as also described further (chapter 4), an altered crop development and/or a possible reduction in grain production up to 96% 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).

2.5.4 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. Moreover, although the general effect indicates increased SOC and soil nutrient concentrations in AFS, this effect may be site-specific whereby on some of the fields only limited effects were observed. It is unclear to which site-specific factors (such as historical field heterogeneities or management activities) these differing effects are linked. In order to implement a field-specific approach, further research would be necessary to gain insight in these causal factors. 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, and 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, several of these difficulties may be overcome through the development and use of adapted fertilisation software applications that take (changing) field-specific nutrient-gradients into account.

2.6 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 30m 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.

2.7 Appendix

2.7.1 Appendix 2.1

A) Boundary planted fields: observed minimum (“Min.”), maximum (“Max.”), mean value and standard error (“Mean ± S.E.”, based on integration of LMM effect relations) and ratio of standard deviation to the mean 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) $^{-1}$.

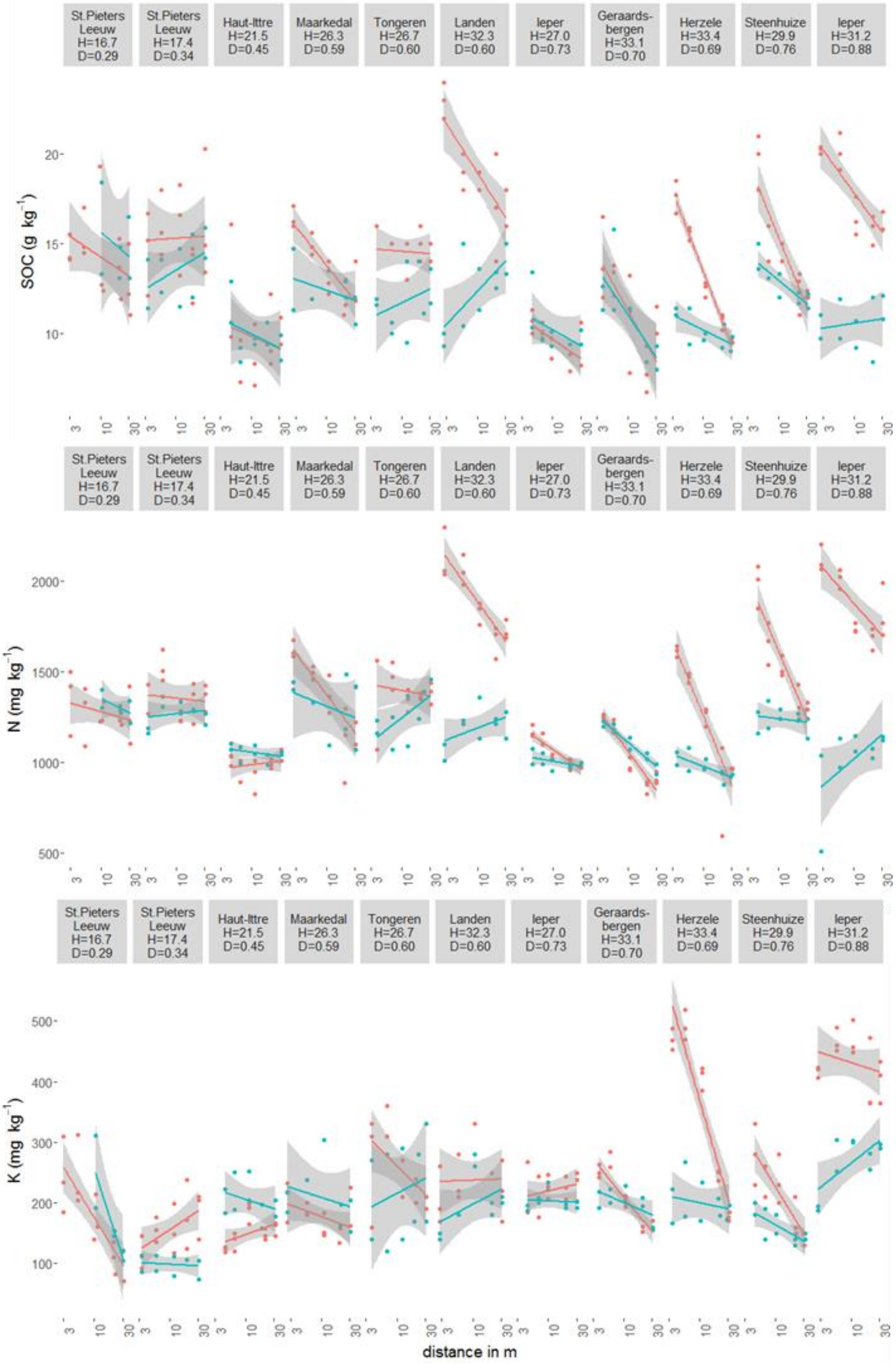
		Min.	Max.	Mean ± S.E	S.D.: Mean	2 m	5 m	10 m	20 m	30 m
SOC	T+	6.7	24.0	13.5±1.2	0.26	16.8	15.2	14.0	12.9	12.2
	T-	8.0	18.4	11.8±1.5	0.18	12.0	11.9	11.8	11.6	11.6
N	T+	593.3	2300.0	1335.8±101.2	0.25	1613.4	1479.6	1378.4	1277.2	1218.0
	T-	506.1	1460.0	1150.7±120.5	0.14	1140.4	1145.4	1149.1	1152.9	1155.1
K	T+	71.5	518.0	227.7±35.7	0.43	290.0	260.0	237.3	214.6	201.3
	T-	74.3	330.0	192.2±43.0	0.29	193.3	192.8	192.4	192.0	191.8
Mg	T+	81.6	364.0	197.9±24.5	0.33	215.8	207.2	200.7	194.1	190.3
	T-	88.2	324.4	181.7±17.7	0.31	173.3	177.3	180.4	183.5	185.2
P	T+	19.2	577.5	221.8±47.5	0.57	247.7	235.2	225.8	216.3	210.8
	T-	23.0	513.2	193.0±45.9	0.58	192.9	192.9	193.0	193.0	193.0
Na	T+	7.1	54.0	19.0±3.4	0.52	27.8	23.6	20.4	17.2	15.3
	T-	7.9	32.0	14.0±3.7	0.38	14.1	14.0	14.0	14.0	14.0
C:N	T+	7.8	18.5	10.2±0.7	0.15	10.5	10.3	10.2	10.1	10.1
	T-	7.8	21.7	10.1±1.1	0.13	10.4	10.2	10.2	10.1	10.0
Ca	T+	1175.6	4646.7	2155.5±312.6	0.33	2244.9	2201.8	2169.2	2136.6	2117.6
	T-	924.3	4472.1	2126.3±369.9	0.39	2074.4	2099.4	2118.4	2137.3	2148.3
pH-KCl	T+	5.6	7.2	6.4±0.2	0.05	6.4	6.4	6.4	6.5	6.5
	T-	5.5	7.4	6.4±0.2	0.07	6.4	6.4	6.4	6.4	6.5

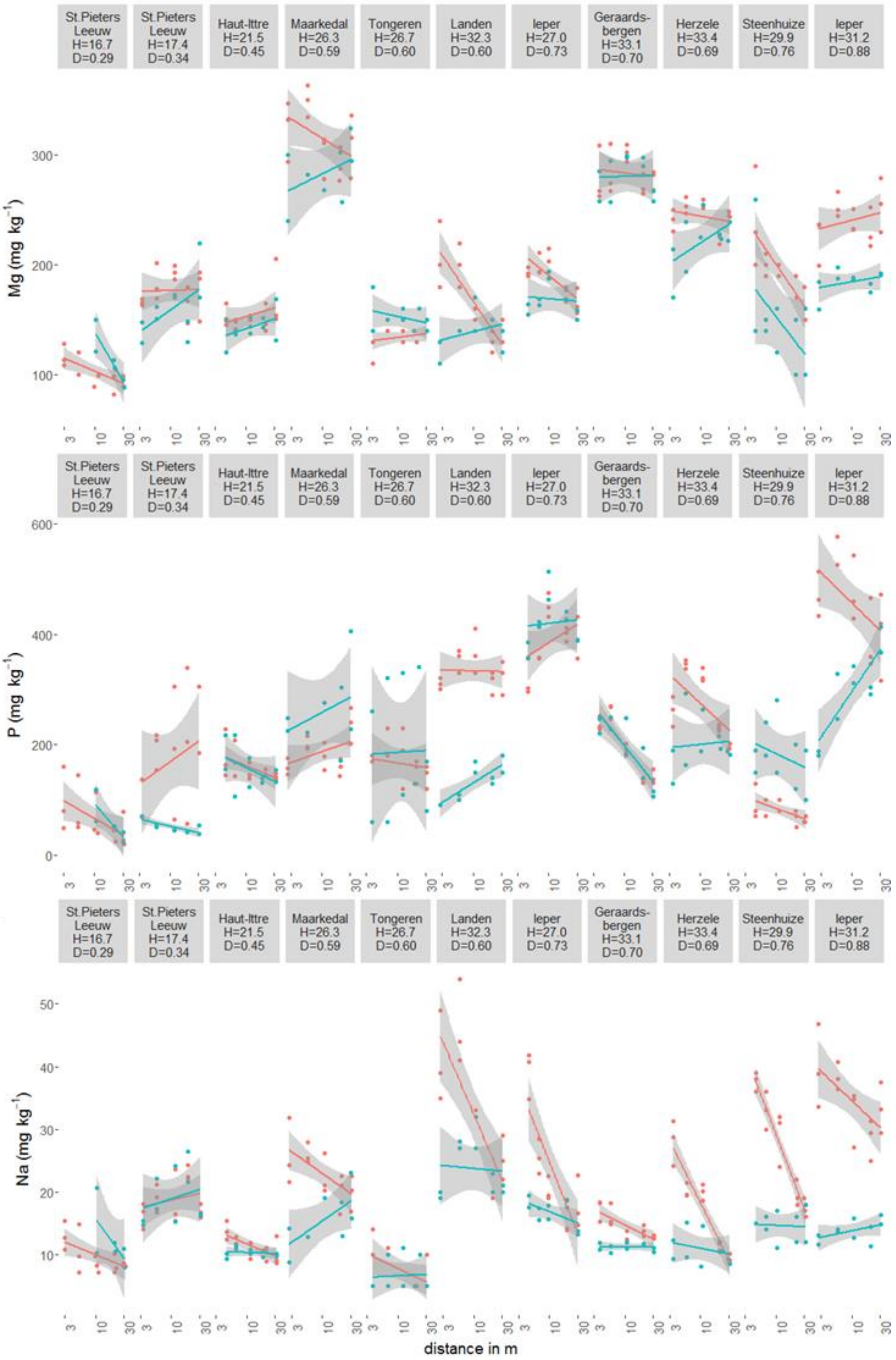
B) Alley cropping fields: mean soil concentration ± S.E. of analysed variables at sampled locations (2m: near tree row, 12m: at centre in between two tree rows). Min. and max. values indicate range of analysed samples. Organic carbon content is expressed in g (kg dm) $^{-1}$, soil nutrient concentrations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

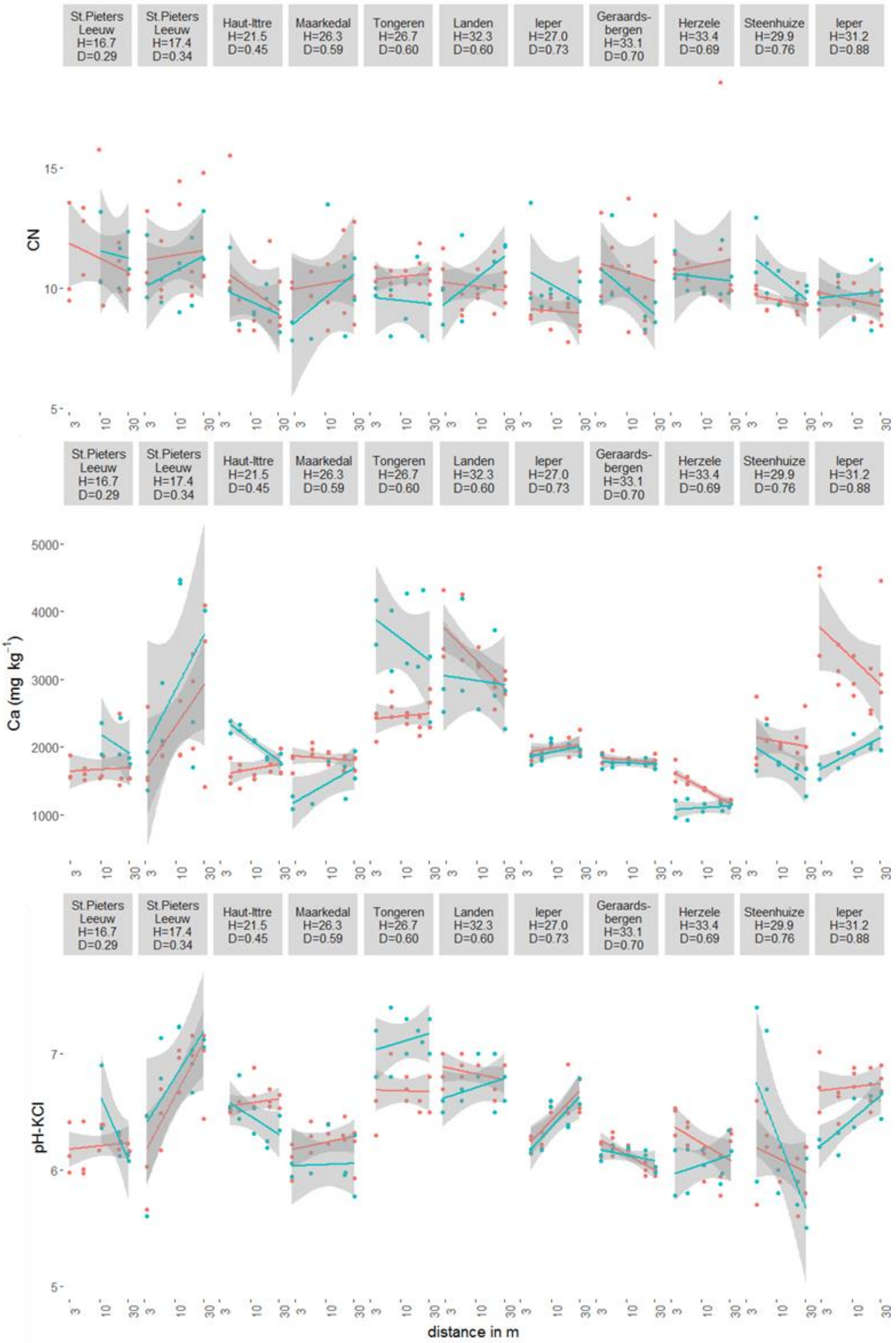
	Min.	Max.	Mean ± S.E		
			2 m (edge)	5 m	12 m (centre)
SOC	7.3	26.0	13.6±0.7	14.1±0.7	13.5±0.7
N	960.0	1750.0	1208.1±30.8	1226.4±36.3	1259.7±41.2
K	70.0	400.0	202.7±13.8	217.0±14.1	217.0±13.5
Mg	50.0	200.0	112.7±5.2	111.8±5.5	112.4±5.0
P	70.0	460.0	243.5±22.5	252.1±23.0	242.3±24.2
C:N	6.8	15.9	11.2±0.4	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

2.7.2 Appendix 2.2

Concentration of analysed variables in upper soil layer of each boundary planted field bordered by Populus x 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).

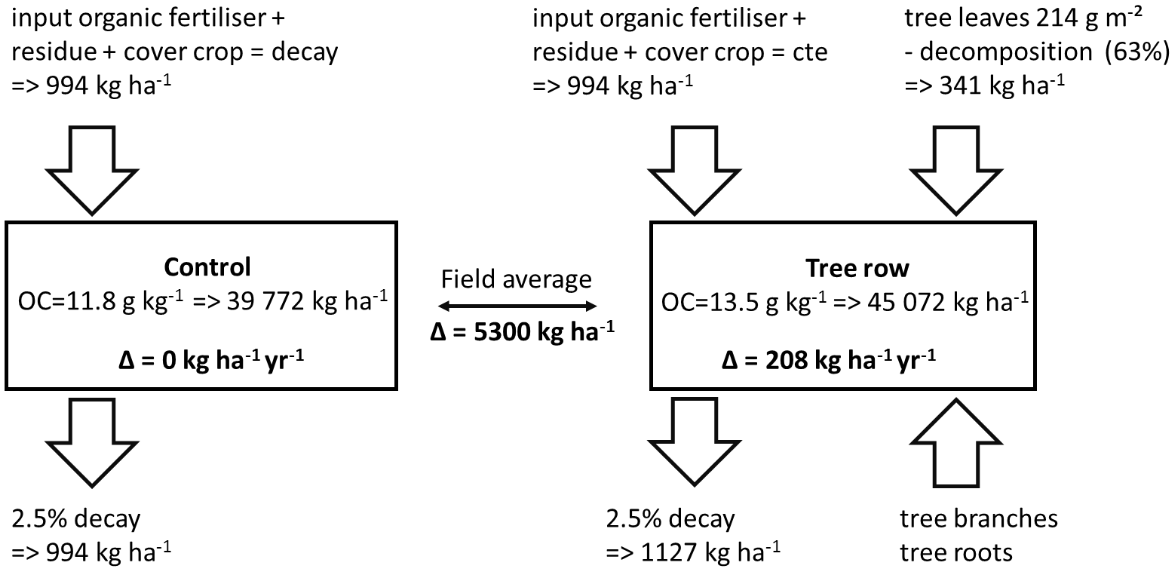



St.Pieters Leeuw H=16.7 D=0.29
St.Pieters Leeuw H=17.4 D=0.34
Haut-Ittre H=21.5 D=0.45
Maarkedal H=26.3 D=0.59
Tongeren H=26.7 D=0.60
Landen H=32.3 D=0.60
Ieper H=27.0 D=0.73
Geraards-bergen H=33.1 D=0.70
Herzele H=33.4 D=0.69
Steenhuize H=29.9 D=0.76
Ieper H=31.2 D=0.88
Mg (mg kg^{-1})
100
200
300
P (mg kg^{-1})
0
200
400
600
Na (mg kg^{-1})
10
20
30
40
50
3
10
30
distance in m


St.Pieters Leeuw H=16.7 D=0.29
St.Pieters Leeuw H=17.4 D=0.34
Haut-Ittre H=21.5 D=0.45
Maarkedal H=26.3 D=0.59
Tongeren H=26.7 D=0.60
Landen H=32.3 D=0.60
Ieper H=27.0 D=0.73
Geraards-bergen H=33.1 D=0.70
Herzele H=33.4 D=0.69
Steenhuize H=29.9 D=0.76
Ieper H=31.2 D=0.88
CN
15
10
5
Ca (mg kg^{-1})
5000
4000
3000
2000
1000
pH-KCl
7
6
5
3
10
30
distance in m

2.7.3 Appendix 2.3

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 1.1a), 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).



3. Gradients in abundance and diversity of ground-dwelling arthropods in temperate silvoarable fields

After: Pardon P., Reheul D., Mertens J., Reubens B., De Frenne P., De Smedt P., Proesmans W., Van Vooren L., Verheyen K., 2018. Gradients in abundance and diversity of ground-dwelling arthropods in temperate silvoarable fields. Agric. Ecosyst. Environ. 270-271, 114-128.

3.1 Abstract

Ground-dwelling arthropods play an important role in agricultural systems by providing multiple ecosystem services (ES); they affect nutrient and carbon cycling and provide biological pest control, among others. The presence of semi-natural landscape features, such as the tree component of agroforestry systems (AFS), may contribute to an increase in functional agrobiodiversity and may optimize the delivery of abovementioned ES in agricultural landscapes. However, potential patterns in abundance and diversity in temperate AFS have hardly been investigated for detritivorous soil-dwelling arthropods and only to a limited extent for predatory arthropods. Therefore we have assessed the abundance and diversity of woodlice (Isopoda), millipedes (Diplopoda), rove beetles (Coleoptera: Staphylinidae) and carabids (Coleoptera: Carabidae) in function of distance to the tree row in a set of temperate arable AFS. Abundance and diversity of woodlice and millipedes was significantly increased in the tree rows. In case of mature trees, this higher abundance of detritivores extended into the nearby arable zone. No consistent beneficial effect of tree presence on abundance of predatory arthropods was observed, although a limited increase in carabid diversity occurred in the arable zone in the close vicinity of the tree rows. These results indicate that the tree component of temperate AFS contributes to the preservation of arthropod biodiversity and the enhancement of associated ES, both in the tree rows and in the nearby arable field zone.

3.2 Introduction

Ground-dwelling arthropods play an important role in agricultural systems by providing multiple ES, such as biological pest control by carnivorous taxa, nutrient and carbon cycling by detritivorous species, etc. (Fischer et al., 2013; Isaacs et al., 2009; Losey and Vaughan, 2006). Within the agricultural matrix, the occurrence of several functionally important taxa of arthropods is strongly linked to the presence of (semi-)natural landscape elements such as hedgerows, tree lines, grassy field margins and small forest patches. These elements provide habitat, reproduction sites, shelter and can act as corridors (Aviron et al., 2005; Bianchi et al., 2006; Garratt et al., 2017; Lee et al., 2001; Smith et al., 2012a; Souty-Grosset et al., 2005). The higher and more diverse arthropod presence in these landscape features may lead to a spillover of these invertebrates into adjoining (arable) farmland, including beneficial detritivorous and predatory ground-dwelling species (Bianchi et al., 2006; Fischer et al., 2013). As a result, decomposition processes (Hopkin and Read, 1992; Smith et al., 2008a) and biological pest control in the neighboring agricultural fields may be enhanced (Bianchi et al., 2005; Garratt et al., 2017; Holland and Luff, 2000).

In Western Europe, however, land-use intensification and agricultural mechanization has led to a homogenization and simplification of the rural landscape, characterized by a strong decrease in the number of hedgerows, small forest patches and permanent grasslands (Burel et al., 2004; Fournier and Loreau, 1999). While increasing use-efficiency and productivity of the area of arable land, this has resulted in a major decline of arthropod abundance and diversity in agricultural landscapes (Matson et al., 1997; Tscharntke et al., 2005). Reversing this trend can either be realized by taking farmland out of production to increase the amount of (semi-)natural landscape elements or by increasing the structural heterogeneity of farmland while preserving the provision of agricultural products (Fahrig et al., 2011; Quinkenstein et al., 2009). The implementation of AFS (Manning et al., 2006; Reisner et al., 2007; Tsonkova et al., 2014) is one such alternative. Alley cropping is a particular type of AFS where trees are planted in rows (“alleys”) across the field. This form of AFS can efficiently be combined with the use of modern farming techniques and machinery for the cultivation of agricultural crops in the intercropping zone between the tree rows. These features make it potentially well-suited to provide permanent habitat within the agricultural fields while maintaining agricultural production (Nerlich et al., 2013; Quinkenstein et al., 2009; Tsonkova et al., 2012).

Torralba et al. (2016), who reviewed the concrete effects of AFS on ES delivery, showed that European AFS generally promote the provision of biodiversity and ES compared to conventional agriculture. However, results were variable, with differences among the types of agroforestry practices and ES assessed. In case of alley cropping systems, the presence of tree rows may result in relatively strong gradients at the field level regarding microclimatic conditions (Jose et al., 2004; Smith et al., 2012b), soil nutrient and carbon-status (Cardinael et al., 2015a; Pardon et al., 2017) and crop development (Artru et al., 2016; Reynolds et al., 2007). This may in turn create gradients in habitat suitability for arthropods (Marrec et al., 2015). In addition, the type of crop grown, together with the varying mobility of different arthropod groups and species, may affect colonization of the field after disturbances such as soil tillage practices, insecticide spraying or crop harvesting (Bianchi et al., 2006; Eyre et al., 2009; Marrec et al., 2015). However, the potentially resulting gradients in abundance and diversity of beneficial ground-dwelling arthropods as function of tree row presence, distance to tree rows and crop type have hardly been quantified in arable agroforestry fields for detritivorous arthropods and to only a limited extent for predatory species.

In the present study we have assessed distribution patterns of key arthropod groups as a function of the distance to the tree rows on arable agroforestry fields in temperate Europe (Belgium). We focus on the abundance and diversity of two taxonomic groups of macro-detritivores, i.e. woodlice (Isopoda) and millipedes (Diplopoda), and two groups of carnivores with potential for natural pest control, i.e., carabids (Coleoptera: Carabidae) and rove beetles (Coleoptera: Staphylinidae). We analyze these patterns in two main crops of temperate Europe, i.e. maize (*Zea mays* L.) and winter cereals (*Triticum aestivum* L. and *Hordeum vulgare* L.). In addition, the effects observed in the proximity of the tree rows are compared with distribution and diversity patterns near to treeless grassy borders in the same agricultural fields. This allows us to quantify the specific effect at field level on arthropod abundance and diversity of tree row presence versus the implementation of (treeless) grass strips as an ecological measure. We hypothesized that (i) higher abundance (expressed as “activity-density”, cf. Thomas et al., 1998) and (ii) diversity of the arthropods are found in the tree rows and in their immediate vicinity compared to further distances. Because tree rows affect environmental conditions (e.g., creation of microclimates) and food availability (e.g., tree litter) quite far into the field, (iii) we expect the arthropod activity-density and diversity to be higher in the field zone near the tree rows compared to the situation near the treeless grassy field margins.

3.3 Material and methods

3.3.1 Study sites

As described higher (1.4), two different types of AFS were studied to analyze the effect of a tree row of contrasting age on the abundance and diversity of woodlice, millipedes, carabids and rove beetles in arable alley cropping fields. Six young arable alley cropping fields were selected to investigate the effects of a recently established tree component (Table 3.1, Figure

3.1a). In addition, a subset of eight boundary planted fields was used as a proxy for older alley cropping fields (Table 3.1, Figure 3.1b). Of the eight selected fields (age 15-41 years), four were located on the western side of the boundary planted tree rows and four on the eastern side. All fields were located in Belgium, with a mean annual temperature of 9.7 °C and a mean annual precipitation of 828.1 mm (Grechka et al., 2016). Fields were managed as described higher (1.4).

Table 3.1: Boundary planted fields and alley cropping fields used for arthropod sampling and the cultivated crops in 2015-2016. "NA": fields not included in the measurements in the corresponding year.

Location	Crop 2015	Crop 2016	Location	Crop 2015	Crop 2016
Sint Pieters Leeuw	Grain maize	NA	Lochristi 1	Forage maize	Winter wheat
Haut-Ittre 1	Winter wheat	NA	Lochristi 2	Forage maize	Forage maize
Maarkedal	Grain maize	Grain maize	Lochristi 3	Winter wheat	Forage maize
Tongeren	Winter wheat	NA	Vollezele	Winter barley	NA
Ieper	Grain maize	Grain maize	Haut-Ittre 2	Winter wheat	Winter wheat
Geraardsbergen	Winter barley	NA	Haut-Ittre 3	Grain maize	Winter wheat
Herzele	Forage maize	NA			
Steenhuize	Forage maize	NA			

3.3.2 Arthropod sampling

On the young alley cropping fields, two transects were laid out between and perpendicular to both selected tree rows (Figure 3.1a). Each of these transects had seven sampling points, two of which were located within the tree strips ("A"). The others were located at distances 1 ("B") and 5 ("C") m away from the field edge (near both tree rows) and one in the center of the intercropping zone ("D", approximately at 12 m from the field edge). Due to the large interrow distance at the field in Vollezele, additional sampling points were marked at a distance of 12 m to both tree rows. In all of the alley cropping fields, except for Lochristi 3, two control points were marked, located between 18 to 55 m away from the tree rows ("E"). In each boundary planted field, two transects were installed perpendicular to the tree row and to the treeless border (Figure 3.1b). Each transect consisted of four sampling points located in the field border ("F") and at distances 1 ("G"), 5 ("H") and 30 ("I") m away from the field edge.

At each sampling point in both systems, a pitfall trap (9 cm opening diameter, volume 300 ml) was installed during the last week of May 2015, a period when adults of most species from the studied taxa are active. Traps were filled with 200 ml of a 50/50 mixture of propylene glycol (antifreeze) and water with detergent to reduce surface tension. The traps were in place during four weeks and were emptied after two and four weeks (these two samples were pooled). The collected arthropods were stored in 70% ethanol. For each individual trap the total number of woodlice, millipedes, carabid beetles and rove beetles caught was counted. The captured specimens of every taxon, except for rove beetles, were identified to species level. This procedure was repeated in 2016 in all of the young alley cropping fields, except for Vollezele, and in the boundary planted fields Maarkedal and Ieper (planted with a similar crop in 2016 as in 2015; see Table 3.1).

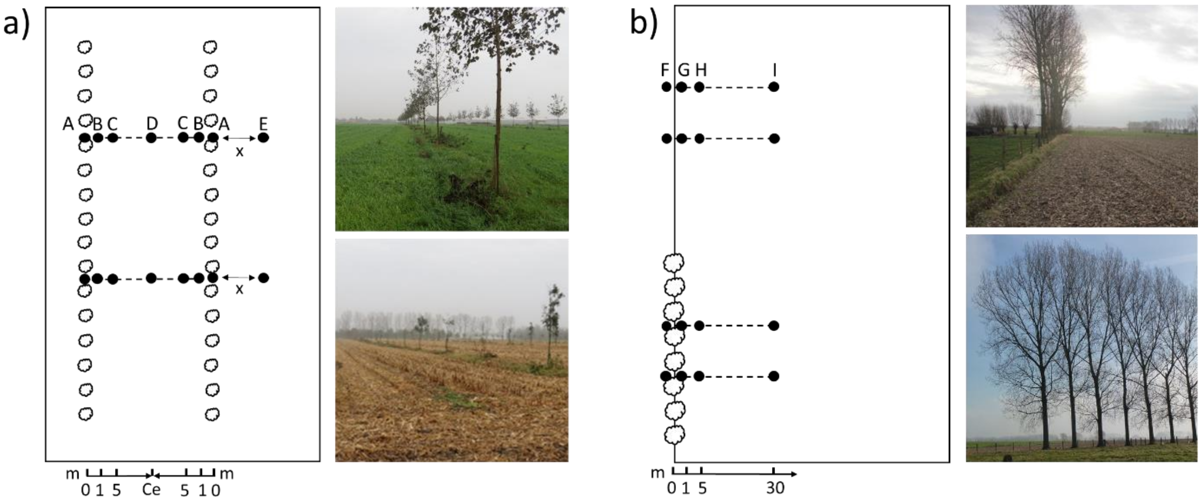


Figure 3.1: Position of pitfall traps in alley cropping (a) and the boundary planted (b) fields. The black dots denote positions where samples were collected."x": distance between nearest tree row and position of the control sample (varying between 18 to 55 m), "Ce": Centre of the intercropping zone.

3.3.3 Data analyses

The occurrence of the arthropod groups under study is described in terms of activity-density, because the number of invertebrates caught in the pitfall traps is a function of both their population density and their activity (Thomas et al., 1998). A generalized mixed effects model with a Poisson error structure was used to investigate differences in activity-density for the young alley cropping fields and the mature boundary planted fields separately. In case of the young alley cropping fields, distance of the sampling plot in relation to the nearest tree row and crop type (maize vs. winter cereals) were included as categorical fixed effects. For the boundary planted fields, the distance in relation to the field edge, crop type and the presence/absence of a tree row were included as fixed effects. 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. To account for this hierarchical structure and non-independence of the data within fields and transects, "field" and "transect" nested within the field were included as random effects for both cropping systems. In addition, the year of sampling was included as a non-nested random effect.

Species richness and the Shannon-Wiener diversity of each sample were calculated separately for woodlice, millipedes and carabid beetles. Generalized mixed effects models with a Poisson error structure and linear mixed effects models were used to analyze differences resulting from tree row-presence and distance in relation to the tree row and/or treeless field edge and crop type for species richness and Shannon-Wiener diversity, respectively. The modeling was performed using the *lme4* package (Bates et al., 2015). In order to identify potential indicator species for the different distances, the Indicator Value (IndVal) index as defined by Dufrêne & Legendre (1997) was calculated. The IndVal index measures the association between a species and the position where it is found. Statistical significance of this association is based on a permutation test (replicated 1000 times). The IndVal analysis was performed using the multipatt function in the indicspecies package (De Caceres and Legendre, 2009). Species comprising less than five individuals in the total dataset of boundary planted or young alley cropping fields were omitted as indicator species. Finally, Nonmetric Multidimensional Scaling (NMDS) was used to visualize multivariate differences in community composition with regard to crop type, distance to the tree row and/or treeless field edge and, in the case of the boundary planted fields, the distinction between the field zone near the tree row and the part near the treeless field edge. All statistical analyses were performed in R version 3.2.5 (R Development Core Team, 2016).

3.4 Results

In the alley cropping fields, a total of 483 woodlice (6 species), 338 millipedes (11 species), 4052 carabids (66 species) and 3911 rove beetles were captured (Appendix 3.1). In the boundary planted fields, a total of 3147 woodlice (6 species), 624 millipedes (14 species), 5099 carabids (60 species) and 3754 rove beetles were sampled. Significant variation in activity-density, species richness and Shannon-Wiener diversity of all arthropod groups under study was found both in the alley cropping fields (Table 3.2) and in the boundary planted fields (Table 3.3).

3.4.1 Detritivorous arthropods: woodlice & millipedes

Alley cropping fields

Activity-density of woodlice and millipedes was significantly affected by the interaction of the distance to the tree rows and the crop type (Table 3.2). Higher detritivore abundance was found in the tree rows as compared to the in-field sampling positions (Figure 3.2), particularly in fields with maize. In the fields with winter cereals, this effect appeared to be less pronounced for woodlice and even absent for millipedes. Species richness and Shannon-Wiener diversity of woodlice and millipedes were significantly affected by distance to the tree rows, with higher values found in the tree rows when compared to the intercropping zone (Table 3.2, Figure 3.2).

Table 3.2: (Generalized) Linear Mixed Modelling results for the alley cropping fields. Included fixed effects are distance to the field edge ("Distance"), crop type ("Crop") and their two-way interaction. Bold characters indicate significant effect (P-value<0.05). (•) indicates 0.05 < P-value < 0.10. "AD"= activity-density, "SR"= species richness, "H"= Shannon-W. diversity.

Main effect:		Distance	Crop	Distance:Crop
Woodlice	*AD*	**<0.0001**	**<0.0001**	**<0.0001**
	SR	**0.0001**	0.1860	0.1174
	H	**<0.0001**	0.7717	0.5887
Millipedes	*AD*	**<0.0001**	0.2469	**0.0005**
	SR	$0.0626^{\bullet}$	0.9878	0.9108
	H	**0.0195**	0.2817	0.6620
Carabids	*AD*	**<0.0001**	**<0.0001**	**<0.0001**
	SR	0.2650	**<0.0001**	0.7423
	H	$0.0770^{\bullet}$	**<0.0001**	0.6532
Rove beetles	*AD*	**<0.0001**	**0.0170**	**<0.0001**

Table 3.3: (Generalized) Linear Mixed Modelling results for the boundary planted fields. Included fixed effects are presence or absence of a tree row ("T+/T-"), distance to the field edge ("Distance"), crop type ("Crop") and their two-way interactions. Bold characters indicate significant effect (P-value<0.05). (•) indicates 0.05 < P-value < 0.10. "AD"= activity-density, "SR"= species richness, "H"= Shannon-W. diversity.

Main effect:		T+T-	Distance	Crop	Distance:T+T-	Distance :Crop	T+T-:Crop
Woodlice	*AD*	**0.0045**	**<0.0001**	0.5349	**<0.0001**	**<0.0001**	0.6556
	SR	**0.0004**	**<0.0001**	0.9077	0.1006	0.1328	0.1209
	H	**0.0017**	**<0.0001**	0.7191	0.1331	0.4350	0.1592
Millipedes	*AD*	$0.0582^{\bullet}$	**<0.0001**	0.6359	0.4185	0.3849	0.6254
	SR	0.1168	**<0.0001**	0.2716	0.9177	0.7458	0.7838
	H	0.3660	**<0.0001**	0.1030	0.9782	0.5259	0.6184
Carabids	*AD*	0.6099	**<0.0001**	0.2178	0.3064	**<0.0001**	0.9820
	SR	0.3468	**0.0013**	0.2042	0.3627	0.2512	0.5209
	H	0.5693	**0.0106**	0.2315	**0.0028**	$0.0540^{\bullet}$	0.8839
Rove beetles	*AD*	**0.0445**	**<0.0001**	**0.0024**	**0.0013**	**<0.0001**	0.5766

Boundary planted fields

Activity-density, species richness and Shannon-Wiener diversity of woodlice and millipedes were significantly affected by distance to the field edge with decreasing values at further distances in the field (Table 3.3, Figure 3.2). In addition, for activity-density, species richness and Shannon-Wiener diversity of woodlice and for activity-density of millipedes, a significant effect of tree presence was found with increased values in and nearby the tree rows when compared to the treeless field edges. No effect of tree row presence on species richness and Shannon-Wiener diversity of millipedes was found. The observed distance-effect of woodlice activity-density was furthermore affected by crop type with rapidly decreasing values at further distances from the field edge in fields with maize, whereas a more gradual decrease was observed in fields with winter cereals (Table 3.3, Figure 3.3).

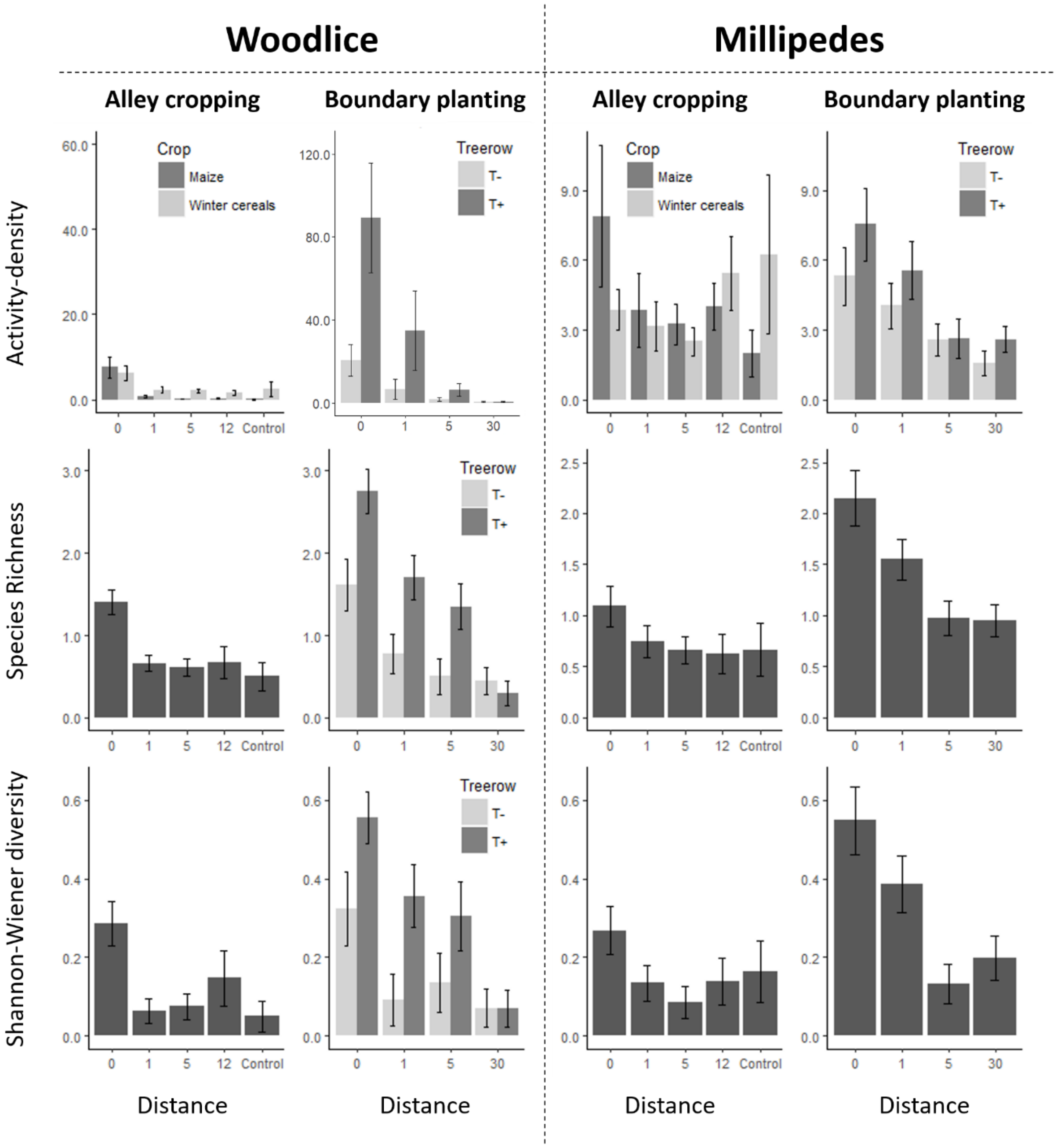


Figure 3.2: Activity-density, species richness and Shannon-Wiener diversity of woodlice and millipedes in alley cropping and boundary planted fields for each level of significant (interactions between) fixed effects. "T+": field edge with tree row, "T-": treeless field edge. Barplots and errorbars indicate mean ± S.E.

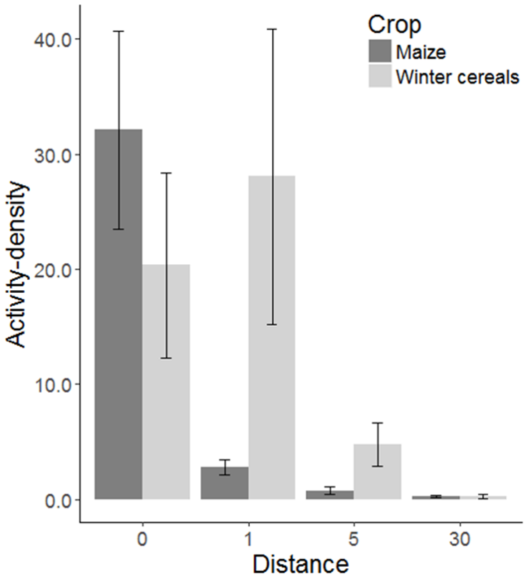


Figure 3.3: Effect of crop type and distance to the field edge on activity-density values of woodlice in the boundary planted fields. Barplots and errorbars indicate mean ± S.E.

3.4.2 Predatory arthropods: carabids and rove beetles

Alley cropping fields

Activity-density of carabids and rove beetles was significantly affected by the interaction of distance to the tree row and the crop type (Table 3.2). Abundance of these predatory arthropods was generally smaller in the tree rows when compared to sampling distances further in the field (Figure 3.4a). In addition, at sampling distances further away from the tree row (control), higher abundances of rove beetles and carabids were observed in the fields with winter cereals when compared to fields with maize. Shannon-Wiener diversity of carabid beetles was slightly higher in and nearby the tree rows (Figure 3.4b). Both species richness and Shannon-Wiener diversity of carabids were increased in the fields with maize when compared to the fields with winter cereals.

Boundary planted fields

The activity-density of the predatory arthropods was significantly affected by the interaction of the distance to the edge and the crop type (Table 3.3). Higher abundance of rove beetles was found in the arable zone when compared to the field edge in the fields with winter cereals (Figure 3.4a). A contrasting effect of the crop type was found for carabid beetles with increased abundance at further distances when compared to the field edge in the fields with maize. For rove beetles, a (limited) tree effect was found with slightly increased abundances near to the tree rows. Species richness of carabid beetles was increased near the field edges but not in the edges themselves (Figure 3.4b). A similar trend in Shannon-Wiener diversity of carabids was found in the arable zone near the tree rows.

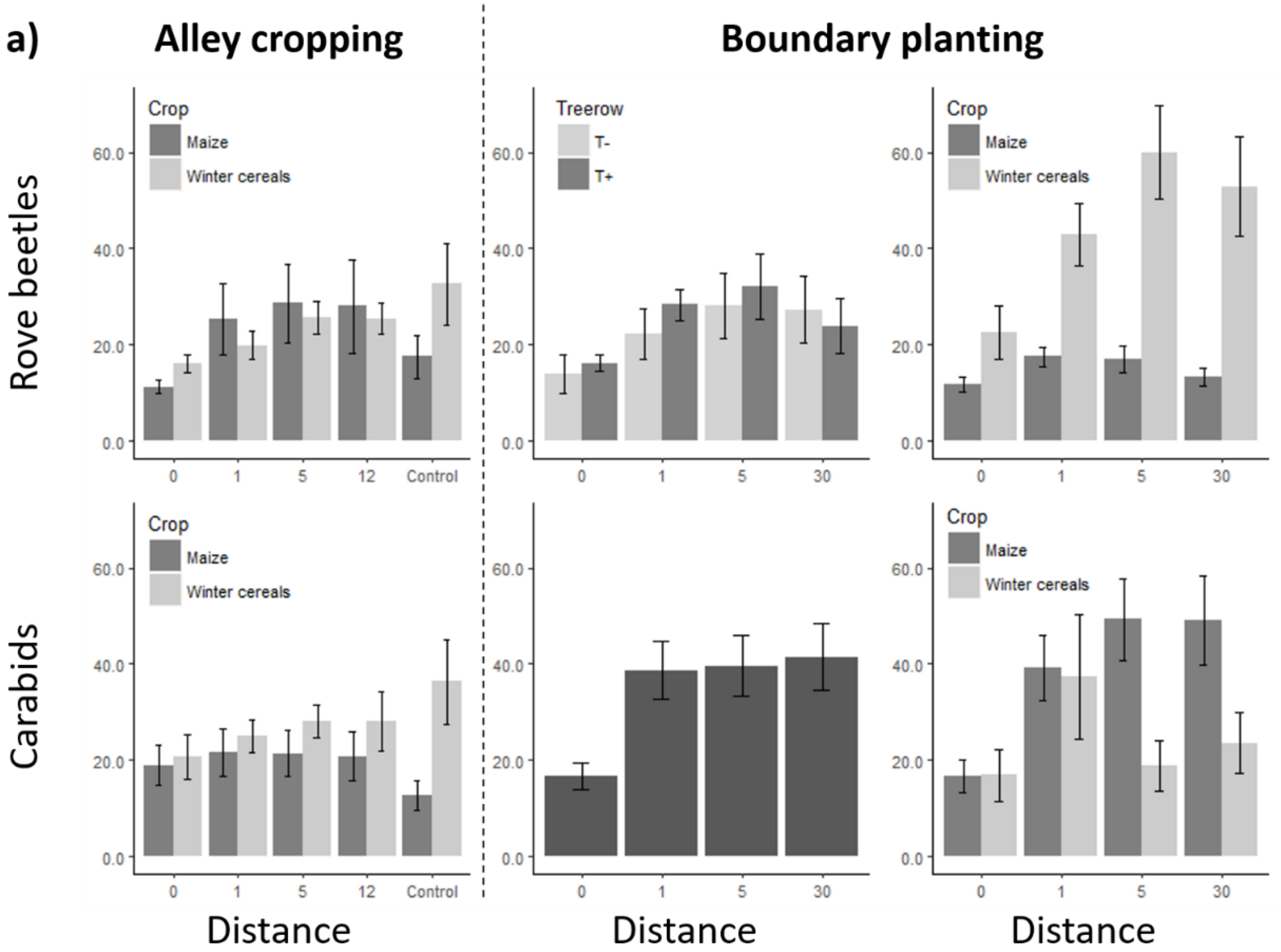


Figure 3.4: a) Activity-density of rove beetles and carabids.

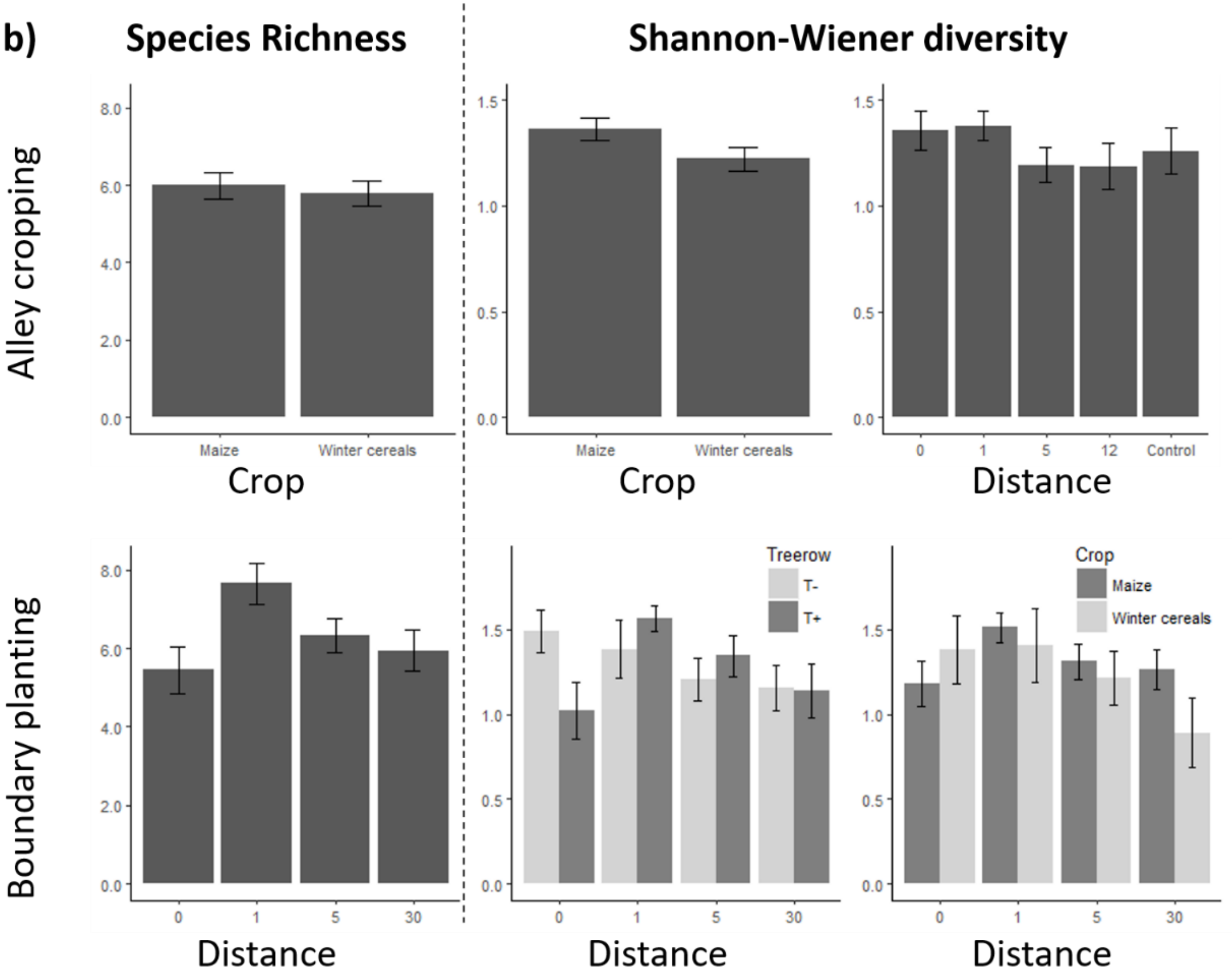


Figure 3.4: b) Species richness and Shannon-Wiener diversity of carabids in alley cropping and boundary planted fields for each level of significant (interactions between) fixed effects. “T+”: field edge with tree row, “T-“: treeless field edge. Barplots and errorbars indicate mean ± S.E.

3.4.3 Indicator species analysis and community composition

Indicator species of carabid beetles were found in the boundary planted fields nearby the treeless field edge as well as in the alley cropping fields at sampling positions of 0, 5 and 12 m from the tree row (Table 3.4). The significance of all indicator species depended on the crop type. No significant indicator species of woodlice or millipedes were found. The influence of crop type on species composition of carabids and woodlice was also indicated by the NMDS plots (Appendix 3.2; 3.3). In addition, an effect of distance to the edge on community composition of woodlice, millipedes and carabids in the boundary planted fields emerges, but this is not the case in the alley cropping fields.

Table 3.4: Indicator species of Carabids in boundary planted fields (T+: field edge with tree row, T-: treeless field edge) and young alley cropping fields. Crop type: (M)= maize, (W)= winter cereals. "n": total number of species-individuals caught in the boundary planted fields or in the alley cropping fields. "ns": not significant.

Distance		*species*	p	n
Boundary planted fields				
T+	0		ns	
	1		ns	
	5		ns	
	30		ns	
T-	0		ns	
	1	*Clivina fossor* (M)	**0.038**	26
		Trechus obtusus (W)	**0.014**	18
		Loricera pilicornis (W)	**0.041**	50
	5	*Bembidion femoratum* (W)	**0.038**	113
	30		ns	
Alley cropping fields				
	0	*Notiophilus biguttatus* (M)	**0.001**	8
	1			
	5	*Bembidion lampros* (M)	**0.002**	326
	12	*Amara familiaris* (M)	**0.048**	5
		Anchomenus dorsalis (W)	**0.047**	552
	Control		ns	

3.5 Discussion

Here we show that tree rows in AFS may create substantial gradients in abundance and diversity of ground-dwelling arthropods. Contrasting trends were found for macro-detritivores and pest predators, with macro-detritivores being more affected by tree presence. However, the observed effects of tree row presence and distance to the trees appeared to be relatively consistent for the alley cropping fields and the boundary planted fields. Although alley cropping and boundary planted fields are two distinct AFS in terms of their spatial design, the tree effects observed in the boundary planted fields with trees of middle- to mature age are expected to be valid for alley cropping systems with older or larger trees as well.

3.5.1 Detritivorous arthropods: woodlice & millipedes

As hypothesized, the observed gradients of woodlice and millipede presence in our study demonstrate the potential of tree rows to increase the abundance of macro-detritivores in arable agroforestry fields, both inside the tree rows and in the nearby arable zone. In addition, similar gradients in detritivore-diversity were observed. The latter may be associated with an enlarged range in litter type processing preference, as well as varying modes of fragmentation, which may facilitate decomposition processes (Heemsbergen et al., 2004; Smith et al., 2008a). As such, this increased detritivore-occurrence is assumed to contribute to the locally augmented soil organic carbon and nutrient concentrations in the arable zone nearby tree rows as observed by Pardon et al. (2017) on the same fields (see chapter 2).

The increased values found in the tree rows are assumed to result from the favorable habitat and refuge conditions (e.g., increased shade, soil and air humidity, food sources and nesting habitat) created by the relatively diverse and permanent presence of vegetation and litter, the absence of regular disturbances and the reduced use of crop protection agents (Dias et al., 2013; Peng et al., 1993; Smith et al., 2008b, 2008a; Souty-Grosset et al., 2005). Strongly contrasting conditions occur in the arable field zone where the agricultural management may cause profound adverse effects on the survival and reproduction of soil communities (Paoletti and Hassall, 1999; Smith et al., 2008b; Souty-Grosset et al., 2005) resulting in the observed decreases in activity-density and diversity.

Based on our results, tree row presence does mitigate the abovementioned decreases in the arable zone, probably through colonization starting from these semi-natural refuges. However, the added value of tree rows when compared to treeless grass margins does appear to differ with macro-detritivore taxonomic group. In the case of woodlice, a clear effect of mature tree rows was observed in the boundary planted fields, with substantially higher abundances and diversity in the arable field zone near the tree rows than inside and near the grassy field edges. The values in these grassy margins are furthermore approximately twice the values observed in the young tree rows in the alley cropping fields. This may be related (i) to the limited time available for colonization of the latter, since woodlice are typically slow dispersers (Woodcock and Pywell, 2009), and (ii) to the limited effect of these trees on microclimatic conditions given their relatively young age and small size. In case of millipedes, however, the increase in activity-density values in and nearby the boundary planted tree rows when compared to the treeless grass edges is relatively limited and even absent in case of species richness and Shannon-Wiener diversity, indicating the overall limited benefit of tree presence for the latter type of macro-detritivores. This discrepancy with woodlice may result from the relatively higher drought-tolerance of millipedes when compared to woodlice (Berg et al., 2008; Dias et al., 2013; Edney, 1977), especially considering the large share of species typical for open habitat types in our dataset, e.g., *Polydesmus inconstans*; *Cylindroiulus caeruleocinctus and Brachyiulus pusillus*, which comprised circa 62% of all millipedes caught (Appendix 3.1). Similarly to woodlice, the increased species richness and Shannon-Wiener diversity of millipedes nearby the edges of the boundary planted fields equal approximately twice the values observed in the recently established alley cropping fields. Considering the slow dispersal speed of millipedes (Hopkin and Read, 1992), this may indicate the importance of the age of semi-natural landscape features for millipede-diversity, rather than the importance of tree row presence.

Besides a colonization effect after field disturbances, the increased abundance and diversity values of woodlice in the arable zone nearby the tree rows might partly result from the mitigation of adverse field conditions by trees, e.g., by increasing the amount of shade (Artru et al., 2016), humidity (Jose et al., 2008) and leaf litter (Wotherspoon et al., 2014). This may promote survival and reproductive success in the arable zone nearby the trees. However, activity-density values in the arable zone near the tree rows were only marginally increased in the maize fields. This may be caused by the more recent field disturbances associated with this crop, which is sown by the end of April, resulting in a shorter period available for colonization starting from the tree rows when compared to fields with winter cereals which are sown in autumn. The limited increase in maize fields, even in the immediate vicinity (1m) of the tree rows, may however indicate that the creation of favorable microclimatic conditions in the arable zone is primarily related to the crop instead of tree-related effects, with the maize being in its early stages of development with little vegetation cover during the period of sampling. This makes it a hostile environment for several taxa of macro-detritivores, which generally favor a relatively damp environment (Smith et al., 2008b; Souty-Grosset et al., 2005).

3.5.2 Predatory arthropods: carabids and rove beetles

Similar to macro-detritivores, carabid and rove beetle abundance in arable fields may be negatively affected by the agricultural management (Kromp, 1999; Thorbek and Bilde, 2004), with the majority of natural enemies depending on non-crop habitats for the provision of hibernation and reproduction sites and alternative prey (Andersen, 1997; Landis et al., 2000). Although increased abundancies of carabids and rove beetles have been noted in woody field margins and the nearby field zone during late spring and/or summer (Dennis and Fry, 1992; Thomas and Marshall, 1999), this was not consistently confirmed in our study. This might indicate that survival and reproduction of predatory arthropods in our research were not negatively affected by the field management in the arable zone. However, several authors have indicated a potential early season redistribution of both carabids and rove beetles from perennial refuges into the field (Dennis et al., 1994; Desender, 1989; Geiger et al., 2009; Pfiffner and Luka, 2000; Riedel, 1991). This movement may be driven by factors such as the presence of higher prey densities in the crop or a preference for open habitat conditions (Fournier and Loreau, 2001; Marrec et al., 2015; Thomas et al., 2002). Further, a large portion of the individuals caught in the present study were species that prefer open habitats, e.g., *Anchomenus dorsalis, Bembidion obtusum, Trechus quadristriatus, Bembidion tetracolum, Pterostichus melanarius* and *Bembidion lampros* (Turin, 2000). In other words, although the presence of tree rows might have resulted in increased populations of natural enemies in the arable zone near the trees, a colonizing movement may have taken place early in the season and may not have been observed during our period of sampling. Therefore, in the future, monitoring would ideally start early after winter to detect potential early colonization movements.

The slightly higher species richness and Shannon-Wiener diversity of carabids observed in the vicinity of the tree rows may result from the presence of both semi-natural and disturbed habitat conditions. This is probably suitable for both open-habitat species as well as forest species (Fischer et al., 2013), resulting in an overall higher diversity. In contrast to woodlice (and millipedes), no consistent crop-type effects were found on carabid abundance. This may be related to the often relatively high mobility of the latter (Lee et al., 2001; Wallin and Ekbom, 1988), which enables fast recolonization of recently disturbed maize fields (Holland and Luff, 2000). Additional explanation might be their higher drought-tolerance when compared to the macro-detritivores, with several species displaying a preference for drier or more exposed habitat conditions (Thiele, 1977).

3.6 Conclusion

We detected strongly increased abundances and diversity of macro-detritivores in SAF. An added value of trees was observed when compared to treeless grass strips, particularly for woodlice. In case of mature trees, these effects extended into the nearby arable zone. Besides augmenting agricultural arthropod biodiversity, this increased detritivore-presence is assumed to enhance decomposition processes and nutrient cycling in arable fields in the vicinity of tree rows.

Although similar gradients in abundance were expected for carabids and rove beetles, this was not observed in our study. This may be related to the time of sampling which, given the high mobility of both carabids and rove beetles, may have been too late to detect potential colonizing movements into the arable zone. A (limited) increase in carabid diversity was, however, found in the immediate vicinity of the tree rows, which may result from the presence of both semi-natural and disturbed habitat conditions.

Farmers may benefit from the enhanced delivery of ES in silvoarable fields linked to the abovementioned increase in abundance and diversity of arthropods (particularly of macro-detritivores). However, to optimize this potential for ES delivery, adapted management might be advisable, e.g., by retaining dead plant material such as pruning residues in the tree rows, striving for a diverse herbaceous composition, and limiting the use of pesticide and herbicides (both in the tree rows and in the arable zone).

3.7 Appendix

3.7.1 Appendix 3.1

List of species sampled in the a) alley cropping fields and b) boundary planed fields for woodlice (Isopoda), millipedes (Diplopoda) and carabids (Coleoptera: Carabidae). Total number of each species caught is given for each sampling distance, crop type and type of field edge in case of boundary planted fields (tree row vs treeless grassy edge). “T+”: field edge with tree row, “T-“: treeless field edge. “C”= control.

a) Alley cropping fields

Isopoda	**Maize**					**Winter cereals**				
Species	**0**	**1**	**5**	**12**	**C**	**0**	**1**	**5**	**12**	**C**
Armadillidium nasatum Budde-Lund, 1885	0	0	0	1	0	0	0	0	0	0
Armadillidium vulgare (Latreille, 1804)	0	0	0	0	0	4	0	0	0	0
Oniscus asellus Linnaeus, 1758	0	0	0	0	0	0	0	0	1	0
Philoscia muscorum (Scopoli, 1763)	69	5	2	1	0	64	30	20	9	7
Porcellio scaber Latreille, 1804	49	31	2	2	1	56	7	13	1	1
Trachelipus rathkii (Brandt, 1833)	14	0	0	2	0	24	19	18	10	20

Diplopoda	**Maize**					**Winter cereals**				
Species	**0**	**1**	**5**	**12**	**C**	**0**	**1**	**5**	**12**	**C**
Brachydesmus superus Latzel, 1884	0	0	0	1	0	1	2	1	2	1
Brachyiulus pusillus (Leach, 1815)	20	19	14	3	1	24	15	11	1	1
Cylindroiulus caeruleocinctus (Wood, 1864)	43	1	0	1	0	17	14	8	7	1
Cylindroiulus punctatus (Leach, 1815)	1	1	0	0	0	1	0	0	0	0
Julus scandinavius Latzel, 1884	1	0	0	0	0	0	0	0	0	0
Leptoiulus kervillei (Brölemann, 1896)	6	0	0	0	0	2	0	0	0	1
Polydesmus coriaceus Porath, 1871	3	1	0	0	1	9	1	7	5	3
Polydesmus denticulatus C.L. Koch, 1847	0	0	0	0	0	1	0	0	0	0
Polydesmus inconstans Latzel, 1884	1	2	6	3	1	7	8	13	23	18
Proteroiulus fuscus (Am Stein, 1857)	1	0	0	0	0	0	0	0	0	0
Tachypodoiulus niger (Leach, 1815)	1	0	0	0	0	0	1	0	0	0

Carabidae	**Maize**					**Winter cereals**				
Species	**0**	**1**	**5**	**12**	**C**	**0**	**1**	**5**	**12**	**C**
Agonum muelleri (Herbst 1874)	3	1	2	1	1	3	5	3	5	1
Amara aenea (DeGeer, 1774)	2	14	4	0	0	22	2	3	2	15
Amara anthobia A. Villa & G.B. Villa, 1833	1	0	0	0	0	0	0	0	0	0
Amara aulica (Panzer, 1796)	1	0	0	0	0	2	1	0	1	0
Amara bifrons (Gyllenhal, 1810)	29	45	13	2	16	0	0	0	0	11
Amara communis (Panzer, 1797)	0	1	0	0	0	0	0	0	0	0
Amara familiaris (Duftschmid, 1812)	1	1	1	2	0	0	0	0	0	0
Amara fulva (Müller, 1776)	0	6	4	2	0	0	0	0	0	0
Amara lunicollis Schiødte, 1837	0	3	0	0	0	0	0	0	0	0
Amara ovata (Fabricius, 1792)	0	3	0	0	0	0	0	0	0	0
Amara plebeja (Gyllenhal, 1810)	25	1	2	0	0	18	4	1	2	0
Amara similata (Gyllenhal, 1810)	3	4	2	0	0	0	0	0	0	0
Amara spreta Dejean, 1831	0	2	0	0	0	5	0	0	0	0
Anchomenus dorsalis (Pontoppidan, 1763)	33	0	2	1	0	47	151	156	92	70
Anisodactylus binotatus (Fabricius, 1787)	0	1	0	0	0	1	0	1	0	0
Asaphidion flavipes (Linnaeus, 1760)	0	0	0	0	0	2	2	0	0	0

Bembidion deletum Audinet-Serville, 1821	0	0	0	0	0	0	0	2	0	0
Bembidion femoratum Sturm, 1825	0	3	2	0	0	0	0	0	0	0
Bembidion lampros (Herbst, 1784)	13	62	100	35	17	14	32	29	16	8
Bembidion lunulatum (Geoffroy, 1785)	0	0	0	0	0	0	0	1	0	0
Bembidion obtusum Audinet-Serville, 1821	2	7	1	2	2	20	7	15	25	4
Bembidion tetracolum Say, 1823	6	19	29	9	16	82	98	72	63	47
Bradycellus harpalinus (Audinet-Serville, 1821)	0	0	1	0	0	0	0	0	0	0
Bradycellus verbasci (Duftschmid, 1812)	1	1	0	0	0	0	0	0	0	0
Calathus fuscipes (Goeze, 1777)	2	1	0	0	1	1	0	1	1	0
Calathus melanocephalus (Linnaeus, 1758)	2	1	1	0	1	2	0	0	0	0
Calathus mollis (Marsham, 1802)	2	1	2	5	1	0	0	0	0	0
Calathus rotundicollis Dejean, 1828	0	0	0	0	0	0	0	0	1	0
Carabus granulatus Linnaeus, 1758	0	0	0	0	0	0	2	0	1	0
Carabus violaceus subsp. purpurascens Fabricius, 1787	8	3	0	0	0	3	3	4	0	2
Clivina fossor (Linnaeus, 1758)	4	14	23	14	7	10	11	12	7	7
Demetrias atricapillus (Linnaeus, 1758)	0	0	0	0	1	1	0	0	0	0
Dyschirius globosus (Herbst, 1784)	3	0	0	0	0	1	1	0	0	0
Dyschirius salinus Schaum, 1843	0	1	0	0	0	0	0	0	0	0
Harpalus affinis (Schrank, 1781)	1	2	2	0	1	7	3	0	0	5
Harpalus attenuatus Stephens, 1828	0	0	0	0	0	0	0	1	0	0
Harpalus distinguendus (Duftschmid, 1812)	1	0	1	0	0	0	0	0	0	0
Harpalus griseus (Panzer, 1796)	1	0	0	0	0	0	1	0	0	0
Harpalus latus (Linnaeus, 1758)	1	0	0	0	0	0	0	1	0	0
Harpalus rufipes (De Geer, 1774)	29	19	9	3	7	9	11	7	3	4
Harpalus tardus (Panzer, 1796)	0	3	0	0	1	1	1	0	0	0
Leistus ferrugineus (Linnaeus, 1758)	2	0	0	0	0	0	0	0	0	0
Leistus fulvibarbis Dejean, 1826	0	0	0	0	0	0	0	1	0	0
Leistus terminatus (Panzer, 1793)	1	0	0	0	0	0	0	0	0	0
Limodromus assimilis (Paykull, 1790)	0	0	0	0	0	2	1	0	1	0
Loricera pilicornis (Fabricius, 1775)	2	0	0	3	0	13	19	13	11	7
Microlestes maurus (Sturm, 1827)	0	0	1	0	0	0	0	0	0	0
Nebria brevicollis (Fabricius, 1792)	7	6	2	0	0	13	4	2	1	2
Nebria salina Fairmaire & Laboulbène, 1854	4	7	7	0	0	14	8	4	1	2
Notiophilus biguttatus (Fabricius, 1779)	7	1	0	0	0	0	0	0	0	0
Notiophilus palustris (Duftschmid, 1812)	0	0	1	0	0	0	0	0	0	0
Notiophilus quadripunctatus Dejean, 1826	2	3	0	0	0	1	4	0	0	1
Ophonus rufibarbis (Fabricius, 1792)	0	1	0	0	0	0	0	0	0	0
Poecilus cupreus (Linnaeus, 1758)	8	0	1	0	0	9	18	16	9	3
Poecilus versicolor (Sturm, 1824)	8	7	2	0	0	1	2	3	3	4
Pterostichus diligens (Sturm, 1824)	3	0	0	0	0	2	4	4	0	0
Pterostichus melanarius (Illiger, 1798)	109	169	165	109	26	119	190	296	112	186
Pterostichus strenuus (Panzer, 1796)	0	1	0	0	0	6	1	0	0	0
Pterostichus vernalis (Panzer, 1796)	7	1	0	1	1	3	3	3	1	3
Stomis pumicatus (Panzer, 1796)	0	0	0	0	0	0	0	1	0	0
Syntomus foveatus (Geoffroy, 1785)	0	1	0	0	2	0	0	0	0	0
Syntomus truncatellus (Linnaeus, 1760)	0	1	1	1	1	0	0	0	0	0
Synuchus vivalis (Illiger, 1798)	0	0	0	0	0	0	1	0	0	0
Tachyta nana (Gyllenhal, 1810)	0	0	2	0	0	4	3	11	5	5
Trechus obtusus Erichson, 1837	4	0	0	0	2	0	0	1	0	0
Trechus quadristriatus (Schrank, 1781)	23	17	25	18	10	20	9	12	28	13

b) Boundary planted fields

Isopoda	**Maize**								**Winter cereals**							
	T+				**T-**				**T+**				**T-**			
Species	**0**	**1**	**5**	**30**	**0**	**1**	**5**	**30**	**0**	**1**	**5**	**30**	**0**	**1**	**5**	**30**
Armadillidium vulgare (Latreille, 1804)	663	69	18	2	56	10	0	2	206	390	14	0	11	19	5	0
Ligidium hypnorum (Cuvier, 1792)	1	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0
Oniscus asellus Linnaeus, 1758	19	4	2	0	24	1	0	0	0	0	0	0	0	2	0	0
Philoscia muscorum (Scopoli, 1763)	173	20	12	1	104	4	3	5	33	76	35	3	18	26	12	1
Porcellio scaber Latreille, 1804	582	35	4	1	44	1	0	2	87	103	36	2	114	54	5	0
Trachelipus rathkii (Brandt, 1833)	0	0	0	0	0	0	0	0	15	2	4	0	4	1	4	0

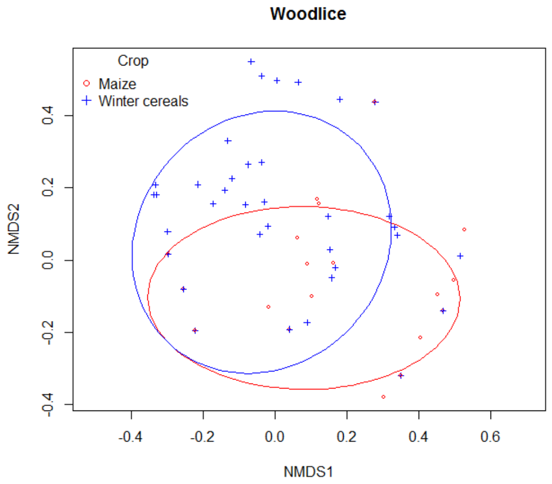
Diplopoda	**Maize**								**Winter cereals**							
	T+				**T-**				**T+**				**T-**			
Species	**0**	**1**	**5**	**30**	**0**	**1**	**5**	**30**	**0**	**1**	**5**	**30**	**0**	**1**	**5**	**30**
Allajulus nitidus (Verhoeff, 1891)	3	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0
Brachydesmus superus Latzel, 1884	0	1	0	0	1	1	0	0	2	0	0	1	0	0	0	0
Brachyiulus pusillus (Leach, 1815)	9	24	5	26	24	21	23	11	3	3	1	7	8	16	13	8
Cylindroiulus caeruleocinctus (Wood, 1864)	24	11	12	0	6	1	0	0	3	2	1	0	1	0	0	0
Cylindroiulus punctatus (Leach, 1815)	2	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0
Julus scandinavius Latzel, 1884	4	2	2	0	1	0	0	0	15	0	0	0	1	0	0	0
Leptoiulus kervillei (Brölemann, 1896)	4	2	0	0	4	0	0	0	4	0	1	0	1	0	1	0
Polydesmus angustus Latzel, 1884	2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Polydesmus coriaceus Porath, 1871	9	5	2	4	3	4	1	0	43	14	12	5	11	6	0	2
Polydesmus denticulatus C.L. Koch, 1847	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
Polydesmus inconstans Latzel, 1884	6	21	14	6	15	9	2	2	8	13	2	2	6	7	4	6
Propolydesmus testaceus C.L. Koch, 1847	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
Proteroiulus fuscus (Am Stein, 1857)	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
Tachypodoiulus niger (Leach, 1815)	5	0	1	1	9	2	0	1	4	11	0	0	5	9	5	0

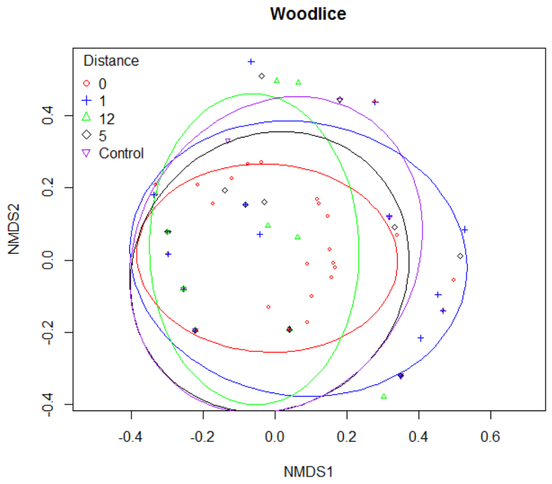
Carabidae	**Maize**								**Winter cereals**							
	T+				**T-**				**T+**				**T-**			
Species	**0**	**1**	**5**	**30**	**0**	**1**	**5**	**30**	**0**	**1**	**5**	**30**	**0**	**1**	**5**	**30**
Acupalpus meridianus (Linnaeus, 1760)	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
Agonum muelleri (Herbst 1874)	2	0	0	11	1	9	3	6	1	0	0	1	1	2	1	1
Amara aenea (DeGeer, 1774)	2	4	4	2	21	11	0	3	14	3	0	3	17	8	1	1
Amara anthobia A. Villa & G.B. Villa, 1833	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Amara familiaris (Duftschmid, 1812)	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0
Amara lunicollis Schiødte, 1837	1	1	0	0	1	0	0	1	0	0	0	0	0	0	0	0
Amara plebeja (Gyllenhal, 1810)	1	1	1	0	3	1	1	0	2	0	0	5	7	4	1	1
Amara similata (Gyllenhal, 1810)	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
Amara spreta Dejean, 1831	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0
Anchomenus dorsalis (Pontoppidan, 1763)	11	8	11	5	26	9	2	1	11	44	35	48	11	63	57	29
Anisodactylus binotatus (Fabricius, 1787)	0	0	0	0	1	0	0	0	0	0	0	0	2	1	0	0
Asaphidion flavipes (Linnaeus, 1760)	2	6	5	1	1	7	0	1	1	1	0	1	2	1	0	1
Badister bullatus (Schrank, 1798)	2	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
Bembidion femoratum Sturm, 1825	2	5	5	13	0	6	5	6	2	16	8	6	2	11	24	2
Bembidion guttula (Fabricius, 1792)	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
Bembidion iricolor Bedel, 1879	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Bembidion lampros (Herbst, 1784)	3	41	67	42	9	96	85	43	1	5	1	0	2	2	2	0
Bembidion lunulatum (Geoffroy, 1785)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1
Bembidion mannerheimii Sahlberg, 1827	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Bembidion obtusum Audinet-Serville, 1821	6	15	32	17	7	11	7	11	8	24	3	2	3	5	8	0
Bembidion properans (Stephens, 1828)	0	0	1	0	0	1	0	1	0	0	0	0	0	0	0	0
Bembidion quadrimaculatum (Linnaeus, 1760)	1	0	3	6	3	2	2	4	0	0	0	0	0	0	0	0
Bembidion tetracolum Say, 1823	14	137	196	98	21	122	169	84	10	15	4	20	5	6	10	6
Calathus melanocephalus (Linnaeus, 1758)	0	0	0	0	2	2	0	0	0	0	0	1	0	0	0	0
Carabus granulatus Linnaeus, 1758	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Carabus problematicus Herbst, 1786	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
Clivina fossor (Linnaeus, 1758)	0	0	4	1	0	9	4	8	0	0	0	0	0	0	0	0
Demetrias atricapillus (Linnaeus, 1758)	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
Diachromus germanus (Linnaeus, 1758)	0	1	0	0	0	1	0	0	0	0	0	0	2	0	0	0
Dyschirius globosus (Herbst, 1784)	1	5	0	4	2	4	4	5	0	0	0	0	0	0	0	0
Harpalus affinis (Schrank, 1781)	0	0	0	1	0	0	0	0	0	0	0	0	4	1	0	0

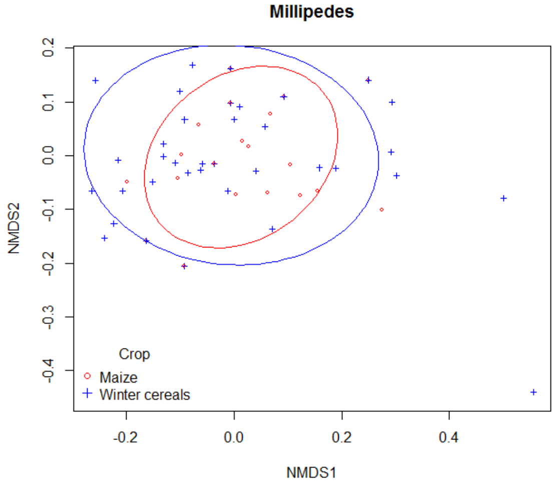
Harpalus latus (Linnaeus, 1758)	2	1	0	0	2	0	0	0	0	1	0	0	0	0	0	0
Harpalus rubripes (Duftschmid, 1812)	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Harpalus rufipes (De Geer, 1774)	4	5	4	3	19	19	7	2	1	1	0	0	5	2	1	3
Harpalus tardus (Panzer, 1796)	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0
Leistus ferrugineus (Linnaeus, 1758)	1	1	1	0	0	0	0	0	0	1	0	0	0	0	0	0
Limodromus assimilis (Paykull, 1790)	2	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0
Loricera pilicornis (Fabricius, 1775)	1	0	0	0	0	2	1	0	8	5	6	5	8	9	3	2
Nebria brevicollis (Fabricius, 1792)	60	48	26	1	21	10	0	0	22	8	0	3	3	1	0	1
Nebria salina Fairmaire & Laboulbène, 1854	10	9	7	1	0	5	1	0	12	6	0	2	2	2	2	4
Notiophilus biguttatus (Fabricius, 1779)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
Notiophilus palustris (Duftschmid, 1812)	1	0	2	1	1	1	0	0	0	0	0	0	0	0	0	0
Notiophilus quadripunctatus Dejean, 1826	1	5	2	4	0	2	0	2	0	0	0	0	1	0	0	1
Ophonus rufibarbis (Fabricius, 1792)	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
Oxypselaphus obscurus (Herbst, 1784)	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
Parophonus maculicornis (Duftschmid, 1812)	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0
Patrobus atrorufus (Ström, 1768)	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Poecilus cupreus (Linnaeus, 1758)	0	1	2	19	3	7	6	6	0	0	0	0	0	0	0	4
Poecilus versicolor (Sturm, 1824)	5	0	2	1	2	2	0	1	0	0	0	0	0	0	0	1
Pterostichus diligens (Sturm, 1824)	0	3	0	0	5	1	0	0	0	0	0	0	0	0	0	0
Pterostichus madidus (Fabricius, 1775)	1	2	0	0	0	0	0	0	0	1	0	0	0	0	0	0
Pterostichus melanarius (Illiger, 1798)	44	122	265	413	55	174	263	363	9	21	16	36	11	12	12	62
Pterostichus strenuus (Panzer, 1796)	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0
Pterostichus vernalis (Panzer, 1796)	0	1	1	0	2	2	2	2	0	0	0	1	0	1	0	0
Stomis pumicatus (Panzer, 1796)	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
Synuchus vivalis (Illiger, 1798)	1	3	2	1	0	0	1	0	0	0	0	0	0	0	0	0
Tachyta nana (Gyllenhal, 1810)	1	31	4	6	2	5	2	4	0	0	0	0	0	0	0	0
Trechoblemus micros (Herbst, 1784)	0	4	0	2	0	0	0	3	0	0	0	0	0	0	0	0
Trechus obtusus Erichson, 1837	0	0	0	1	0	0	1	0	0	1	1	0	2	11	1	0
Trechus quadristriatus (Schrank, 1781)	7	20	48	17	10	13	18	47	7	106	9	4	0	8	17	0

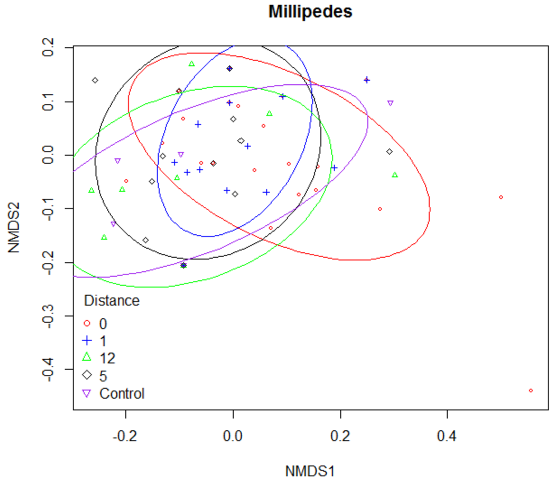
3.7.2 Appendix 3.2

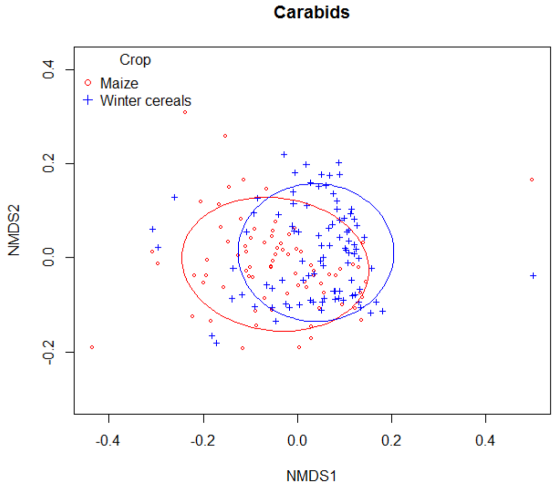
NMDS plots of alley cropping fields for woodlice, millipedes and carabids. Ellipses represent 68% confidence interval. Differences in community composition appear to be primarily determined by crop type for woodlice and carabids and distance to the tree row in case of millipedes.

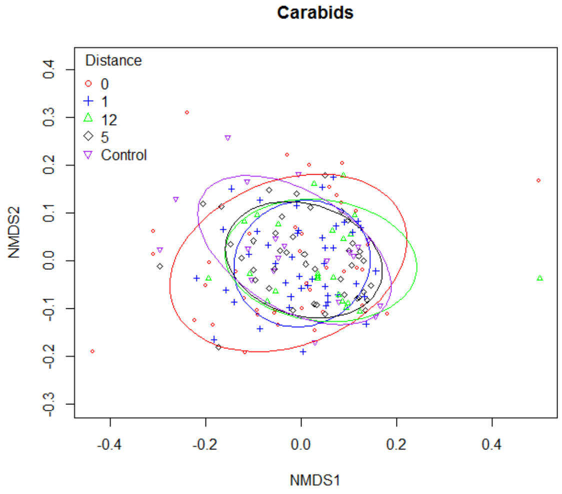






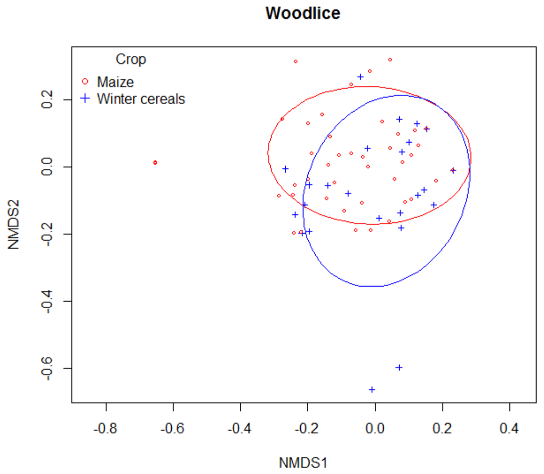


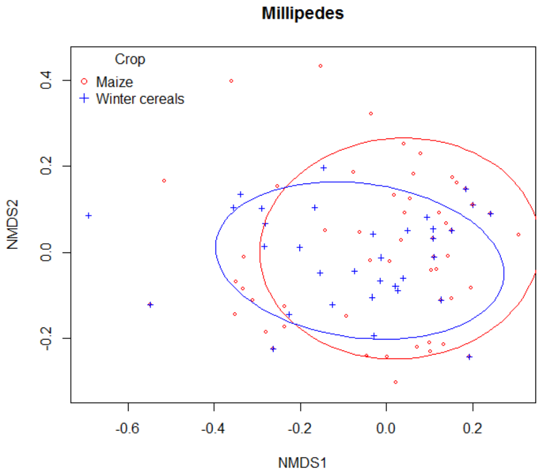


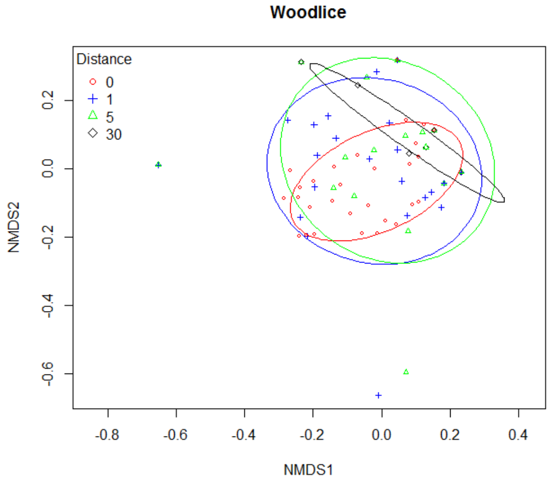


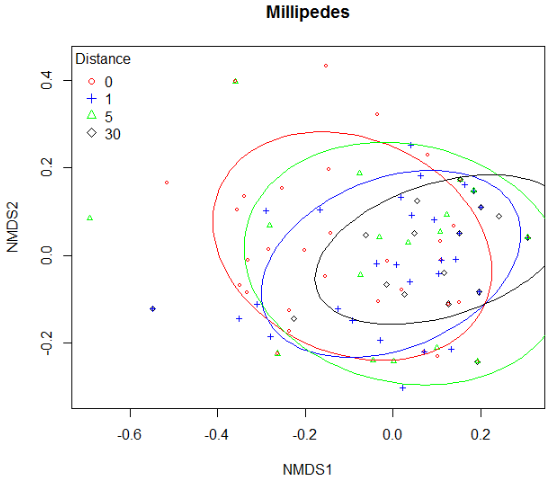
3.7.3 Appendix 3.3

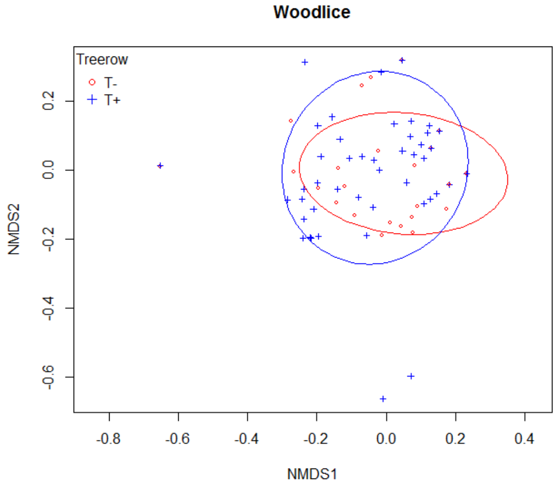
NMDS plots of boundary planted fields for woodlice, millipedes and carabids. Ellipses represent 68% confidence interval. Differences in community composition appear to be primarily determined by crop type and distance to the field edge for carabids, and by distance to the field edge for woodlice and millipedes.

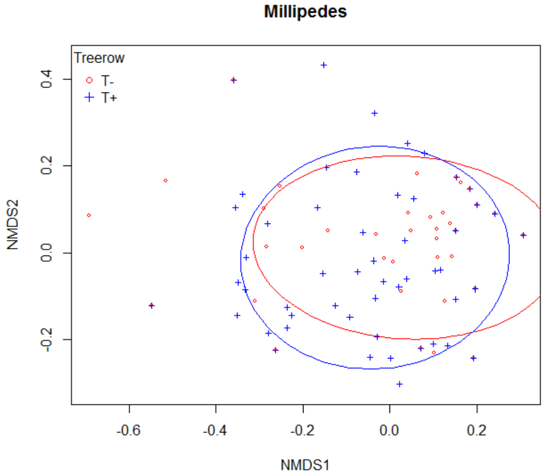


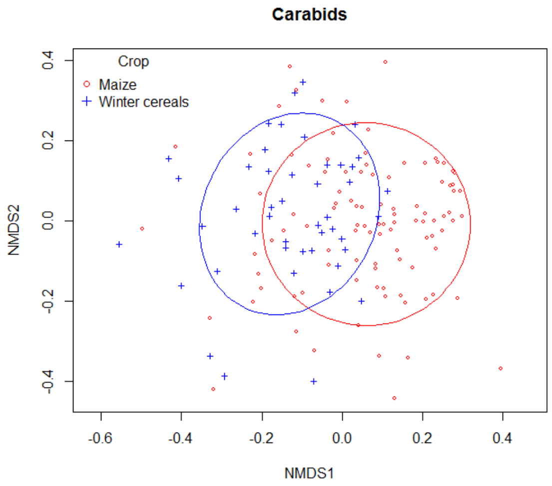


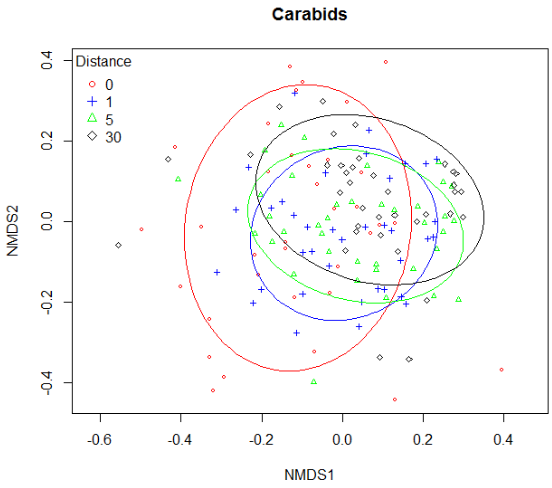


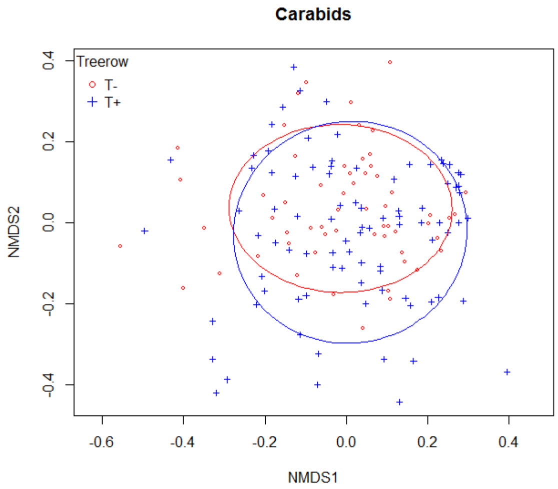







Carabids
Crop
Maize
Winter cereals
NMDS2
NMDS1
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.4
-0.2
0.0
0.2
0.4


Carabids
Distance
0
1
5
30
NMDS2
NMDS1
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.4
-0.2
0.0
0.2
0.4


Carabids
Treerow
T-
T+
NMDS2
NMDS1
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.4
-0.2
0.0
0.2
0.4

4. Effects of temperate agroforestry on yield and quality of different arable intercrops

After: Pardon P., Reubens B., Mertens J., Verheyen K., De Frenne P., De Smet G., Van Waes C., Reheul D., 2018. Effects of temperate agroforestry on yield and quality of different arable intercrops. Agricultural Systems 166, 135-151.

4.1 Abstract

Agroforestry systems (AFS) are considered to be a sustainable agricultural practice, as they deliver a wide range of ecosystem services (ES) while maintaining agricultural primary production. To optimize the productivity of AFS, the recommendation is to use well adapted tree-crop combinations, thereby limiting competition for resources and maximizing synergies. However, yield and quality data on arable crops in temperate AFS are scarce, in particular for AFS with a mature tree component. Here we assessed the influence of tree rows of contrasting growth stage on yield and quality of key western European arable crops. We focused on maize, potato, winter wheat and winter barley during three consecutive years (2015-2017) on a set of 16 arable agroforestry fields in Belgium comprising 6 young (2 to 7 year old) alley cropping fields and 10 fields bordered by a row of deciduous trees of moderate to older age (15 to 48 years old). Both tree size and crop type were key determinants of yield and quality of the investigated arable crops. While effects on crop yield were limited for all crops near young tree rows, substantial yield reductions were observed near mature trees, in particular for maize and potato (both spring crops). Effects on crop quality were limited for all crops under study, with substantial effects only arising near the oldest tree rows. To optimize the provisioning service of AFS, the cultivation of winter cereals may be advisable over maize and potato towards the end of the rotation of an AFS. In addition, poplar trees should be harvested when they reach their target diameter for industrial processing. If tree rows are preserved for the delivery of other ES, however, substantial impacts on crop yield and quality should be taken into account.

4.2 Introduction

In temperate regions, the concept of agroforestry is receiving renewed attention (Borremans et al., 2016; Jose et al., 2004; Nair, 2007; Quinkenstein et al., 2009) because it is considered to be a more sustainable agricultural practice than conventional western European agricultural methods. AFS combine plant production with environmental enhancement and the delivery of ES such as carbon sequestration and erosion control (Smith et al., 2012a; Torralba et al., 2016). As described higher, in particular the practice of alley cropping whereby trees are planted in rows across the field may offer a promising land use alternative (Quinkenstein et al., 2009).

The study of SAF has revealed the existence of multiple potential interactions between trees and intercrops, affecting the availability of resources such as light (Artru et al., 2016; Lin, 2010; Smith et al., 2012a), water (Gillespie et al., 2000; Jose et al., 2004), soil organic matter, and nutrient availability (Cardinael et al., 2015a; Pardon et al., 2017). The occurrence and magnitude of these interactions appear to be strongly linked to the design and management of the AFS, the prevailing environmental conditions (climate, soil type, etc.) and the in-field location (Artru et al., 2016; Jose et al., 2008; Reynolds et al., 2007). This variation in growing conditions, both among and within AFS, may in turn affect the yield and development of the cultivated intercrops.

In most parts of western Europe, maize (*Zea mays* L.), potato (*Solanum tuberosum* L.), wheat (*Triticum aestivum* L.) and barley (*Hordeum vulgare* L.) are the most frequently cultivated arable crops (FAO, 2018; Leff et al., 2004). These crops may exhibit considerable variation in the resources needed, both in space (e.g., rooting depth, leaf area index) and in time (e.g., phenology, time to maturity). As a result, not all of them are equally well adapted for use as an intercrop in AFS. But actual quantitative data about the performance (yield and quality) of these crops in temperate silvoarable (alley cropping) systems is limited (Chauhan et al., 2012; Gillespie et al., 2000; Jose et al., 2008; Luedeling et al., 2016; Tsonkova et al., 2012). This is especially the case for AFS with a mature tree component. To address this research gap, we here empirically assessed the yield and quality of two spring crops (maize, potato) and two winter crops (winter wheat, winter barley) in AFS as function of the distance to the deciduous tree rows on an extended set of 16 SAF fields in temperate Europe (Belgium). We hypothesized i) a reduced yield and ii) altered quality of the intercrop in the immediate vicinity of the tree rows. We furthermore expected that the magnitude of the observed effects and their extent into the field is dependent on iii) the crop type and iv) size class of the tree rows.

4.3 Material and methods

4.3.1 Study sites

As described in 1.4, two types of AFS were studied to analyze the effects of a tree component of varying size on the yield and quality of intercrops in arable alley cropping fields (Table 4.1, Figure 4.1). A subset of 10 boundary planted fields (15-48 years old) was selected as a proxy for older arable alley cropping systems in Belgium. These boundary planted fields were grouped into two size classes. The size class denoted as “fields with middle-aged trees” comprised the fields bordered by a row of trees with a circumference larger than 90 cm (diameter at breast height [DBH] of 28.6 cm) and smaller than 200 cm (DBH of 63.7 cm), which is commonly considered to be the maximum diameter for optimal industrial processing (Oldenburger, 2008).The size class denoted as “fields with long-standing trees” comprised the fields with the oldest tree rows in the dataset with a circumference larger than 200 cm (DBH > 63.7 cm). Although these trees exceed the economically optimal harvest size, they are assumed to be beneficial for several ES (e.g., biodiversity, landscape, etc.). In addition, six young alley cropping fields (2 to 7 years old) were selected to investigate the effect of a recently established tree component. All fields were located in Belgium, with climatic conditions as described in Table 1.1 and field management as described in 1.4.

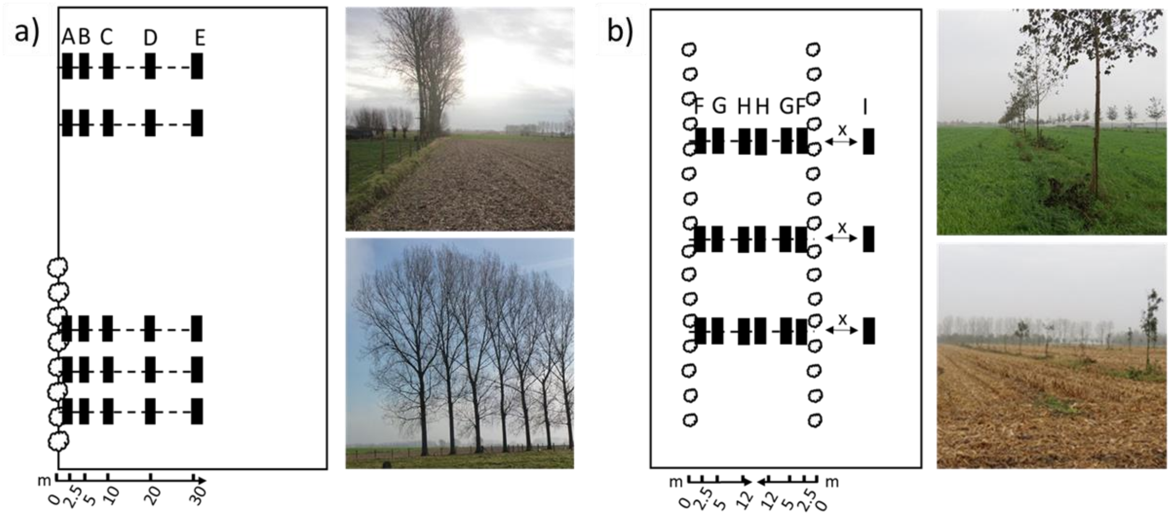


Figure 4.1: Position of the sampling plots in the boundary planted (a) and young alley cropping (b) fields. The black rectangles denote positions where experimental harvests of the crop were conducted. ”x” denotes the distance between the nearest tree row and position of the control point in the alley cropping fields (ranging between 18 to 55 m).

Table 4.1: Boundary planted and alley cropping fields used for the assessment of crop yield and quality and crops cultivated in 2015-2016-2017. "NA": field not included in the measurements of the corresponding year.

Location	2015	2016	2017
Boundary planted fields			
Sint Pieters-Leeuw 1	Grain maize	NA	NA
Sint Pieters- Leeuw 2	Winter wheat	Forage maize	Winter wheat
Haut-Ittre 1	Winter wheat	NA	Winter wheat
Maarkedal	Grain maize	Grain maize	Potato
Tongeren	Winter wheat	Forage maize	Winter wheat
Ieper 1	Grain maize	Grain maize	NA
Geraardsbergen	Winter barley	NA	NA
Herzele	Forage maize	Winter wheat	Forage maize
Steenhuize	Forage maize	Winter wheat	Forage maize
Ieper 2	Winter barley	Grain maize	Potato
Alley cropping fields			
Vollezele	Winter barley	Potato	Winter wheat
Lochristi 1	Forage maize	Winter wheat	Forage maize
Lochristi 2	Forage maize	Forage maize	Potato
Haut-Ittre 2	NA	NA	Potato
Haut-Ittre 3	Forage maize	NA	Winter wheat
Lochristi 3	NA	NA	Grain maize

4.3.2 Crop yield

On each of the boundary planted fields, three and two transects were installed perpendicular to the tree row and to the treeless border, respectively (Figure 4.1a). In each transect, five sampling plots were marked, the center of which was located at distances 2.5 ("A"), 5 ("B"), 10 ("C"), 20 ("D") and 30 m ("E") away from the tree row/treeless field edge. On the young alley cropping fields, three transects were laid out between and perpendicular to both selected tree rows (Fig. 1b). In each transect, six sampling plots were marked, the center of which was located at distances 2.5 ("F"), 5 ("G") and 12 m ("H") from the closest tree row. Three control points ("I") were marked at a distance varying between 18 to 55 m from the tree rows. 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. The location of transects and sampling plots was maintained as strictly as possible throughout the consecutive sampling years as different crops were rotated on the fields.

In each of the sampling plots, crop yield was measured following a crop-specific protocol. On the fields intercropped with maize, every sampling plot consisted of two neighboring maize rows with a total length of 5 m (interrow distance: 0.75 m). In the case of forage maize, plants were cut manually at approximately 10 cm above ground level, after which the whole plants (including foliage, stem and fruits) were weighed and biomass yield per plot was determined. In the case of grain maize, the cobs were threshed using a Wintersteiger combine (type: *NM-elite*). A similar approach was used for potatoes: two neighboring rows over a total length of 5 m/row were harvested manually. After demarcation of the plots (minimal surface per plot of 1.5 x 6.5 m = 9.75 m^2), winter wheat and winter barley were harvested using a Wintersteiger combine and the harvested grain (caryopses) was weighed.

4.3.3 Crop quality

For every plot, a sample of the harvested crop was collected for further quality analyses. Samples were oven-dried at 70 °C to determine the dry matter concentration (%). After grinding, the starch concentration (%) and the organic matter digestibility (OMD) (%) of forage maize and crude protein (CP) concentration (%) of forage maize and winter cereals were determined using Near Infrared Spectroscopy (NIRS). Crude protein yield (kg ha^{-1}) was calculated based on crop yield data and CP concentrations. For starch, the reference method for the NIRS calibration was ISO 6493, for CP concentration ISO 5983-2, and for OMD, the method described in De Boever et al. (1988). Potatoes were sorted according to diameter to determine the harvest fraction with tuber diameter > 35 mm. Underwater weight (UWW, g per 5 kg tubers) was determined on a sample of the 35-70 mm fraction with an *AW-W8 Explorer underwater weigher*.

4.3.4 Data analyses

For each crop, yield and quality were analyzed separately for the three size classes using a linear-mixed effect model (LMM). Distances to field edges were transformed logarithmically to linearize the response variables. In case of the young alley cropping fields, the logarithm of the distance to the nearest tree row was used as a fixed effect. For the boundary planted fields, both the logarithm of the distance to the field edge, the presence/absence of a tree row and their interaction were included as fixed effects. 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. To account for year-related effects and the hierarchical nature and non-independence of the data within fields and transects, “year”, “field” and “transect” nested in “field” were included as random effects for both cropping systems. Average values of crop yield and quality within the measurement zone of the study fields were obtained based on integration of the LMM effect relations, because sampling distances were not homogeneously distributed over the study fields with relatively more measuring points in the vicinity of the tree rows. All analyses were performed using the *lmer* function in the *lme4* package in R (Bates et al., 2015; R Development Core Team, 2016).

4.4 Results

4.4.1 Crop yield

Gradients as function of distance to the tree rows

On the boundary planted fields, significant variation in crop yield was observed for both tree size classes and for all crops under study (Figure 4.2). This can be explained by the interaction between the distance to the field edge and tree row presence. Crop yield decreased closer to the trees. The magnitude of this tree effect and its extent into the field did change with the tree size class and crop type, however. At a distance of 2.5 m from the tree rows on the fields with middle-aged trees, relative yield of forage maize, grain maize, potato and winter wheat equaled 36, 32, 30 and 65% of the yield at a distance of 30 m from the trees (Appendix 4.1 & 4.3). On the fields with long-standing trees, relative yield of forage maize, grain maize, potato, wheat and barley, equaled 4, 26, 27, 59 and 80%, respectively.

On the young alley cropping fields, yields of forage maize, potato and winter wheat were significantly affected by distance to the tree rows (Table 4.2, Figure 4.2). At a distance of 2.5 m from the tree rows, relative yields were respectively 84, 79 and 84% of the yields at a distance of 12 m from the trees (Appendix 4.1 & 4.3).

Overall effects

The overall crop yields in the arable zone near the trees were lower than crop yields in the control zone as a result of the abovementioned gradients (Table 4.2). Between 2.5 m and 30 m away from the field edge, relative average yields of forage maize, grain maize, potato, and winter wheat in the vicinity of middle-aged trees were 86; 78; 76 and 99% of yields in the control zone. On the fields with long-standing trees, relative yields in the vicinity of the tree rows equaled 57; 74; 72; 72 and 91% of yields in the control zone in case of forage maize, grain maize, potato, winter wheat and winter barley, respectively. These reductions in crop yield were ca. 1.5 to 2 times higher than abovementioned values when only considering the zone between 2.5 and 12 m from the trees (except for wheat on the fields with middle-aged trees where this value equals 7.5). However, the effects of the crop type and age class remained similar (Table 4.2).

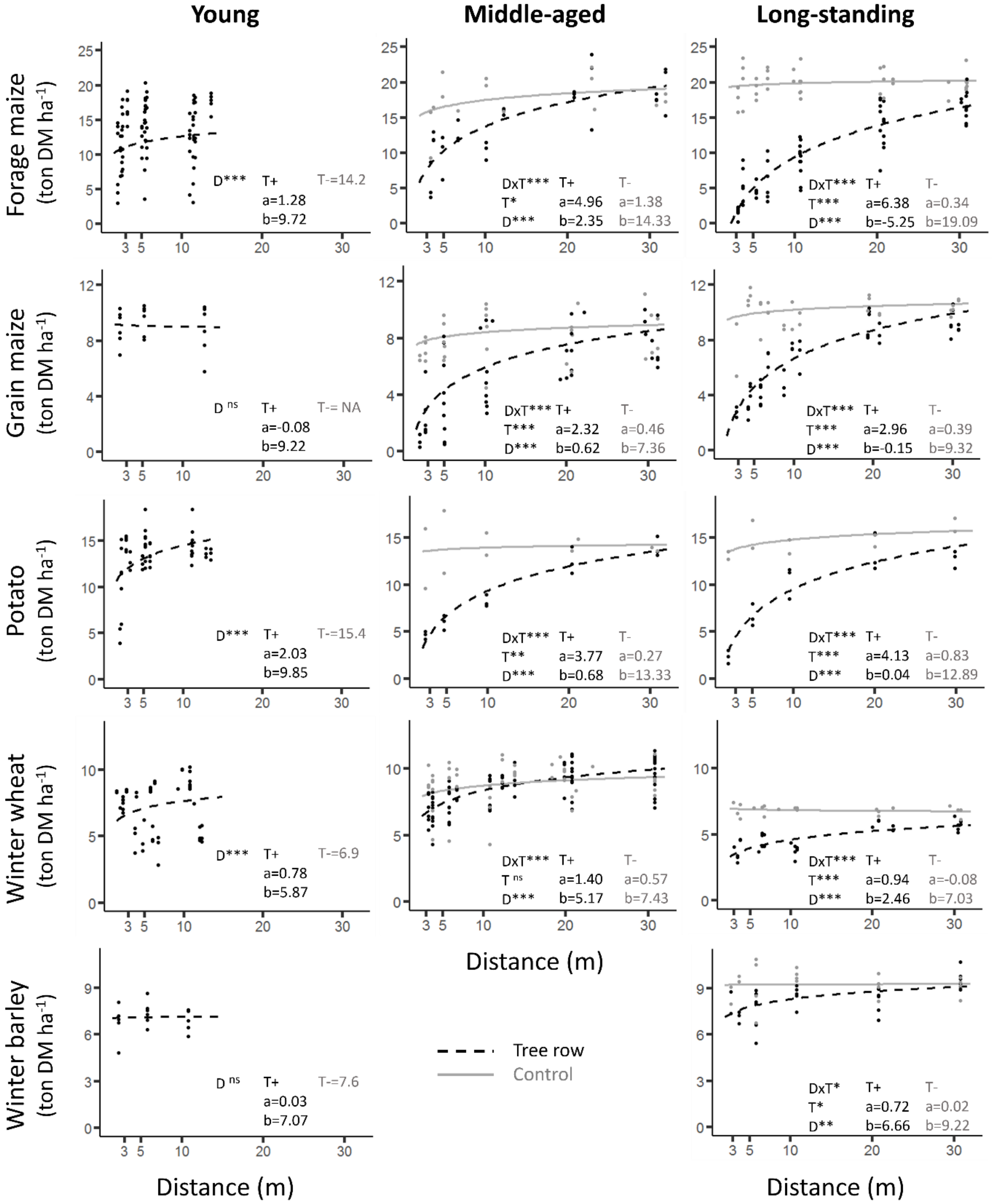


*Figure 4.2: Yield (tons DM ha^{-1}) for five arable crops as function of tree row presence and distance (m) to the tree row and/or treeless field edge for different tree sizes (young, middle-aged and long-standing trees). Fitted lines represent linear mixed-effect models with black dashed lines representing the tree row, and grey full lines the control plots. Significance of fixed effects: ^{ns} P >0.1, $^{\cdot}$P <0.1,*P <0.05,**P <0.01 and ***P <0.001, “D”: distance, “T”: Tree row presence, “DxT”: interaction. Model formula: y= a*ln(distance in m) + b, “T-“: Control zone, “T+”: Tree row.*

In the zone between 2.5 and 12 m to the tree rows on the young alley cropping fields, average yield of wheat was 5.8% higher than yields in the control plots (Table 4.2). Yields of forage maize, potato and winter barley were 85, 89 and 93%, respectively, of yields in the control plots.

Table 4.2: Yield (mean ± S.E. in tons DM ha^{-1}) for five arable crops in the field zone between 2.5 and 12 m and 2.5 and 30 m of the tree rows/treeless field edges (based on LMM effect relationships). "Control points" refers to the control plots on young alley cropping fields, "Control zone": refers to the arable zone near the treeless field edge on fields with middle-aged and long-standing trees.

		Forage maize	Grain maize	Potato	Winter wheat	Winter barley
	2.5 to 12 m					
Young	Tree row	12.1±3.1	9.1±1.4	13.7±2.1	7.3±1.6	7.1±1.2
	Control points	14.2±1.1	*NA*	15.4±0.7	6.9±0.6	7.6±0.4
	Δ Yield (%)	**-14.8**	*NA*	**-11.0**	**5.8**	**-6.6**
Middle-aged	Tree row	11.8±4.6	5.0±1.3	7.8±3.0	7.8±0.8	*NA*
	Control zone	17.0±3.8	8.2±2.1	13.8±2.3	8.5±1.2	*NA*
	Δ Yield (%)	**-30.6**	**-39.0**	**-43.5**	**-8.2**	*NA*
Long-standing	Tree row	6.9±2.2	5.5± 1.2	7.9±2.6	4.2±0.9	8.01±1.4
	Control zone	19.7±2.1	10.0±1.3	14.5±2.0	6.9±0.7	9.26±1.1
	Δ Yield (%)	**-65.0**	**-45.0**	**-45.5**	**-39.1**	**-13.5**
	2.5 to 30 m					
Middle-aged	Tree row	15.4±5.3	6.7±1.6	10.6±3.4	8.8±1.0	*NA*
	Control zone	18.0±4.3	8.6±2.2	14.0±2.6	8.9±1.3	*NA*
	Δ Yield (%)	**-14.4**	**-22.1**	**-24.3**	**-1.1**	*NA*
Long-standing	Tree row	11.5±2.6	7.6±1.4	10.9±3.0	4.9±1.0	8.5±1.6
	Control zone	20.0±2.3	10.3±1.4	15.1±2.3	6.8±0.8	9.3±1.3
	Δ Yield (%)	**-42.5**	**-26.2**	**-27.8**	**-27.9**	**-8.6**

4.4.2 Crop quality

Gradients as function of distance to the tree row

The effect on dry matter concentration of the forage maize samples was limited, except for the fields with long-standing trees, where significantly lower values were found near the tree rows with concentrations equaling 24.2% at 2.5 m from the trees versus 31.1% at 30 m away (Figure 4.3, Appendix 4.3). The CP concentration of forage maize was lower close to the tree rows on the young alley cropping fields, with values at 2.5 m equaling 6.8% versus 7.4% at 12 m. In contrast, on the fields with middle-aged and long-standing trees, the CP concentration was higher at 2.5 m from the tree rows (6.6 and 10.6%, respectively) than at a distance of 30 m away (6.1 and 7.2%, respectively) (Figure 4.3, Appendix 4.3). As a result, relative reductions in protein yield on the latter fields were smaller when compared to the observed reductions in crop yield (Appendix 4.4). On the long-standing fields, lower values of starch concentration were found close to the tree rows, equaling 13.3% at 2.5 m versus 35.5% at 30 m (Figure 4.3, Appendix 4.3). No significant effect of tree presence on OMD of forage maize was found.

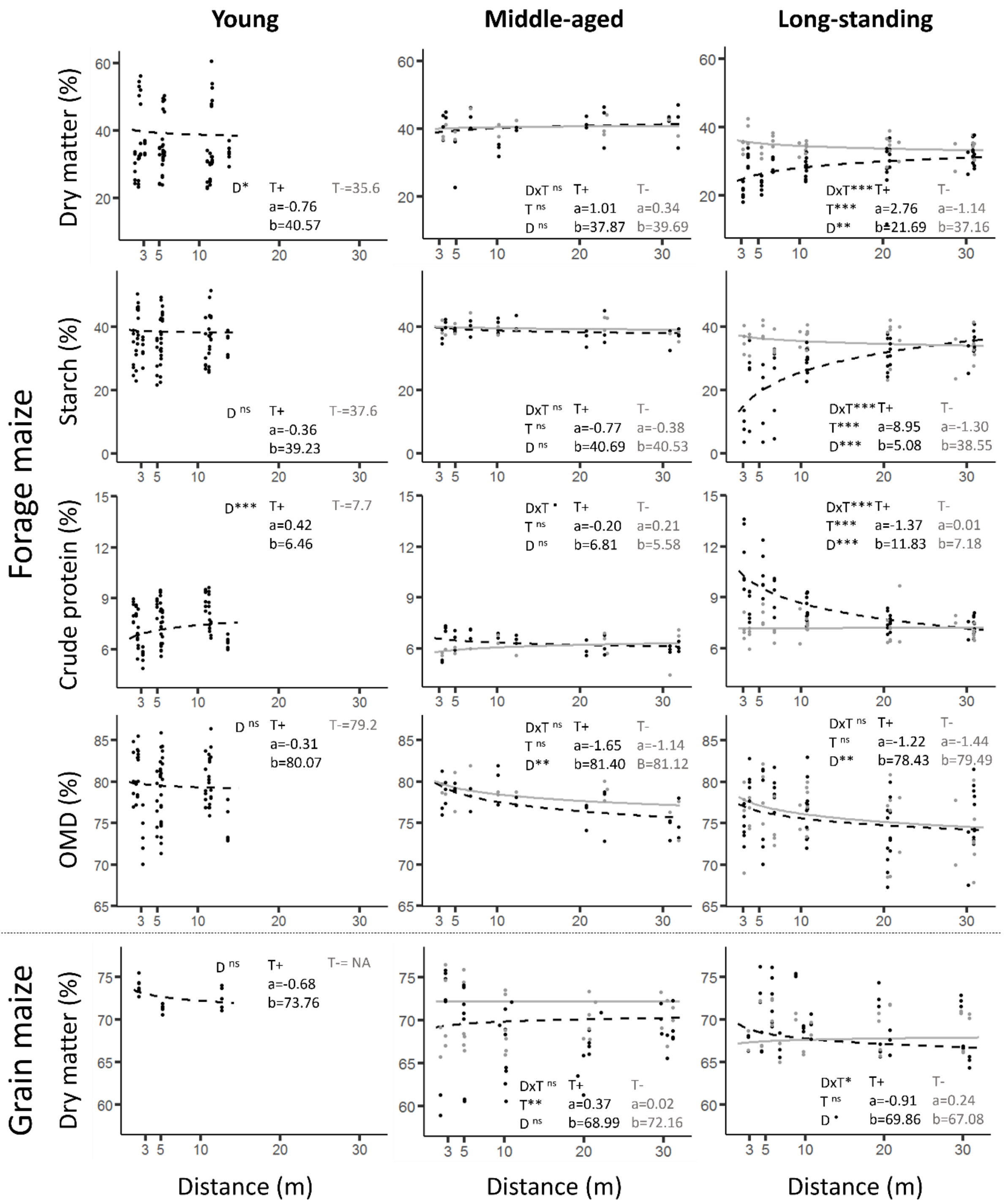


*Figure 4.3: Quality of forage and grain maize as function of tree row presence and distance (m) to tree row and/or treeless field edge for different tree sizes (young, middle-aged and long-standing trees). "OMD": organic matter digestibility. Fitted lines represent linear mixed-effect models with black dashed lines representing the tree row, and grey full lines the control plots. Significance of fixed effects: ^{ns} P >0.1, $^{•}$P <0.1,*P <0.05,**P <0.01 and ***P <0.001, "D": distance, "T": Tree row presence, "DxT": interaction. Model formula: y= a*ln(distance in m) + b, "T-": Control zone, "T+": Tree row.*

In the case of potato, dry matter concentration and UWW of potato tubers decreased with decreasing distance to the tree rows on the fields with long-standing trees. This resulted in lower values at 2.5 m from the trees (16.2% and 286 g per 5 kg tubers^{-1}, respectively) than at

30 m from the trees (19.6% and 347 g per 5 kg tubers^{-1}, respectively) (Figure 4.4, Appendix 4.3).

The CP concentration of the winter wheat samples was higher at a distance of 2.5 m from the trees when compared to a distance of 30 m (absolute increase of 1.3 and 2.0% in the case of the fields with middle-aged and long-standing trees, respectively) (Figure 4.5, Appendix 4.3).

Overall effects

As a result of the relatively strong gradients in dry matter and starch concentration of forage maize on the fields with long-standing trees, lower average values for the zone in between a distance of 2.5 and 30 m to the trees were found (dry matter %: 29.9±3.8, starch %: 28.6±8.3) as compared to the control zone (dry matter %: 34.1±4.4, starch %: 35.2±7.1) (Appendix 4.2). In these fields, the average CP concentration in between 2.5 and 30 m of the field edge was considerably higher close to the trees (8.2±1.0%) when compared to the control zone (7.2±1.1%) (Appendix 4.2). A significantly lower average dry matter concentration of grain maize was observed near the tree rows (70.0±4.7%) on the fields with middle-aged trees when compared to the control zone (72.2±7.0%) in the area between 2.5 and 30 m from the field edge (Figure 4.3, Appendix 4.2). This trend, however, was not corroborated by the data from the fields with long-standing trees.

In between 2.5 and 30 m of the field edge, average dry matter concentration and UWW of potato tubers were lower near the long-standing trees (18.5±2.2% and 328±31.8 g 5 kg tubers^{-1}, respectively) when compared to the control zone (20.3±1.7% and 361±24.6 g 5 kg tubers^{-1}, respectively) (Appendix 4.2). The fraction of the tubers with diameter >35 mm was significantly lower near the trees in all size classes (Figure 4.4; Appendix 4.3).

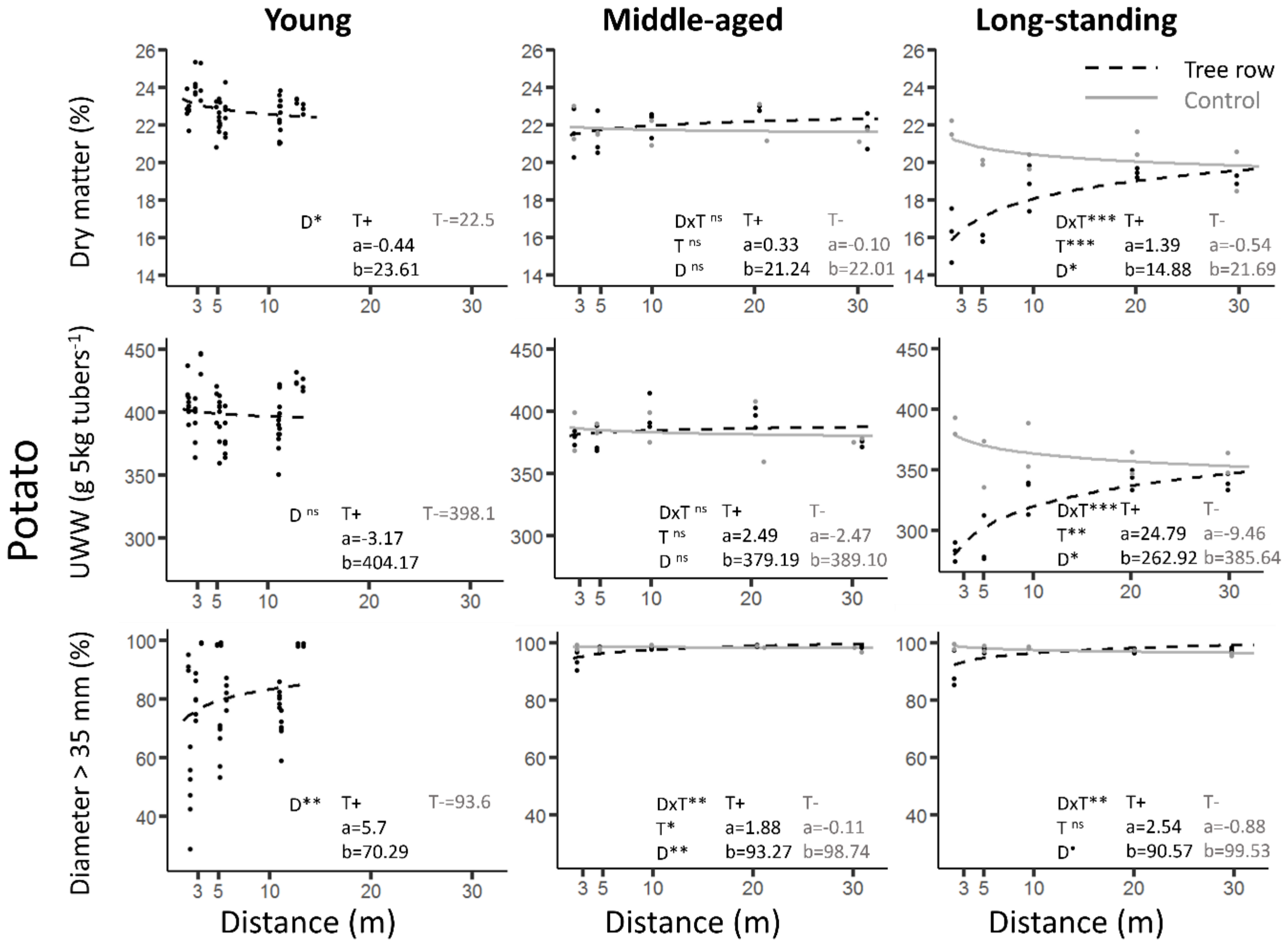


*Figure 4.4: Quality of potato as function of tree row presence and distance (m) to tree row and/or treeless field edge for different tree sizes (young, middle-aged and long-standing trees). "UWW": underwater weight. Fitted lines represent linear mixed-effect models with black dashed lines representing the tree row, and grey full lines the control plots. Significance of fixed effects: ^{ns} P >0.1, $^{\bullet}$P <0.1,*P <0.05,**P <0.01 and ***P <0.001, "D": distance, "T": Tree row presence, "DxT": interaction. Model formula: y= a*ln(distance in m) + b, "T-": Control zone, "T+": Tree row.*

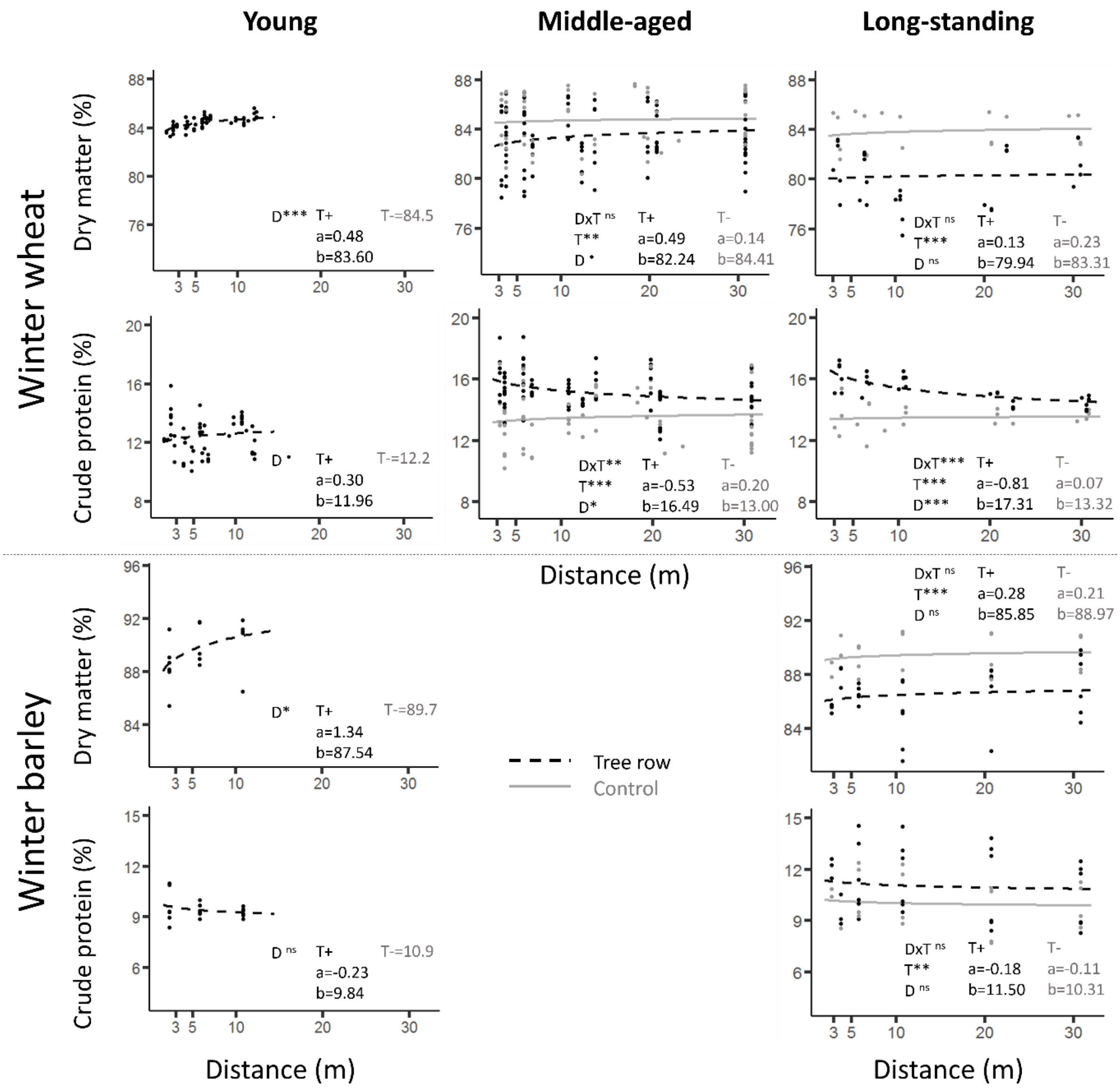


*Figure 4.5: Quality of winter cereals as function of tree row presence and distance (m) to tree row and/or treeless field edge for different tree sizes (young, middle-aged and long-standing trees). Fitted lines represent linear mixed-effect models with black dashed lines representing the tree row, and grey full lines the control plots. Significance of fixed effects: ^{ns} P >0.1, $^{\bullet}$P <0.1,*P <0.05,**P <0.01 and ***P <0.001, "D": distance, "T": Tree row presence, "DxT": interaction. Model formula: y= a*ln(distance in m) + b, "T-": Control zone, "T+": Tree row.*

Significantly lower average dry matter concentrations of the wheat samples were found near the tree rows (83.5±2.1%) on the fields with middle-aged trees when compared to the control zone (84.8±2.1%) in the area between 2.5 and 30 m of the field edge (Figure 4.5, Appendix 4.2). A similar effect was observed on the fields with long standing trees for winter wheat and barley. In case of winter wheat, average dry matter concentration of wheat samples was 80.3±2.5% in the area between 2.5 and 30 m from the trees and 83.9±2.8% in the control zone. In case of winter barley, these values equaled 86.6±3.0% and 89.5±2.5%, respectively. The CP concentration of the winter wheat samples was increased as a result of tree presence (Figure 4.5, Appendix 4.3). On the boundary planted fields, average CP concentration at a distance between 2.5 and 30 m to the field edge equaled 15.1±1.2 and 15.2±1.2% near the tree rows on the middle-aged and long-standing fields, respectively. Average CP concentration in the control zones on these fields equaled 13.5±1.4 and 13.5±1.0%, respectively. Average CP concentration of the winter barley samples was significantly higher on the fields with long standing trees (11.0±1.4%) in comparison to the control zone (10.0±2.2%).

4.5 Discussion

As also described in chapter 2 & 3, simultaneous with the observed reductions in crop yield, increased soil nutrient concentrations have been found near the tree rows on the fields in our dataset (Pardon et al., 2017), as well as increased macro-detritivore presence, which may result in enhanced organic matter decomposition and nutrient cycling (Pardon et al., under review). This may indicate that lack of nutrients was not a main factor determining the observed patterns in crop yield in our research, in contrast to competition for light and water. These observations are in accordance with the findings of Jose et al. (2000) and Miller and Pallardy (2001). In addition, as argued before, slight differences in e.g. tillage and fertilization or other edge effects may further affect yield and quality of arable crops near the tree rows and/or field edges. However, to date, the actual quantification of tree effects on yield of different crops remains limited and little differentiation is made between young and older AFS. Although results are assumed to vary according to intra-row and inter-row distance of the trees in actual alley cropping systems, our research indicates that both crop type and tree size class are the main factors determining the magnitude of tree effects on crop yield and quality and their extent into the field.

4.5.1 Maize

Maize, a thermophile spring crop, exhibits a large overlap in growing season with deciduous trees. In Belgium, maize is generally not planted before the end of April, whereas leaf sprouting of poplar trees generally occurs during April and leaves are unfolded by the beginning of May (Verstraeten et al., 2004). Although measurements in older temperate AFS are scarce, research on fields with poplar trees of moderate age (approximately 10 years of age) (Ding and Su, 2010; Reynolds et al., 2007; Thevathasan and Gordon, 2004) or with a densely-planted tree component (Peng et al., 2009) often indicates that the reduction in incident Photosynthetically Active Radiation (PAR) is the key driver for the observed reductions in (grain) maize yield. Maize, a C4 crop, is characterized by a higher light saturation point and hence higher susceptibility to shading compared to C3 crops (Reynolds et al., 2007). Together with the different degree of overlap in growing season, this may partly explain the strong reduction in forage maize yield compared to crops such as winter wheat (C3). In addition, in a study of soil moisture dynamics in the transects used for experimental harvesting in one of our fields (Ieper 1) (Coussement et al., 2018), the use of electrical resistivity tomography indicated a lower soil moisture content near the trees, most notably during dry spells. In other research under Mediterranean conditions, competition for water in alley cropping fields is often assumed to be tempered because of altered rooting patterns of the trees with increased root densities in deeper soil layers and avoidance of the upper soil layers as a result of the frequent soil management activities in arable fields, in particular when combined with winter crops (Cardinael et al., 2015b; Mulia and Dupraz, 2006). However, it is not clear to what extent this tree-response occurs under temperate climatic conditions and the results of Coussement et al. (2018) indicate that competition for water is indeed present near the tree rows. Hence, both competition for light and soil moisture may have contributed to the observed decreases in crop yield on the boundary planted fields in our research.

Impacts on quality of forage maize are small on the young alley cropping fields and the fields with middle-aged trees. The increased moisture concentration of forage maize samples near the tree rows on the fields with long-standing trees is most probably related to a delay in maturity as suggested by Mbewe and Hunter (1986), who found a similar simultaneous increase in moisture concentration (12%) and CP concentration (21%) under artificial shade conditions. Several authors have indicated the presence of increased total (Pardon et al., 2017) and mineral soil nitrogen concentrations (Jose et al., 2000b; Oelbermann and Voroney, 2007) near tree rows as a result of leaf litter fall, etc. This higher nitrogen availability may have led to the increased CP as also observed in the research of Damian et al. (2017), Eltelib et al. (2006) and Sheaffer et al. (2006), where the effect of different N fertilization regimes on CP of forage maize was studied. The effect of increased soil N concentrations may be magnified as a result of a lower nutrient dilution, considering the observed decreases in plant growth near the tree rows. In addition, potential reductions in water availability near the trees may have contributed to the increased CP concentration, as also observed by authors including Çarpıcı et al. (2017) and Islam et al. (2012) who investigated CP concentration in silage maize under differing watering regimes.

Similar to forage maize, strong effects of tree presence on yield of grain maize were observed in the fields with middle-aged and long-standing trees, which is assumed to result from competition for light and/or water (Jose et al., 2000b; Reynolds et al., 2007; Thevathasan and Gordon, 2004). As described by Gommers et al. (2013), plants submitted to shade may display a shade avoidance response, thereby increasing the (relative) amount of carbon being allocated towards stem elongation which may negatively affect kernel yield. However, in the young alley cropping fields, values in the outer maize rows near the trees were even increased (although not significant). A similar effect was observed by Gillespie et al. (2000) near walnut trees of similar age (3 years old) where this was attributed to increased light availability in the outer rows and reduced competition for moisture with adjacent maize rows. Hence, although growing grain maize is not recommended in older AFS, our results suggest that it may be suited for integration in crop rotations in young alley cropping systems.

4.5.2 Potato

The yield decline in potato was quite similar to the decline observed in maize, which may be related to the similar large overlap in growing season of trees and crops. Also similar to forage maize, substantial effects on crop quality (i.e. UWW and dry matter concentration of potato tubers) only occurred near the long-standing trees. Research focusing on the effect of reduced availability of light and/or water have shown negative effects on the yield and quality of potato. Several other authors have described significant reductions in tuber size (Mushagalusa et al., 2008; Singh, 1988) and number of tubers (O'Brien et al., 1998), resulting in reduced total tuber biomass yield under application of artificial shade. Reduced water availability during tuber initiation may lead to a decreased number of tubers per plant (Heuer and Nadler, 1995; Martin et al., 1992). After the period of tuber initiation, water limitation may negatively affect both final tuber size (Onder et al., 2005; Shock et al., 1998; Yuan et al., 2003) and the dry matter concentration (Fabeiro et al., 2001), which is closely linked to underwater weight (Haase, 2004).

4.5.3 Winter wheat and winter barley

The least negative effects of tree presence on crop yield were observed for winter wheat and winter barley. This is in accordance with the suggestion that cultivation of winter cereals may be a successful strategy to limit tree-crop competition throughout the rotation of an AFS. However, at least one additional crop with limited susceptibility to tree-crop competition should be cultivated to constitute a durable rotation. Whereas grain maize may be included in the rotation during the first years of tree growth, further research would be necessary to identify other crops suited for cultivation in temperate regions near older trees and quantify the actual impact on crop yield and quality. Examples of such a crop rotation can for example be found in the Dauphine province in SE-France where walnut-orchards are combined with amongst others winter cereals and/or maize as main crops during the first years of intercropping (Mary et al., 1998). As trees mature, maize is omitted (in part also because of the incompatibility with nut-harvesting activities in September) and crops with a short life cycle are preferred for subsequent intercropping. As described by Mary et al. (1998), examples of the latter crop type include soybean, vegetables or flowers.

As discussed earlier, yield of C3 plants such as wheat and barley may be less affected by shading when compared to crops such as maize (Reynolds et al., 2007; Thevathasan and Gordon, 2004). In addition, they show limited overlap in growing season with deciduous tree species, since winter cereals are sown in fall and are generally already in the stage of flag leaf formation at the time of tree leaf sprouting in April (Artru, 2017; de Jong, 1989; Dufour et al., 2013; Gill et al., 2009; Robert et al., 1993). This may explain the even smaller effect of tree presence observed for barley when compared to wheat, with winter barley generally being harvested before winter wheat (in Belgium, 3 to 4 weeks earlier). According to Wang et al. (2003), shading of winter wheat results in reduced dry matter allocation in particular to the grains, whereas this effect is less pronounced in the above-ground vegetative parts. Tree presence may furthermore affect root growth of winter wheat, resulting in reduced root length densities and root diameters, as shown by Zhang et al. (2015) in case of intercropping with Persian walnut. As also indicated in other research where the effects of shade are studied, the observed decreases in grain yield may be related to reductions in both number of grains per m² and weight of the grains (Artru et al., 2016; Dufour et al., 2013; Li et al., 2008). This was partly confirmed by the additional observations on the field in Herzele by Artru (2017) in 2016 where the number of wheat grains per m², the number of grains per spike and thousand kernel weight (TKW) was investigated in the transects and distances used for experimental harvesting (Figure 4.1a). A decrease in number of grains per m² of 67% and 45% was observed at 3 and 10 m from the trees, respectively when compared to the sampling position at 30 m from the trees. In contrast, increased values of TKW were found in the sampling plots at distances 3, 5 and 10 m from the trees when compared to sampling positions at 30 m. According to Artru (2017), this was attributed to a simultaneous decrease in the number of grains per spike, equaling a 48% reduction at 3 m from the trees when compared to sampling positions at 30 m from the tree row, allowing the limited number of remaining grains to become fully filled. The limited decrease in average wheat yield of 1.1% at a distance between 2.5 and 30 m from the field edge on the fields with middle-aged trees was partly caused by the increased yield levels near the trees at the sampling distances of 20 and 30 m as compared to the control zone. These increased values may be related to enhanced microclimatic conditions. Increased yield of winter barley and wheat has been observed in silvoarable systems under Mediterranean conditions with hybrid walnut by Arenas-Corraliza et al. (2018), where this was attributed to the sheltering effect of the trees during heat weaves, thereby buffering maximum temperatures and the potential reduction of the desiccant effect of wind. The beneficial effect of trees on microclimate has also been described for temperate climatic conditions (Nuberg, 1998). However, further research is needed to confirm the prevalence of beneficial effects in relation to tree-crop competition at such limited distances to mature tree rows in temperate regions. On the young alley cropping fields in our research, a wheat yield increase of 5.8% was observed when compared to the control points. Also in past research, enhanced wheat yield has been found in young temperate alley cropping systems: for example, Zhang (1999) observed an increase of 8.4% in an AFS in southern Ontario (Canada) with a tree component of 10-12 years old. The improved yields were attributed to improved microclimatic conditions and increased nutrient availability in the AFS (Thevathasan and Gordon, 2004; Zhang, 1999). The increased wheat yield near the tree rows on the young alley cropping fields and the fields with middle-aged trees are not corroborated by the data from the fields with long-standing trees where even at the furthest measuring distance (30 m) crop yield is decreased near the tree rows when compared to the control zone. Although a further-reaching effect on crop yield may be expected near these long-standing trees, it is not clear if other factors (such as potential heterogeneity in soil conditions and/or cultivation practices) may have contributed to the observed decrease.

For both winter wheat and barley, the decrease in dry matter concentration of the grain was consistent across all size classes. As observed in other research (e.g., Chauhan et al., 2011), and confirmed in the experiment of Artru (2017) on the field in Herzele, this decrease may have been caused by a delay in physiological maturity and/or ripening of the crop near the tree rows. In addition, as is often common practice when harvesting wheat and/or barley in temperate regions, harvesting is not started before noon to allow the vaporization of humidity originating from nocturnal fog and dew deposition, to reduce the moisture concentration of the grain. As a result of potential reductions in wind speed and increased shade, this vaporization may have been hampered near the tree rows. To limit the resulting heterogeneities in dry matter concentration at the field level, postponing the harvesting activities to a later time in the growing season and later in the day may be advisable.

On the boundary planted fields, tree row presence resulted in a significant increase in CP concentration of wheat and barley. This has also been observed by authors including Artru et al. (2017) and Dufour et al. (2013) under artificially shaded conditions. In the latter study, this was attributed to a simultaneous increase in LAI (8%) and a decrease in number of grains per ear (31%) of the wheat. As such, the source of metabolites used for proteins synthesis slightly increased, while the sink made up of the grains decreased, resulting in a relative increase in grain CP concentration. In the experiment of Dufour et al. (2013) a similar decrease in PAR was observed on an actual alley cropping field when compared to the artificially shaded conditions whereas only a non-significant increase (2%) in CP concentration of wheat was observed. The walnut trees in the alley cropping field were relatively young (11-12 years old) and of limited size (DBH: 13.8 cm, height: 7.8 m). As such, these results are in accordance with the limited increase of CP concentration observed near the tree rows on the young alley cropping fields in our research. However, our results do indicate a significant augmentation of this effect as trees matured.

4.5.4 Productivity of the tree rows

Although our calculations only concern the arable zone, one should also take into account the surface loss of the tree strips when quantifying total crop yield reduction in AFS. However, this area has a yield potential since (high quality) wood is grown there, if the trees are for timber production. Other tree species may produce other marketable goods such as fruits, nuts and fodder, at least if the companion crop does not hamper the access to the trees in due time. This might at least partly compensate for the potential loss in arable crop yield. In our research, strong tree effects were observed on the fields with long-standing trees when compared to the young alley cropping fields and fields with middle-aged trees. This indicates the importance of harvesting the poplar trees in time to optimize the total economical production of an AFS (i.e., at a DBH not larger than the maximal DBH for industrial processing). However, older trees surpassing the optimal size for industrial processing may be of particular value for the deliverance of several regulating and supporting ES, such as carbon sequestration and biodiversity conservation, which may be positively related to the size (and/or age) of the trees, as observed on the fields in this research (Pardon et al., 2017; under review). Hence, if the focus of the AFS is the deliverance of these ES, rather than the production of marketable goods, substantial impacts on crop yield and quality can be expected.

4.6 Conclusion

We have found that tree size and crop type are the main determinants of the crop yield and quality in arable AFS. Yield of maize and potato may be strongly reduced towards the end of the agroforestry rotation, i.e., in fields with large trees. The effect on yield of winter wheat and barley is considerably less impacted by tree presence when compared to the abovementioned crops. Negative effects on crop quality were observed only to a limited extent on the young alley cropping fields and fields with mature trees. Our results indicate that to optimize the production potential of AFS, poplar trees should be harvested when they reach their target diameter for industrial processing. If tree rows are preserved for the delivery of other ES, substantial impacts on crop yield and quality may occur.

4.7 Appendix

4.7.1 Appendix 4.1

Linear mixed modelling results of A) crop yield (ton DM ha^{-1}) and B) quality parameters for five crops and three tree size classes. “OMD”: organic matter digestibility, “UWW”: underwater weight in g (5 kg tubers)$^{-1}$. Included fixed effects are distance to the Tree row in case of young alley cropping fields (“Young”) and distance to the field edge, presence or absence of a tree row (“T+/T-”) and their interaction in case of boundary planted fields (“Middle-aged” and “Long-standing”). Bold characters indicate significant effect (P-value<0.05). (•) indicates 0.05 < P-value < 0.10. “R^2c”: conditional R^2, “R^2m”: marginal R^2. Model formula: y= a*ln(distance in m) + b.

		Fixed effect					Parameter estimates LMM			
					R^2c	R^2m	Tree row		Control zone	
		Ln(distance)	T+T-	T+T- :Ln(distance)			a	b	a	b
A) CROP YIELD (ton DM ha^{-1})										
Forage maize	Young	**p=0.0006**			0.78	0.03	1.2789	9.7187		
	Middle-aged	**p<0.0001**	**p=0.0259**	**p=0.0005**	0.72	0.59	4.9601	2.3547	1.3804	14.3272
	Long-standing	**p<0.0001**	**p<0.0001**	**p<0.0001**	0.93	0.87	6.3815	-5.2513	0.3447	19.0861
Grain maize	Young	p=0.7603			0.68	0.00	-0.0842	9.2221		
	Middle-aged	**p<0.0001**	**p<0.0001**	**p<0.0001**	0.87	0.43	2.3153	0.6216	0.4627	7.3635
	Long-standing	**p<0.0001**	**p<0.0001**	**p<0.0001**	0.90	0.78	2.9640	-0.1487	0.3862	9.3187
Potato	Young	**p=0.0002**			0.36	0.20	2.0273	9.8473		
	Middle-aged	**p<0.0001**	**p=0.0036**	**p<0.0001**	0.89	0.79	3.7690	0.6763	0.2660	13.3348
	Long-standing	**p<0.0001**	**p=0.0003**	**p<0.0001**	0.91	0.89	4.1317	0.0393	0.8277	12.8920
Winter wheat	Young	**p<0.0001**			0.96	0.03	0.7751	5.8680		
	Middle-aged	**p<0.0001**	p=0.1654	**p<0.0001**	0.78	0.27	1.3976	5.1670	0.5704	7.4316
	Long-standing	**p<0.0001**	**p<0.0001**	**p<0.0001**	0.84	0.82	0.9355	2.4633	-0.0762	7.0266
Winter barley	Young	p=0.9161			0.04	0.00	0.0331	7.0719		
	Middle-aged	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*
	Long-standing	**p=0.0071**	**p=0.0171**	**p=0.0251**	0.46	0.30	0.7150	6.6585	0.02048	9.2211
B) CROP QUALITY										
Forage maize										
Dry matter (%)	Young	**p=0.0345**			0.96	0.00	-0.7607	40.5740		
	Middle-aged	p=0.1769	p=0.9638	p=0.5801	0.61	0.02	1.0107	37.8726	0.3421	39.6868
	Long-standing	**p=0.0035**	**p<0.0001**	**p<0.0001**	0.77	0.37	2.7632	21.6933	-1.1439	37.1555
Crude protein (%)	Young	**p<0.0001**			0.90	0.03	0.4214	6.4613		
	Middle-aged	p=0.6208	p=0.2363	p=0.0751•	0.20	0.10	-0.1954	6.8076	0.2135	5.5810

	Long-standing	**p<0.0001**	**p<0.0001**	**p<0.0001**	0.79	0.47	-1.3695	11.8313	0.0104	7.1759
Starch (%)	Young	p=0.5068			0.86	0.00	-0.3572	39.2290		
	Middle-aged	p=0.1866	p=0.3610	p=0.7002	0.05	0.05	-0.7728	40.6873	-0.3841	40.5281
	Long-standing	**p<0.0001**	**p=0.0006**	**p<0.0001**	0.64	0.50	8.9460	5.0790	-1.2950	38.5520
OMD (%)	Young	p=0.3719			0.73	0.00	-0.3121	80.0743		
	Middle-aged	**p=0.0001**	p=0.1579	p=0.4731	0.34	0.30	-1.6541	81.4015	-1.1400	81.1160
	Long-standing	**p=0.0014**	p=0.6238	p=0.7992	0.32	0.08	-1.2201	78.4310	-1.4371	79.4852
Grain maize										
Dry matter (%)	Young	p=0.1172			0.12	0.12	-0.6809	73.7629		
	Middle-aged	p=0.6046	**p=0.0076**	p=0.7002	0.78	0.02	0.3734	68.9875	0.0197	72.1563
	Long-standing	p=0.0501•	p=0.8448	**p=0.0114**	0.93	0.01	-0.9097	69.8575	0.2360	67.0760
Potato										
Dry matter (%)	Young	**p=0.0305**			0.16	0.08	-0.4351	23.6093		
	Middle-aged	p=0.4002	p=0.6126	p=0.2395	0.20	0.08	0.3259	21.2430	-0.1030	22.0100
	Long-standing	**p=0.0297**	**p=0.0005**	**p<0.0001**	0.73	0.73	1.3904	14.8774	-0.5377	21.6904
UWW (g 5 kg tubers^{-1})	Young	p=0.2879			0.41	0.27	-3.1700	404.1680		
	Middle-aged	p=0.8584	p=0.8350	p=0.3882	0.03	0.03	2.4910	379.1880	-2.4710	389.1030
	Long-standing	**p=0.0192**	**p=0.0011**	**p<0.0001**	0.84	0.78	24.7850	262.9160	-9.4570	385.6390
Diameter fraction >35 mm	Young	**p=0.0002**			0.88	0.04	5.6730	70.2850		
	Middle-aged	**p=0.0052**	**p=0.0262**	**P=0.0029**	0.73	0.73	1.8760	93.2684	-0.1123	98.7424
	Long-standing	p=0.0600•	p=0.2239	**P=0.0023**	0.40	0.40	2.5399	90.5712	-0.8780	99.5266
Winter wheat										
Dry matter (%)	Young	**p<0.0001**			0.49	0.36	0.4779	83.5987		
	Middle-aged	p=0.0743•	**p=0.0040**	p=0.3874	0.49	0.07	0.4916	82.2427	0.1394	84.4105
	Long-standing	p=0.4626	**p<0.0001**	p=0.8455	0.82	0.33	0.1329	79.9449	0.2261	83.3074
Crude protein (%)	Young	p=0.0689•			0.76	0.02	0.2947	11.9623		
	Middle-aged	**p=0.0341**	**p<0.0001**	**p=0.0022**	0.22	0.67	-0.5327	16.4912	0.2035	13.0039
	Long-standing	**p=0.0009**	**p<0.0001**	**p=0.0002**	0.65	0.78	-0.8124	17.3129	0.0687	13.3237
Winter barley										
Dry matter (%)	Young	**p=0.0409**			0.20	0.20	1.3405	87.5394		
	Long-standing	p=0.3541	**p<0.0001**	p=0.8911	0.53	0.37	0.2839	85.8546	0.2070	88.9733
Crude protein (%)	Young	p=0.3067			0.05	0.05	-0.2343	9.8354		
	Long-standing	p=0.2345	**p=0.0030**	p=0.7938	0.90	0.05	-0.1828	11.5036	-0.1146	10.3139

4.7.2 Appendix 4.2

Crop quality (mean ± S.E.) for five crops and three tree size classes in the field zone between 2.5 and 12 m and 2.5 and 30 m of the tree rows and treeless field edges (based on LMM effect relations). “CP”: crude protein, “OMD”: organic matter digestibility, “UWW”: underwater weight. “Control points” refers to the control plots on young alley cropping fields, “Control zone”: refers to the arable zone near the treeless field edge on fields with middle-aged and long-standing trees.

		Forage maize				Grain maize	Potato			Winter wheat		Winter barley	
		Dry matter (%)	Starch (%)	CP (%)	OMD (%)	Dry matter (%)	Dry matter (%)	UWW (g 5 kg tubers^{-1})	Diameter fraction <35 mm	Dry matter (%)	CP (%)	Dry matter (%)	CP (%)
2.5 to 12m													
Young	Tree row	39.1±6.9	38.6±5.8	7.3±1.0	79.5±2.8	72.5±1.6	23.2±0.7	398.2±19.8	81.1±13.4	84.5±0.3	12.5±1.0	90.1±2.4	9.4±0.9
	Control points	35.6±2.2	37.6±1.9	7.7±0.3	79.2±0.9	*NA*	22.5±0.3	398.1±4.6	93.6±1.9	84.5±0.2	12.2±0.6	89.7±1.6	10.9±0.4
	Δ (%)	**9.8**	**2.7**	**-5.2**	**0.4**	*NA*	**3.1**	**0.0**	**-13.4**	**0.0**	**2.5**	**0.4**	**-13.8**
Middle-aged	Tree row	39.8±6.1	39.2±4.7	6.4±1.0	78.3±3.3	69.7±4.1	21.9±1.7	383.9±26.9	96.8±2.9	83.2±1.8	15.5±1.1	*NA*	*NA*
	Control zone	40.3±5.5	39.8±3.8	6.0±0.8	79.0±2.7	72.2±6.5	21.8±1.3	384.4±20.8	98.3±2.2	84.7±1.9	13.4±1.3	*NA*	*NA*
	Δ (%)	**-1.2**	**-1.5**	**6.7**	**-0.9**	**-3.5**	**0.5**	**-0.1**	**-1.5**	**-1.8**	**15.7**	*NA*	*NA*
Long-standing	Tree row	26.9±3.3	22.1±7.1	9.2±0.8	76.8±3.9	68.1± 2.1	17.5± 1.9	310.0± 27.5	95.4± 4.8	80.2±2.1	15.8±1.1	86.4±2.5	11.2±1.2
	Control zone	35.0±4.0	36.1±6.2	7.2±1.0	76.1±3.2	67.5±4.4	20.7±1.4	367.7±21.3	97.9±3.7	83.7±2.5	13.5±0.8	90.7±1.1	10.1±2.0
	Δ (%)	**-23.1**	**-38.8**	**27.8**	**0.9**	**0.9**	**-15.5**	**-15.7**	**-2.6**	**-4.2**	**17.0**	**-4.7**	**10.9**
2.5 to 30m													
Middle-aged	Tree row	41.5±7.0	38.7±5.4	6.3±1.2	77.1±3.9	70.0±4.7	22.1±2.0	385.7±31.4	98.2±2.6	83.5±2.1	15.1±1.2	*NA*	*NA*
	Control zone	41.6±6.3	39.5±4.4	6.1±1.0	78.1±3.1	72.2±7.0	21.7±1.5	382.6±24.3	98.2±3.4	84.8±2.1	13.5±1.4	*NA*	*NA*
	Δ (%)	**-0.2**	**-2.0**	**3.3**	**-1.3**	**-3.0**	**1.8**	**0.8**	**0.0**	**-1.5**	**11.9**	*NA*	*NA*
Long-standing	Tree row	29.9±3.8	28.6±8.3	8.2±1.0	75.7±4.5	67.5±2.4	18.5±2.2	328.0±31.8	97.2±5.6	80.3±2.5	15.2±1.2	86.6±3.0	11.0±1.4
	Control zone	34.1±4.4	35.2±7.1	7.2±1.1	75.2±3.7	67.7±4.6	20.3±1.7	360.8±24.6	97.2±4.3	83.9±2.8	13.5±1.0	89.5±2.5	10.0±2.2
	Δ (%)	**-12.3**	**-18.8**	**13.9**	**0.7**	**-0.3**	**-8.9**	**-9.1**	**0.0**	**-4.3**	**12.6**	**-3.3**	**10.0**

4.7.3 Appendix 4.3

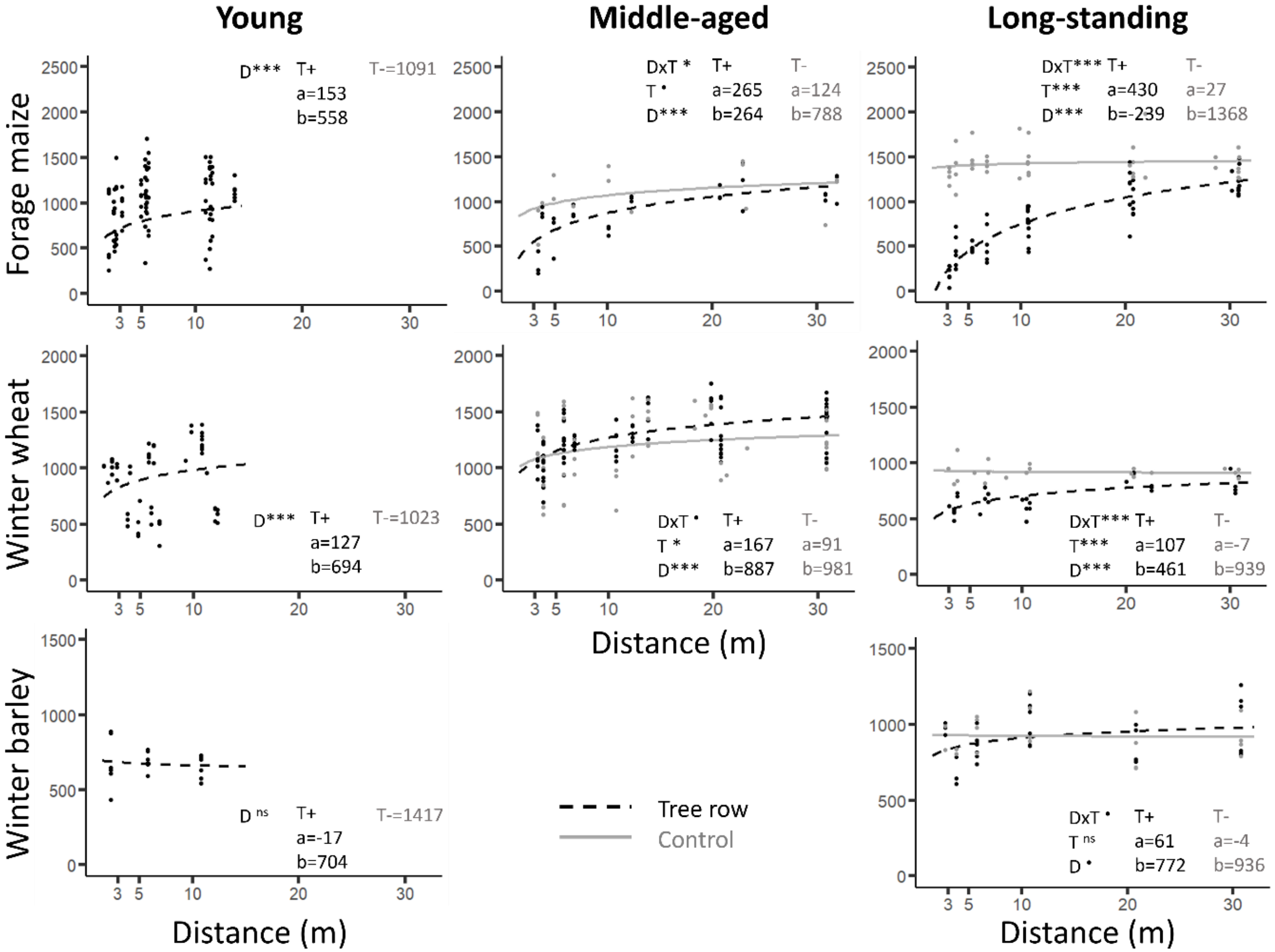
Crop yield and quality for 5 crops and 3 tree size classes following linear mixed model at distances “2.5m”, “5m”, “10m”, “20m” and “30m”. “OMD”: organic matter digestibility, “UWW”: underwater weight. “Control zone”: arable zone near treeless field edge on fields with middle-aged and long-standing trees.

				Distance				
				2.5 m	5 m	10 m	20 m	30 m
Forage maize	*Yield (ton DM ha^{-1})*	Young	Tree row	10.9	11.8	12.7		
		Middle-aged	Tree row	6.9	10.3	13.8	17.2	19.2
			Control zone	15.6	16.5	17.5	18.5	19.0
		Long-standing	Tree row	0.6	5.0	9.4	13.9	16.5
			Control zone	19.4	19.6	19.9	20.1	20.3
	Dry matter (%)	Young	Tree row	39.9	39.3	38.8		
		Middle-aged	Tree row	38.8	39.5	40.2	40.9	41.3
			Control zone	40.0	40.2	40.5	40.7	40.9
		Long-standing	Tree row	24.2	26.1	28.1	30.0	31.1
			Control zone	36.1	35.3	34.5	33.7	33.3
	Crude protein (%)	Young	Tree row	6.8	7.1	7.4		
		Middle-aged	Tree row	6.6	6.5	6.4	6.2	6.1
			Control zone	5.8	5.9	6.1	6.2	6.3
		Long-standing	Tree row	10.6	9.6	8.7	7.7	7.2
			Control zone	7.2	7.2	7.2	7.2	7.2
	Starch (%)	Young	Tree row	38.9	38.7	38.4		
		Middle-aged	Tree row	40.0	39.4	38.9	38.4	38.1
			Control zone	40.2	39.9	39.6	39.4	39.2
		Long-standing	Tree row	13.3	19.5	25.7	31.9	35.5
			Control zone	37.4	36.5	35.6	34.7	34.1
	OMD (%)	Young	Tree row	79.8	79.6	79.4		
		Middle-aged	Tree row	79.9	78.7	77.6	76.4	75.8
			Control zone	80.1	79.3	78.5	77.7	77.2
		Long-standing	Tree row	77.3	76.5	75.6	74.8	74.3
			Control zone	78.2	77.2	76.2	75.2	74.6
Grain maize	*Yield (ton DM ha^{-1})*	Young	Tree row	9.1	9.1	9.0		
		Middle-aged	Tree row	2.7	4.3	6.0	7.6	8.5
			Control zone	7.8	8.1	8.4	8.7	8.9
		Long-standing	Tree row	2.6	4.6	6.7	8.7	9.9
			Control zone	9.7	9.9	10.2	10.5	10.6
	Dry matter (%)	Young	Tree row	73.1	72.7	72.2		
		Middle-aged	Tree row	69.3	69.6	69.8	70.1	70.3
			Control zone	72.2	72.2	72.2	72.2	72.2
		Long-standing	Tree row	69.0	68.4	67.8	67.1	66.8
			Control zone	67.3	67.5	67.6	67.8	67.9
Potato	*Yield (ton DM ha^{-1})*	Young	Tree row	11.7	13.1	14.5		
		Middle-aged	Tree row	4.1	6.7	9.4	12.0	13.5
			Control zone	13.6	13.8	13.9	14.1	14.2
		Long-standing	Tree row	3.8	6.7	9.6	12.4	14.1
			Control zone	13.7	14.2	14.8	15.4	15.7

	Dry matter (%)	Young	Tree row	23.2	22.9	22.6		
		Middle-aged	Tree row	21.5	21.8	22.0	22.2	22.4
			Control zone	21.9	21.8	21.8	21.7	21.7
		Long-standing	Tree row	16.2	17.1	18.1	19.0	19.6
			Control zone	21.2	20.8	20.5	20.1	19.9
	UWW (g 5 kg tubers^{-1})	Young	Tree row	401.3	399.1	396.9		
		Middle-aged	Tree row	381.5	383.2	384.9	386.7	387.7
			Control zone	386.8	385.1	383.4	381.7	380.7
		Long-standing	Tree row	285.6	302.8	320.0	337.2	347.2
			Control zone	377.0	370.4	363.9	357.3	353.5
	Diameter fraction > 35mm (%)	Young	Tree row	75.5	79.4	83.3		
		Middle-aged	Tree row	95.0	96.3	97.6	98.9	99.6
			Control zone	98.6	98.6	98.5	98.4	98.4
		Long-standing	Tree row	92.9	94.7	96.4	98.2	99.2
			Control zone	98.7	98.1	97.5	96.9	96.5
Winter wheat	*Yield (ton DM ha^{-1})*	Young	Tree row	6.6	7.1	7.7		
		Middle-aged	Tree row	6.4	7.4	8.4	9.4	9.9
			Control zone	8.0	8.3	8.7	9.1	9.4
		Long-standing	Tree row	3.3	4.0	4.6	5.3	5.6
			Control zone	7.0	6.9	6.9	6.8	6.8
	Dry matter (%)	Young	Tree row	84.0	84.4	84.7		
		Middle-aged	Tree row	82.7	83.0	83.4	83.7	83.9
			Control zone	84.5	84.6	84.7	84.8	84.9
		Long-standing	Tree row	80.1	80.2	80.3	80.3	80.4
			Control zone	83.5	83.7	83.8	84.0	84.1
	Crude protein (%)	Young	Tree row	12.2	12.4	12.6		
		Middle-aged	Tree row	16.0	15.6	15.3	14.9	14.7
			Control zone	13.2	13.3	13.5	13.6	13.7
		Long-standing	Tree row	16.6	16.0	15.4	14.9	14.5
			Control zone	13.4	13.4	13.5	13.5	13.6
Winter barley	*Yield (ton DM ha^{-1})*	Young	Tree row	7.1	7.1	7.1		
		Long-standing	Tree row	7.3	7.8	8.3	8.8	9.1
			Control zone	9.2	9.3	9.3	9.3	9.3
	Dry matter (%)	Young	Tree row	88.8	89.7	90.6		
		Long-standing	Tree row	86.1	86.3	86.5	86.7	86.8
			Control zone	89.2	89.3	89.4	89.6	89.7
	Crude protein (%)	Young	Tree row	9.6	9.5	9.3		
		Long-standing	Tree row	11.3	11.2	11.1	11.0	10.9
			Control zone	10.2	10.1	10.1	10.0	9.9

4.7.4 Appendix 4.4

a) Crude protein yield (kg ha^{-1}) of forage maize and winter cereals as function of tree row presence and distance (m) to tree row and/or treeless field edge for different tree sizes (young, middle-aged and long-standing trees). Fitted lines represent linear mixed-effect models with black dashed lines representing the tree row, and grey full lines the control plots. Significance of fixed effects: ns P >0.1, •P <0.1,*P <0.05,**P <0.01 and ***P <0.001, "D": distance, "T": Tree row presence, "DxT": interaction. Model formula: y= a*ln(distance in m) + b, "T-": Control zone, "T+": Tree row.



b) Linear mixed modelling results of crude protein yield (kg ha^{-1}) of forage maize and winter cereals. Included fixed effects are distance to the tree row in case of young alley cropping fields (“Young”) and distance to the field edge, presence or absence of a tree row (“T+/T-”) and their interaction in case of boundary planted fields (“Middle-aged” and “Long-standing”). Bold characters indicate significant effect (P-value<0.05). (•) indicates 0.05 < P-value < 0.10. “R^2c”: conditional R^2, “R^2m”: marginal R^2. Model formula: y= a*ln(distance in m) + b.

	Fixed effect			R^2c	R^2m	Parameter estimates LMM			
						Tree row		Control zone	
	Ln(distance)	T+T-	T+T-:Ln(distance)			a	b	a	b
Forage maize									
Young	**p<0.0001**			0.80	0.06	153.35	558.14		
Middle-aged	**p<0.0001**	p=0.0833•	**p=0.0432**	0.64	0.45	265.16	263.69	123.75	787.66
Long-standing	**p<0.0001**	**p<0.0001**	**p<0.0001**	0.87	0.84	429.53	-238.81	26.54	1367.55
Winter wheat									
Young	**p<0.0001**			0.95	0.04	126.85	694.25		
Middle-aged	**p<0.0001**	**p=0.0204**	p=0.0551•	0.54	0.20	167.37	887.38	90.81	980.51
Long-standing	**p=0.0005**	**p<0.0001**	**p=0.0003**	0.71	0.64	106.56	461.18	-6.72	938.90
Winter barley									
Young	p=0.6633			0.01	0.01	-17.26	704.06		
Middle-aged	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*
Long-standing	p=0.0660•	p=0.7581	p=0.0793•	0.68	0.05	61.08	771.93	-4.24	935.88

c) Crude protein yield (kg ha^{-1}) of forage maize and winter cereals (mean ± S.E.) for three tree size classes in the field zone between 2.5 and 12 m and 2.5 and 30 m of the tree rows and treeless field edges (based on LMM effect relations). “Control points” refers to the control plots on young alley cropping fields, “Control zone”: refers to the arable zone near the treeless field edge on fields with middle-aged and long-standing trees.

		Forage maize	Winter wheat	Winter barley
2.5 to 12m				
Young	Tree row	849±270	935±244	671±154
	Control points	1091±91	868±108	831±28
	Δ (%)	**-22.2**	**7.7**	**-19.3**
Middle-aged	Tree row	767±336	1205±178	*NA*
	Control zone	1023±272	1153±179	*NA*
	Δ (%)	**-25.0**	**4.5**	*NA*
Long-standing	Tree row	576±197	663±133	888±166
	Control zone	1417±153	926±109	928±181
	Δ (%)	**-59.4**	**-28.4**	**-4.3**
2.5 to 30m				
Middle-aged	Tree row	960±387	1327±207	*NA*
	Control zone	1113±314	1219±122	*NA*
	Δ (%)	**-13.7**	**8.9**	*NA*
Long-standing	Tree row	890±228	741±156	932±193
	Control zone	1437±177	921±126	924±202
	Δ (%)	**-38.1**	**-19.5**	**0.9**

5. Juglans regia in temperate arable agroforestry systems: effects on soil characteristics, arthropod diversity and crop yield

After: Pardon P., Mertens J., Reubens B., Reheul D., Coussement T., Elsen A., Nelissen V., Verheyen K., Juglans regia in temperate arable agroforestry systems: effects on soil characteristics, arthropod diversity and crop yield. Submitted to Renew. Agric. Food Syst.

5.1 Abstract

Agroforesty is considered to be a sustainable land use practice as it combines agricultural production with multiple beneficial effects such as carbon sequestration, enhanced nutrient cycling and increased biodiversity. Quantification of these beneficial effects in temperate arable fields is still limited, however, and most studies focus on one sole parameter (i.e., impact on crop productivity, soil quality, biodiversity, etc.). Combined effects are only rarely considered, resulting in a lack of integrated quantification. Here we assess the effect of rows of walnut trees (*Juglans regia* L.) on soil organic carbon (SOC), soil nutrient status, the presence of potentially beneficial ground-dwelling arthropods, and on the yield and quality of neighboring arable crops. Significantly higher SOC and soil nutrient concentrations were found near the trees, which is assumed to be primarily a result of tree leaf litter input. Abundance of macro-detritivorous arthropods was increased in and near the tree rows, whereas no significant influence of tree presence was found on the presence of the predatory arthropod taxa under study. Yield of all crops under study was reduced as a result of tree presence, with the strongest reductions observed for grain maize and sugar beet near the trees (<10 m). In addition, alteration of crop quality was observed near tree rows with decreased dry matter concentration of grain samples and increased crude protein concentration of winter cereals.

5.2 Introduction

The intentional inclusion of trees and shrubs into crop and/or animal production systems on the same land is referred to as “agroforestry”, a term first used by Bene et al. (1977) (Dupraz and Liagre, 2008; Nair et al., 2010; Smith et al., 2012a). As a result of agricultural intensification and mechanization, the occurrence of woody features in the agricultural matrix has substantially decreased throughout the 20th century (Quinkenstein et al., 2009; Torralba et al., 2016). Although this transition to intensified production methods has increased use-efficiency and productivity of agricultural land, it is simultaneously associated with negative effects such as increased soil erosion, water pollution, and biodiversity loss (Mast et al., 2012; Matson et al., 1997; Tscharntke et al., 2005). Recently, interest in agroforestry has been growing again, because this type of cropping system has been linked to the potential mitigation of several of the side-effects of intensified production (Malézieux et al., 2009; Reisner et al., 2007; Tsonkova et al., 2014).

As described higher, production systems with rows of trees alongside or in the fields (e.g., alley cropping, boundary planting) appear to offer a promising land use alternative (Quinkenstein et al., 2009; Tsonkova et al., 2012). This form of AFS can efficiently be combined with the use of modern farming techniques and machinery for the cultivation of crops in the intercropping zone between the tree rows. The potential beneficial effects of tree rows on several regulating (e.g., biological pest control, carbon sequestration), supporting (e.g., soil fertility, nutrient cycling, habitat) and provisioning (overall agricultural productivity) ES are described by various authors (Jose et al., 2004; Pardon et al., 2017; Quinkenstein et al., 2009; Tsonkova et al., 2012). Until now, quantification of these beneficial effects in temperate arable fields has been limited for several aspects and for different tree-crop combinations. In addition, demand for the reliable provision of almost all ES is increasing (Bennett et al., 2009; MEA, 2005), whereas most studies focus on only one aspect of how the woody component affects the ES (e.g., the impact on crop productivity, soil quality, biodiversity or another parameter) but rarely a combination of all of them (Bianchi et al., 2006; Fagerholm et al., 2016; Jose, 2009; Power, 2010; Thomas et al., 2001; Torralba et al., 2016). As a result, observed beneficial effects are often assumed to affect crop yield, for instance, without simultaneous measurement. This lack of integrated quantification is assumed to be one of the primary stumbling blocks to translate the abovementioned increased interest in AFS into increased adoption in practice (Luedeling et al., 2016; Tsonkova et al., 2014).

Here we used an integrated approach to assess the effect of rows of walnut trees (*Juglans regia* L.) on soil organic carbon (SOC), soil nutrient status, the presence of potentially beneficial ground-dwelling arthropods and the yield and quality of neighboring arable crops. Walnut trees are economically important because of their fruits and valuable timber (Reisner et al., 2007). Moreover, they are characterized by a late budburst (Dufour et al., 2013) which delays competition for light with neighboring arable crops. As a result, they are considered a suitable tree species for use in AFS. We hypothesized that tree row presence results in i) an increase in SOC and soil nutrients, ii) an increase in abundance and diversity of ground-dwelling arthropods and iii) a crop type dependent influence on crop yield and quality.

5.3 Material and methods

5.3.1 Study site

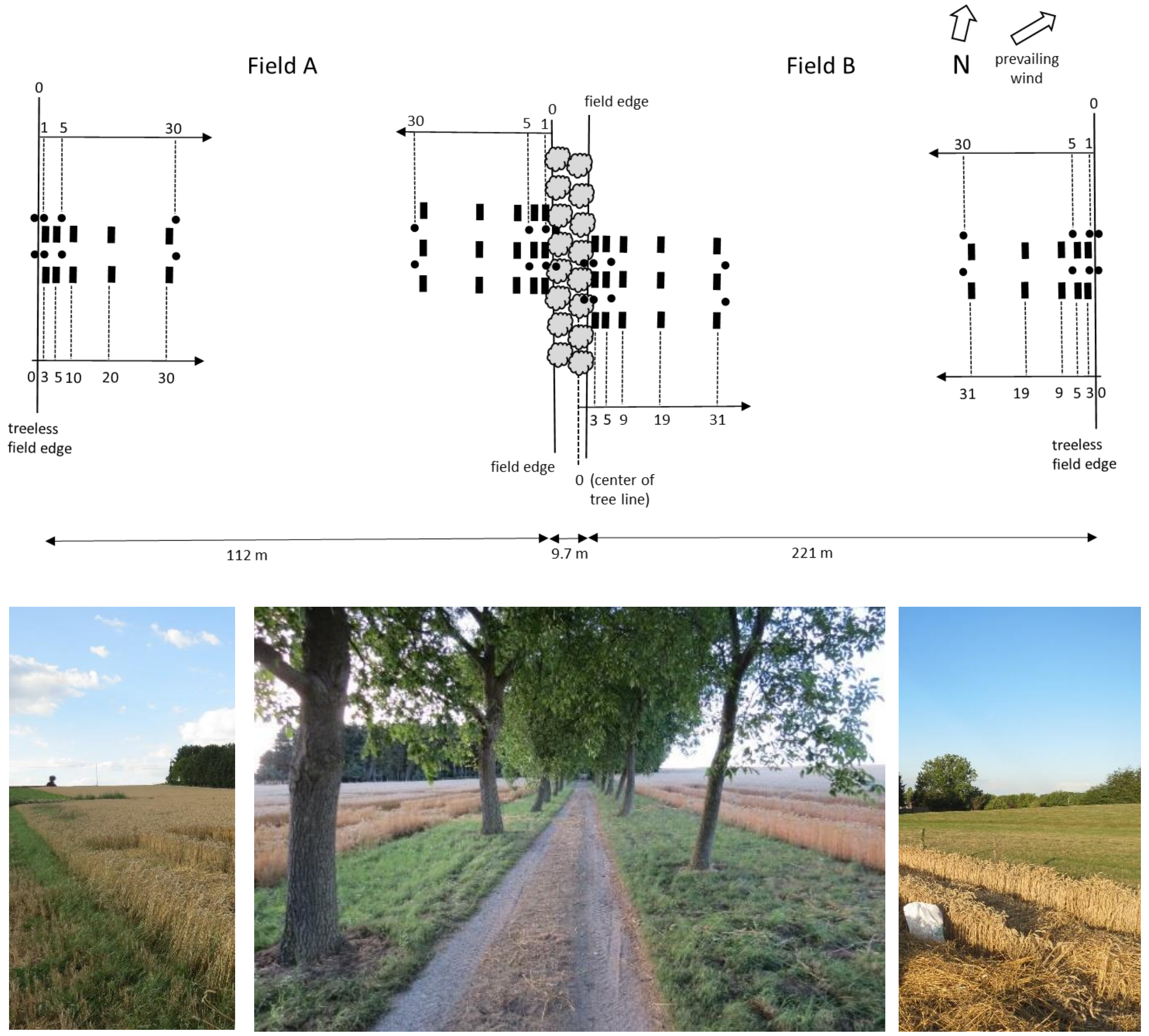


Figure 5.1: Experimental design near tree rows and treeless field edges. The black rectangles denote locations of soil sampling and harvest measurements, black dots denote locations of pitfall traps. Below: tree rows (middle) and treeless control situations (left and right). Length of the tree row and the treeless control borders on field "A" and "B" equals 251, 108 and 240 m, respectively.

In Belgium, mature alley cropping systems or boundary planted fields with walnut are scarce. Therefore, a double alley of walnut trees, bordered on each side by an arable field, was used as a proxy to study the effect of mature walnut tree rows on a set of soil characteristics (2015), ground-dwelling arthropod fauna (2015-2016) and crop yield (2015-2016-2017) in AFS (Figure 5.1, Table 5.1). The tree rows are oriented north-south, which is commonly considered to be the most favorable orientation for temperate AFS (Reynolds et al., 2007; Smith et al., 2012b). The field with trees on its east side is called “field A” below; the field with trees on its west side, “field B”. The distance between the two rows, which are separated by a path, equals 4.7 m. As indicated in 1.4, the intra-row distance between trees is approx. 9 m. The trees were planted in 1947, diameter at breast height (DBH) and height of the trees equal 41.8 cm and 12.8 m, respectively. The total width and length of the tree row equals 9.7 m and 251 m, respectively. The grass in the alleys is mown to facilitate harvest of the walnuts. The soil was a Haplic Luvisol (loess parent material). Climatic conditions are given in Table 5.1 and field management was as described in 1.4. Both arable fields are only partially bordered by the tree rows. The length of the treeless control border of fields “A” and “B” equals 108 m and 240 m, respectively.

Table 5.1: crop rotation on the arable fields.

Field	*2015*	*2016*	*2017*
A	Winter wheat	Winter triticale	Sugar beet
B	Winter wheat	Winter barley	Grain maize

5.3.2 Soil sampling

In both fields perpendicular to the tree rows and to the treeless borders, three and two transects were installed, respectively (Figure 5.1). In each transect, five sampling plots (1.5 m x 6.5 m) were marked, the center of which was located at distances approximately 3, 5, 10, 20 and 30 m away from the tree row/treeless field edge. If a sampling plot coincided with a tire track resulting from agricultural machinery use, the plot was repositioned slightly to a location next to the track. To ensure a representative sample, each sample consisted of a mixture of eight subsamples taken within the plough layer (0-23 cm) of these plots with a gouge auger. Soil sampling was conducted on January 19th 2016, before the fields were fertilized. After sieving (<2 mm), the soil samples were analyzed for plant available K, P, Mg, Na and Ca using inductively coupled plasma after extraction in ammonium-lactate (Egnér et al., 1960). Total N was determined by Kjeldahl digestion (reference method: ISO 11261). A heated potassium dichromate oxidation was used to analyze SOC (reference method: ISO 14235:1998). pH-KCl of soil samples was determined at a 1:5 soil:liquid (volume fraction) ratio with H_2O and 1 M KCl (reference method: ISO 10390).

5.3.3 Functional biodiversity: ground-dwelling arthropods

Two transects were installed perpendicular to the tree rows and to the treeless borders in each field (Figure 5.1). In each transect, four sampling points were marked: one in the field edge and three at distances 1, 5 and 30 m away from the field edge. At each sampling point a pitfall trap (9 cm opening diameter, volume 300 ml) was installed on May 25th 2015. Traps were filled with 200 ml of a 50% propylene glycol (antifreeze) solution with detergent to reduce surface tension. The traps were kept in place during four weeks until June 22th 2015, and were emptied once in between on June 8th 2015. The collected arthropods were stored in 70% ethanol. Further analysis focused on two taxonomic groups of macrodetritivores which may enhance nutrient and carbon cycling, i.e. woodlice (Isopoda) and millipedes (Diplopoda). In addition, two predatory taxa which may contribute to biological pest control were investigated, i.e. carabids (Coleoptera: Carabidae) and rove beetles (Coleoptera: Staphylinidae) (Bianchi et al., 2005; Garratt et al., 2017; Holland and Luff, 2000). The total number of woodlice, millipedes, carabid beetles and rove beetles caught was counted for each trap. The captured specimens of every taxon, except for rove beetles, were identified to species level. This procedure was repeated in 2016.

5.3.4 Crop yield and quality

Crop yield was measured following a crop-specific protocol in each of the plots used for soil sampling. The location of transects and sampling plots was maintained as strictly as possible throughout the consecutive sampling years, as different crops were grown during the monitored period on the fields in the dataset (Table 5.1). Winter wheat (*Triticum aestivum* L.), winter barley (*Hordeum vulgare* L.) and winter triticale (x *Triticosecale* Wittm.) were harvested using a Wintersteiger plot combine (type: *NM elite*) and the harvested grain (caryopses) was weighed. On the field intercropped with grain maize (*Zea mays* L.) in 2017, every sampling plot consisted of two neighboring rows over a total length of 5 m (interrow distance 0.75 m). The cobs were threshed using a Wintersteiger combine. A similar approach was used in 2017 when sugar beets (*Beta vulgaris* L.) were grown: two neighboring rows were harvested over a total length of 5 m (interrow distance 0.45 m). Leaves and petioles of sugar beets were harvested separately from roots to determine shoot:root biomass ratio. A representative sample of the harvested crop was collected for every plot for further quality analyses. Samples were oven-dried at 70° to determine dry matter (DM) concentration. Crude protein concentration of winter cereals was determined after grinding using Near Infrared Spectroscopy (reference method: ISO 5983-2).

5.3.5 Data analyses

Gradients in soil variables, yield and crop quality were modeled using a linear-mixed effect model (LMM). Distances to field edges were transformed logarithmically to linearize the response variables. The logarithm of the distance to the field edge, the presence/absence of a tree row and their interaction were included as fixed effects. The data have a hierarchical structure with measuring points nested in transects. These transects are in turn nested at the level of the experimental field. To account for this hierarchical nature and non-independence of the data within fields and transects, “field” and “transect” nested in field were included as random effects.

Average concentrations of SOC, soil nutrients, crop yield and quality were obtained for the field zone between 3 and 30 m of the tree rows. This was done based on integration of the LMM effect relations, because 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).

Equation 1:

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

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).

The occurrence of the arthropod groups under study is described in terms of activity-density (number of individuals), because the number of invertebrates caught in the pitfall traps is a function of both their population density and activity (Thomas et al., 1998). Species richness (number of different species) of each sample was calculated separately for woodlice, millipedes and carabid beetles. A generalized mixed effects model with a Poisson error structure was used to investigate differences in activity-density and species richness. The position in relation to the field edge, the presence/absence of a tree row and their interaction were included as categorical fixed effects. “field”, “transect” nested in field and the year of sampling were included as random effects.

All analyses were performed using the software program “R” (R Development Core Team, 2016).

5.4 Results

5.4.1 Soil characteristics

Significant variation was found for SOC, soil nutrient concentrations of N, K, Mg, P, Ca and pH-KCl. These variations can be explained by the interaction between presence/absence of a tree row and distance to the field edge (Table 5.2, Figure 5.2). The largest increases of abovementioned variables were found near the field edge with trees. Values at a distance of 3 m from the tree row displayed a 22, 16, 59, 33, 103, 32 and 5% increase for SOC, N, K, Mg, P, Ca and pH-KCl, respectively, when compared to sampling locations at the same distance of the treeless field edge. These differences decreased exponentially with increasing distance to the field edge. As a result of the observed gradients, an average increase in SOC stock of 2.3 ton ha^{-1} was seen in the AFS within the field area under study (i.e., the zone between 3 and 30 m from the tree row) (Table 5.2), corresponding with an average SOC accumulation rate of 33 kg C ha^{-1} yr^{-1}. Similarly, the observed differences in soil nutrient concentration correspond to an average increase in soil nutrient stocks near the tree rows (i.e., the zone between 3 and 30 m from the tree row) of 156 kg K ha^{-1}; 23 kg Mg ha^{-1}; 157 kg P ha^{-1} and 168 Ca kg ha^{-1} when compared to the control part of the field. An average decrease in total N stock of 25 kg ha^{-1} was found in the 0–23 cm soil layer.

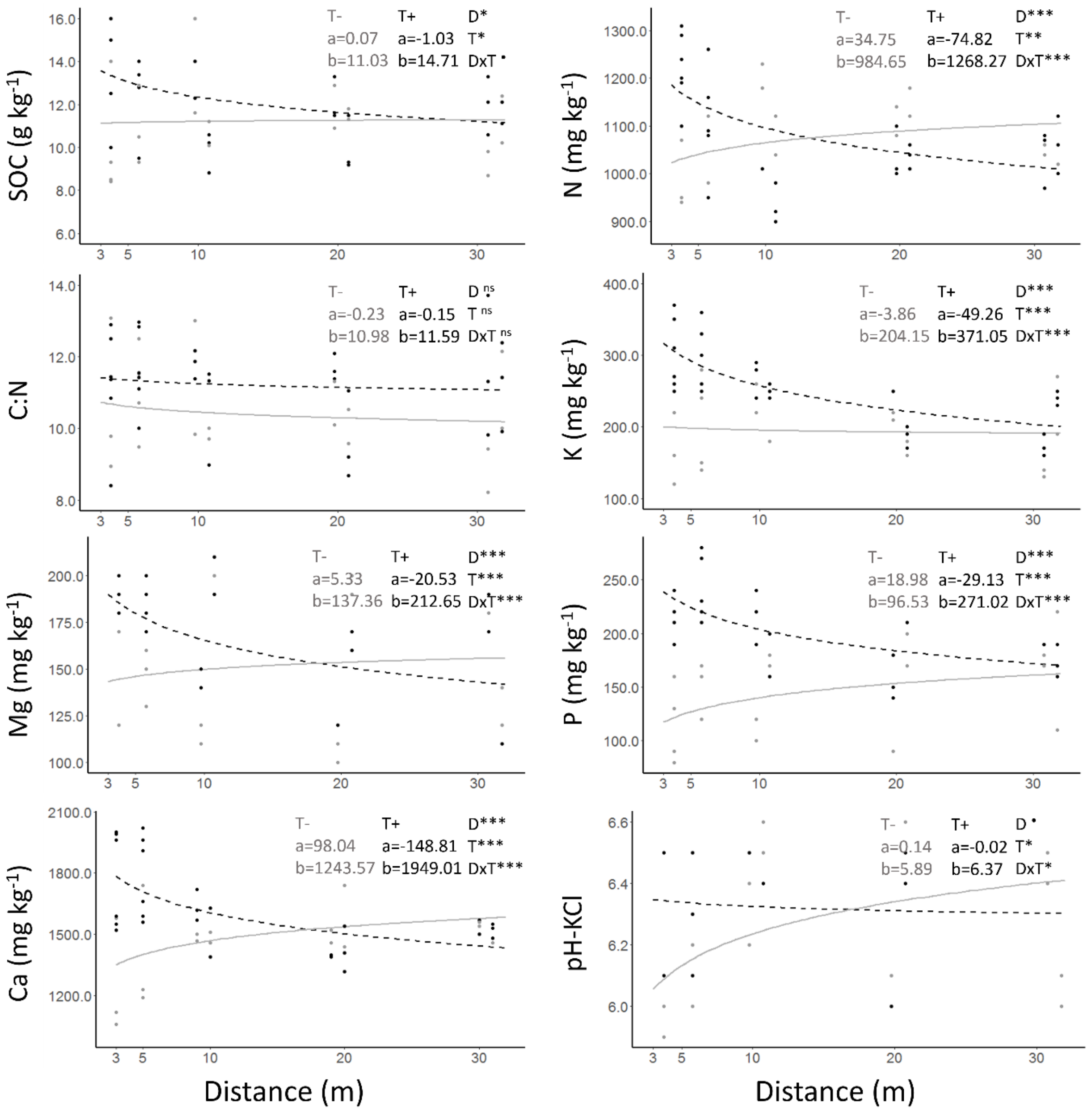


*Figure 5.2: Soil characteristics as function of distance (m) to tree row and/or treeless field edge. Lines according to linear mixed modeling results, black (dashed): tree row, grey: control zone. Model formula: Y= a*log (distance in m) +b. Significance of fixed effects: $^{\bullet}P < 0.1$, $^{*}P < 0.05$, $^{**}P < 0.01$ and $^{***}P < 0.001$, “D”: distance, “T”: Tree row presence, “DxT”: interaction.*

*Table 5.2: Linear mixed modelling (LMM) results for soil characteristics (SOC: g (kg dm)$^{-1}$, soil nutrient concentrations: mg (kg dm)$^{-1}$), crop yield (ton DM ha^{-1} of grain in case of winter cereals and maize and of roots in case of sugar beet) and crop quality (dry matter conc.: %, crude protein conc.: %). Fixed effects include distance to the field edge, presence or absence of a tree row ("T+/T-") and their interaction. Model formula: Y= a*log (distance in m) +b. Bold characters indicate P-value<0.05. (•) indicates 0.05 < P-value < 0.10. "R²c": conditional R², "R²m": marginal R². SOC- (ton ha^{-1}) and soil nutrients stocks (kg ha^{-1}) along the evaluated transects (i.e. between a distance of 3 and 30m from the field edge) are expressed in kg ha^{-1}. "Δ (%)": relative difference between average yield or quality near tree row and control zone.*

	Fixed effect					Average (±S.E.)			
	Ln(distance)	T+T-	T+T- :Ln(distance)	R²c	R²m	Tree row (n=30)	Control zone (n=20)		
SOIL CHARACTERISTICS								*Soil nutrient stocks in kg ha^{-1} (0-23 cm)*	
								Tree row	*Control zone*
SOC	**0.0435**	**0.0258**	0.0568•	0.53	0.13	12.0±2.4	11.2±3.0	40.4	38.1
N	0.0597•	0.3756	**0.0003**	0.47	0.22	1069.5±105.9	1077.0±150.5	3609	3634
C:N	0.3917	0.0592•	0.8550	0.40	0.08	11.2±1.6	10.4±2.3	-	-
K	**<0.0001**	**<0.0001**	**<0.0001**	0.87	0.38	240.2±51.7	193.9±46.4	810	654
Mg	**0.0020**	**0.0080**	**<0.0001**	0.88	0.12	158.1±36.0	151.5±27.7	534	511
P	**0.1280**	**<0.0001**	**<0.0001**	0.57	0.57	193.6±38.0	147.0±60.2	653	496
Ca	0.0541•	**0.0031**	**<0.0001**	0.42	0.21	1553.6±190.7	1504.1±248.6	5243	5075
pH-KCl	0.2633	0.1379	**0.0323**	0.19	0.14	6.3±0.3	6.3±0.4	-	-
CROP YIELD AND QUALITY								*Δ (%) Tree row vs. Control zone*	
Winter wheat									
Ton (DM)	**<0.0001**	**0.0019**	**<0.0001**	0.82	0.66	11.3±1.9	11.9±1.7	-5.0	
Dry matter (%)	0.1981	**0.0035**	**0.0017**	0.88	0.07	82.7±0.7	83.3±1.0	-0.7	
Crude protein (%)	**0.0414**	**<0.0001**	**<0.0001**	0.83	0.28	14.8±2.0	13.6±2.3	8.9	
Winter barley									
Ton (DM)	**<0.0001**	**0.0001**	0.5272	0.79	0.79	6.6±0.7	7.4±0.6	-10.6	
Dry matter (%)	**<0.0001**	**0.0006**	**<0.0001**	0.85	0.85	86.8±1.4	87.7±1.1	-1.0	
Crude protein (%)	0.7345	**0.0031**	**0.0041**	0.49	0.49	12.5±2.3	11.6±1.8	8.1	
Winter Triticale									
Ton (DM)	**<0.0001**	**0.0123**	**0.0139**	0.87	0.80	7.1±1.6	8.0±1.2	-11.9	
Dry matter (%)	**<0.0001**	0.1014	**0.0211**	0.66	0.63	83.4±1.3	83.6±1.0	-0.2	
Crude protein (%)	0.4008	0.1219	**<0.0001**	0.62	0.62	13.5±1.5	13.4±1.2	0.6	
Sugar beet									
Ton (DM)	**<0.0001**	**0.0002**	**0.0015**	0.87	0.87	22.5±4.8	26.4±3.7	-14.8	
Dry matter (%)	0.5589	0.3285	0.2326	0.09	0.09	23.9±1.2	23.9±0.9	0.0	
Shoot:root	**<0.0001**	**0.0414**	0.3459	0.53	0.53	0.24±0.1	0.22±0.1	11.3	
Grain maize									
Ton (DM)	**<0.0001**	**0.0138**	**<0.0001**	0.82	0.82	8.8±3.5	9.6±2.7	-7.8	
Dry matter (%)	0.3268	**0.0008**	0.1050	0.62	0.65	75.5±3.7	78.5±2.9	-3.8	

5.4.2 Functional biodiversity

A total of 506 woodlice (5 species), 845 millipedes (9 species), 1837 carabids (34 species) and 1894 rove beetles were captured (Appendix 5.1). Significantly increased activity-density values were found for woodlice in and near the tree rows as compared to either 30 m into the field or at the treeless field edges. Species richness of woodlice was significantly higher in the tree rows when compared to the treeless field edges or to 30 m from the tree rows (Table 5.3, Figure 5.3). A limited effect of distance to the field edge was observed near the trees for activity-density of millipedes, with increased values when compared to 30 m from the tree row. However, for the latter type of macro-detritivore, no significant differences in species richness were observed. Activity-density of pest predatory arthropods was increased at further distances (30 m) into the field when compared to the field edge (Table 5.3, Figure 5.3).

Table 5.3: (Generalized) Linear Mixed Modelling results of arthropod groups. Included fixed effects are presence or absence of a tree row ("T+/T-"), distance to the field edge ("Distance") and their interaction. Bold characters indicate P-value<0.05.

Main effect:		Distance	T+T-	Distance:T+T-
Woodlice	Activity-density	**<0.0001**	**0.0001**	**<0.0001**
	Species richness	**0.0026**	**0.0210**	**0.0126**
Millipedes	Activity-density	**0.0004**	0.5193	**<0.0001**
	Species richness	0.6419	0.6194	0.8211
Carabids	Activity-density	**<0.0001**	**0.0316**	0.1566
	Species richness	0.1620	0.7604	0.4390
Rove beetles	Activity-density	**<0.0001**	0.1728	**0.0042**

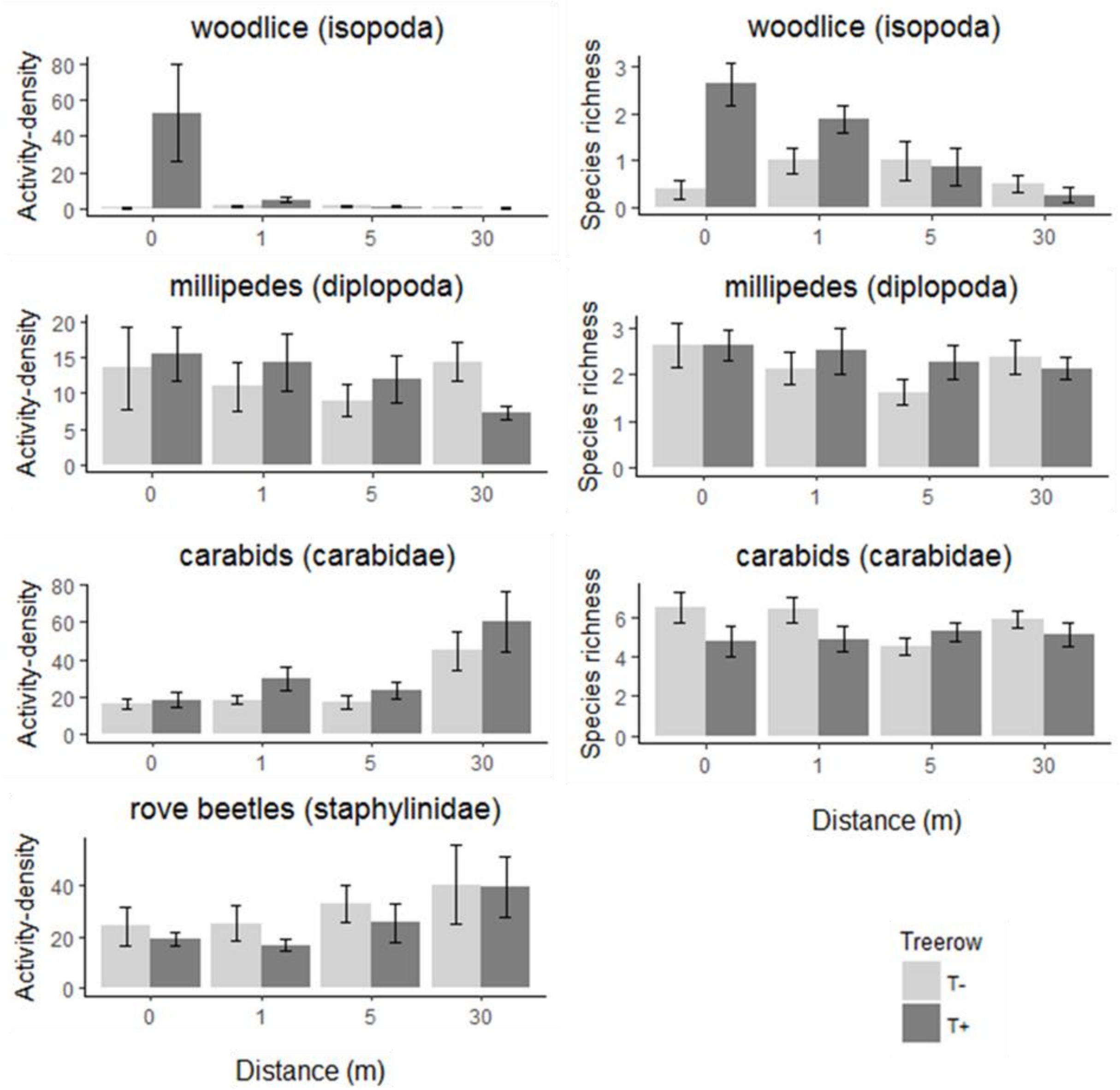


Figure 5.3: Activity-density and species richness of woodlice, millipedes and carabids and activity-density of rove beetles. (dark grey: tree row, light gray: control zone. “T+”: field edge with tree row, “T-”: treeless field edge. Barplots and errorbars indicate mean ± S.E.

5.4.3 Crop yield and quality

Significant variation in crop yield was observed for all crops (Table 5.2, Figure 5.4). This can be explained by the interaction between tree row presence and distance to the field edge for winter wheat, triticale, grain maize and sugar beet. The variation in yield of winter barley can be explained by tree row presence and distance from the field edge. The largest reductions in crop yield were observed at the sampling plots closest to the field edge (3 m) where crop yield was 36, 33, 40 and 75 % lower near the trees for winter wheat, winter triticale, sugar beet and grain maize, respectively, in comparison to the same distances in the control zone (Table 5.2, Figure 5.4). Yield of winter barley decreased as distance from the field edge decreased, but was consistently lower near the trees at all sampling distances when compared to the control zone. Average reductions in crop yield in the transects near the trees (between 3- 30 m) equaled 5.0 %, 10.6 %, 11.9 %, 14.8 % and 7.8 % for winter wheat, winter barley, winter triticale, sugar beet and grain maize, respectively, as compared to the control zone.

Dry matter concentrations of winter barley, triticale and grain maize significantly decreased near the tree rows. An opposite trend was found for dry matter concentration of winter wheat with increasing values at smaller distances to the trees. Crude protein concentration of winter wheat, barley and triticale and shoot:root ratio of sugar beets were significantly increased near the tree rows (Table 1, Fig. 4).

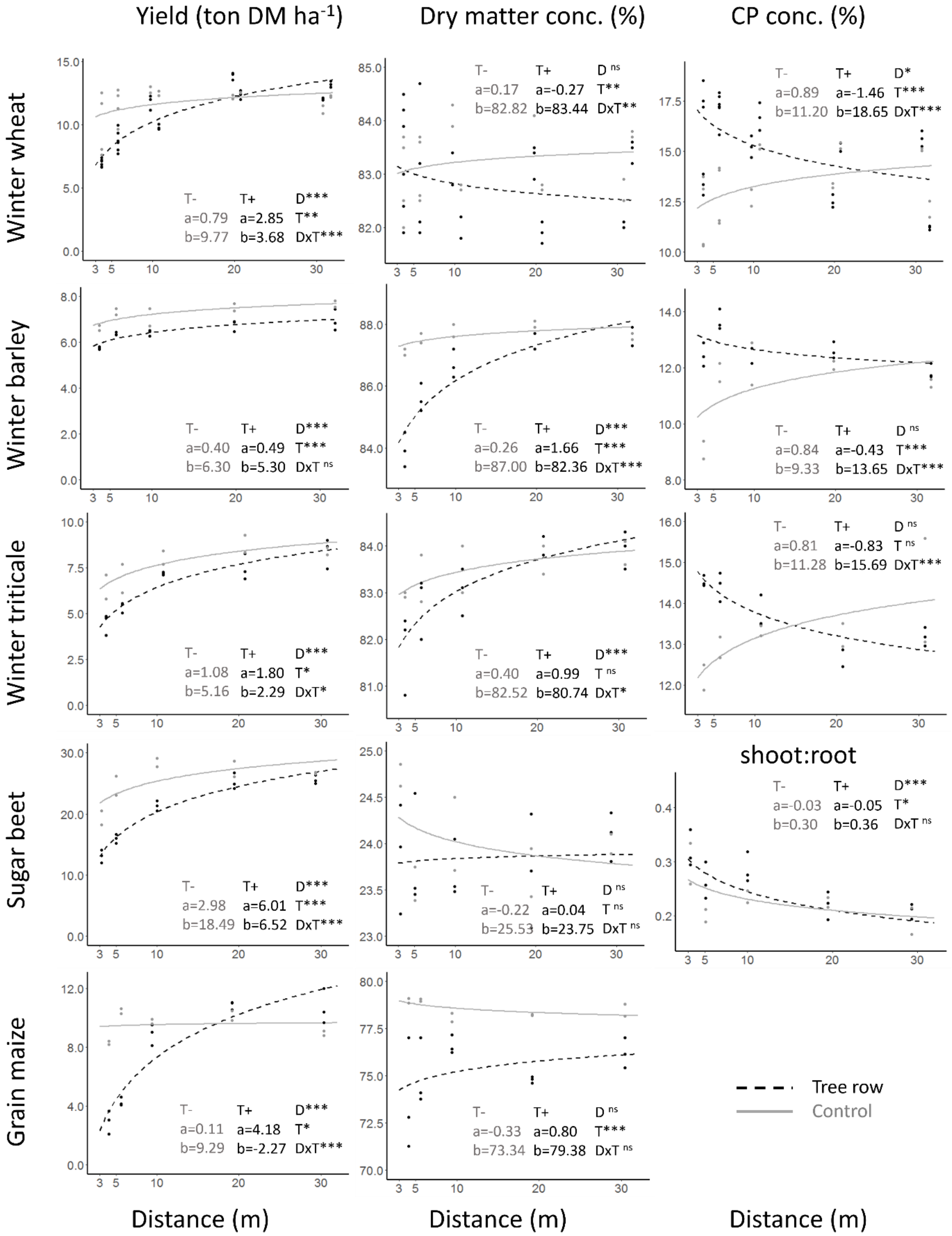


*Figure 5.4: Crop yield (ton DM ha^{-1} of grain in case of winter cereals and maize and of roots in case of sugar beet), dry matter concentration (%), crude protein concentration "CP" (%) and shoot:root ratio of 5 arable crops as function of distance (m) to tree row and/or treeless field edge. Lines according to linear mixed modeling results, black (dashed): tree row, grey: control zone. Model formula: Y= a*log (distance in m) +b. Significance of fixed effects: *P <0.05,**P <0.01 and ***P <0.001, "D": distance, "T": Tree row presence, "DxT": interaction.*

5.5 Discussion

5.5.1 Soil characteristics

Soil organic carbon (SOC)

As hypothesized, increased SOC values were found near the tree rows, which confirms the potential of AFS for belowground (0-23 cm) carbon-sequestration in arable fields. As described in chapter 2 and also suggested by several authors including Bambrick et al. (2010); Cardinael et al. (2017) and Nair et al. (2009), explanatory factors for the observed effects are considered to be the input of organic matter via tree leaf litterfall, and to a lesser extent via branchfall and root decomposition processes. The significant effect of distance to trees on SOC has also been observed in alley cropping fields by among others Wotherspoon et al. (2014). In contrast, several authors have found a homogeneous increase near tree rows in the intercropping zone of alley cropping fields (Bambrick et al., 2010; Cardinael et al., 2015a; Peichl et al., 2006), which was attributed to the limited interrow distances (8 to 15 m) on the fields. Cardinael et al. (2015) analyzed SOC in an alley cropping field near walnut tree rows of a height similar to the trees in our study. The authors observed an increase in SOC stock of 2.1 ton ha^{-1} (0-30 cm soil layer) in the intercropping zone when compared to sole cropping conditions, which is similar to the increase of 2.3 ton observed in our research. The average SOC accumulation rate of 115 kg C ha yr^{-1} observed by Cardinael et al. (2015) is considerably higher than the rate of 33 kg C ha yr^{-1} observed here, probably as a result of the abovementioned limited interrow distance. Similar to our results, reduced crop yields were observed near the tree rows (15% reduction between 1 to 2 m distance) on the fields studied by Cardinael et al. (2015a) as measured by Dufour et al. (2013). As the authors suggested, this may have resulted in lower carbon inputs from crop residues, but this was assumed to be partly counterbalanced by an increased carbon input from tree fine root mortality as a result of the simultaneous increase in tree fine root density observed in the abovementioned zone (Cardinael et al., 2015a).

Soil nutrient conditions

The significantly higher soil nutrient concentrations indicate an increased nutrient availability for the agricultural crop in the arable zone near the tree rows. Similar to SOC, input via leaf litter is considered to be a major causal factor, although in case of K, an additional input may have resulted from nutrient-enriched throughfall water (Meiresonne et al., 2007; Zhang, 1999). In addition, our research seems to confirm that the altered microclimate near tree rows due to increased shade and humidity and the input of organic material may benefit the soil meso- and macrofauna (Jose et al., 2000b; Souty-Grosset et al., 2005). As suggested by Jose et al. (2000), this may result in a more favorable environment for decomposition, which could accelerate nutrient release. Finally, although no total biomass measurements were conducted for winter cereals and grain maize, the decreased crop yields near the trees may indicate that the higher soil nutrient concentrations partly result from a reduced crop uptake. However, this is not considered to be the sole determining factor, considering crop yields were also reduced near the treeless field edges, where no simultaneous increase in soil nutrient concentrations was found.

5.5.2 Functional biodiversity

Macro-detritivores

The increased abundance and species richness of woodlice in the tree rows is assumed to be related to the favorable habitat and refuge conditions such as increased food sources, shade and soil and air humidity (woodlice, like most detritivores, are drought-sensitive organisms) (Dias et al., 2013; Peng et al., 1993; Smith et al., 2008b, 2008a; Souty-Grosset et al., 2005). This contrasts with the arable zone, where the agricultural management may create strongly adverse conditions for survival and reproduction. However, the favorable conditions in the tree rows may lead to a spill-over effect of woodlice into the neighboring arable zone. This colonization effect may be augmented through the mitigating by the trees of adverse field conditions and the creation of a favorable microclimate, e.g., by the abovementioned input of organic matter, shade, etc. (Jose et al., 2000b). The effect on activity-density in the arable zone was, however, considerably smaller near the walnut trees when compared to the results observed in chapter 3, where the effects of mature poplar rows on arthropod abundance were investigated. This may be related to the smaller size (both height and DBH) of the walnut trees and hence the more limited effect on microclimatic conditions in the arable zone in comparison to poplar.

The effect of tree row presence on the presence of millipedes appeared to be substantially smaller when compared to woodlice, which may be caused by the relatively higher drought-resistance of millipedes when compared to woodlice (Berg et al., 2008; Dias et al., 2013; Edney, 1977). Particularly the open-habitat species *Polydesmus inconstans*, *Cylindroiulus caeruleocinctus* and *Brachyiulus pusillus* comprised approximately 96% of all millipedes caught in this study. This value is considerably higher than the value observed near poplar trees in chapter 3, where the share of abovementioned species equaled 62% close to the poplar trees. This dissimilar tree-effect might again be related to the smaller size of the walnut trees and hence a limited effect on the microclimate in the arable zone.

Carnivorous taxa

The higher abundances of carabids and rove beetles in the arable zone when compared to the field edge were unexpected, considering that the majority of natural enemies need non-crop habitats for hibernation and reproduction as well as alternative prey (Andersen, 1997; Landis et al., 2000). Although surprising, these findings were nonetheless similar to the observations near poplar tree rows (chapter 3). As suggested in 3.5, the increased activity-density values in the field may be the result of a potential redistribution of both carabids and rove beetles from perennial (woody) refuges into the field early in the season (Dennis et al., 1994; Desender, 1989; Geiger et al., 2009; Pfiffner and Luka, 2000; Riedel, 1991). The colonizing movement of these often highly mobile arthropod-species may be driven by factors such as the presence of higher prey densities in the crop or a preference for open habitat conditions (Fournier and Loreau, 2001; Marrec et al., 2015; Thomas et al., 2002). However, given the timing of the monitoring period (May-June), this early-season colonization may potentially not have been detected.

5.5.3 Crop yield and quality

In temperate AFS, competition for light (Reynolds et al., 2007), water (Graves et al., 2007; Miller and Pallardy, 2001) and/or nutrients (Gillespie et al., 2000; Jose et al., 2000b) are considered to be the main factors through which trees influence crop yield. Our results indicate that competition for nutrients can be assumed to be of minor importance for the observed yield losses. However, depending on o.a. tree and crop species (Reynolds et al., 2007) and spatial layout (Luedeling et al., 2016), differences in light and water availability may cause considerable variation in crop yield in AFS.

To limit tree-crop competition, winter crops are often favored over spring crops in temperate AFS because of the smaller overlap in growing season and hence in resource needs (Artru, 2017; Gill et al., 2009). This is above all the case if combined with deciduous tree species characterized by a late budburst such as walnut (Dufour et al., 2013). Indeed, yield reductions were lowest for winter cereals when compared to grain maize and sugar beet in the immediate vicinity of the trees (<20 m). In similar research, investigating yield of winter cereals in AFS, this yield loss was attributed to a.o. reduced seed germination, lower grain number per ear and bad grain filling (Artru et al., 2016; Chauhan et al., 2012; Dufour et al., 2013). The reduced grain yield of winter cereals is partly compensated by an increased protein concentration near the trees. This was also observed by (Artru et al., 2016) where application of artificial shade was linked to smaller wheat grain sizes with, as a result, remobilization of N accumulated by the plant leading to a relatively higher grain protein concentration. Remarkably, at distances farther from the field edge (20 m and beyond), yield levels of winter wheat within the transects perpendicular to the tree rows regularly exceeded the yield levels within the control transects. As a consequence, the overall yield reduction observed for winter wheat was quite low and this phenomenon may be related to the creation of a favorable microclimate resulting from tree-presence characterized by for example lower wind stress, resulting in reduced evapotranspiration and higher soil moisture content (Cleugh, 1998; Smith et al., 2012a; Thevathasan and Gordon, 2004). However, no such increase in crop yield was observed at farther distances into the field for winter barley and triticale. The observed decrease in dry matter concentration of winter barley and triticale samples near the tree rows has also been observed by other authors in case of winter wheat (Artru, 2017; Chauhan et al., 2011), where this was attributed to a delay in physiological maturity and/or ripening of the crop near the tree rows. In addition, harvesting of wheat and/or barley was not started before noon, as is common practice in north-western Europe to allow the evaporation of humidity originating from nocturnal fog. The aim is to increase the dry matter concentration of the grain. However, as also described in chapter 4, this evaporation may have been hampered near the tree rows as a result of potential reductions in wind speed and increased shading. These heterogeneities at the field-level might potentially be overcome by postponing the harvest activities to a later time in the growing season as well as harvesting at later times of the day (Pardon et al., 2018). The observed increase in dry matter concentration of the wheat samples near the tree rows in our research (in comparison to farther into the field) probably results from a sheltering effect of the tree crown, as the experimental fields with wheat were subject to rainfall during the morning of the day of harvest.

Sugar beet, a spring crop, displays a significant overlap of its growing season with the tree component. This results in simultaneous demands for resources (e.g., light, water) in time and space (Artru, 2017). With an overall reduction of 14.8%, this yield loss is three times higher than the loss observed for winter wheat. The relatively strong effect of tree presence on root yield of sugar beets is in accordance with the findings of Artru (2017), who performed an artificial shade experiment mimicking shade regimes of hybrid walnut. Thereby, reductions of root yield up to 73% were observed depending on shade regime and, similar to our research, an increase in shoot:root ratio as well as petiole length. Although similar detrimental effects on beet yield were observed by Mirck et al. (2016) near tree rows (3 m) when compared to control levels, increased yields were observed farther from the trees (> 12 m), which was attributed to the beneficial effect of tree-presence on microclimatic conditions. This could not be confirmed in our research, however, with yield levels at the farthest distance (30 m) approaching but not surpassing control levels.

The largest effects on crop yields were found for grain maize near the trees (<10 m). The potential detrimental effect of trees on grain maize yield was also observed by Gillespie et al.

(2000), Peng et al. (2009), Reynolds et al. (2007), and others. Grain maize is a spring crop, but also uses the C4 pathway of photosynthesis and hence becomes light saturated at near full sunlight (approximately 1200 µmol m^{-2} s^{-1} in Flanders), whereas C3 plants (e.g., wheat, beets) become light saturated at approximately 50% of full sunlight (Yin and Struik, 2009). As a result, net assimilation (or ultimately crop growth or yield) of grain maize generally is considerably more susceptible to tree-shading when compared to C3 plants (Reynolds et al., 2007).

5.5.4 Synergies and trade-offs in ES delivery

In an agricultural context, an increase in biodiversity, regulating and supporting ES is often considered as a trade-off with the provisioning ES (Foley et al., 2005; Power, 2010; Torralba et al., 2016). The simultaneous enhancement of the former variables was confirmed in our research near tree rows with walnut, although the observed beneficial effect on abundance and diversity of arthropods was restricted to the macro-detritivorous taxa under study. Crop yield was reduced near the trees and lowest yields were found where the largest increase in SOC, nutrients and presence of macro-detritivorous arthropods was observed. This may confirm the abovementioned trade-off. However, in contrast to several other environmental measures (e.g. input reductions), a primary concept of agroforestry is that the tree strips maintains a production function (e.g., wood, fruit) and hence contribute to the overall provisioning service of AFS. Further optimization of this provisioning service may be achieved by integrating the production of additional agricultural goods in the woody strips (i.e., berry producing shrubs, vegetables, poultry, etc.). The resulting high diversity of agricultural production may furthermore contribute to increased resilience against fluctuations, for example in production costs and market prices (Liebman and Schulte-Moore, 2015) and climate variability or extreme climate events (Altieri et al., 2015; Lin, 2011).

5.6 Conclusion

Increased SOC, soil nutrient concentrations and presence of macro-detritivorous arthropods and decreased crop yields were found near the walnut tree rows in our research. This seems to confirm the trade-off between the enhancement of biodiversity, supporting and regulating ES on the one hand, and provisioning ES on the other hand in conventional agricultural systems. However, the tree strips in AFS maintain a production function (e.g., wood, fruit) which contributes to the provisioning service of this agricultural system and may at least partly compensate for the loss in crop yield. In addition, the resulting diversification of agricultural production may contribute to increased resilience against detrimental factors such as climate variability or extreme climate events and fluctuations in production costs and market prices.

5.7 Appendix

5.7.1 Appendix 5.1

List of sampled species for woodlice (*Isopoda*), millipedes (*Diplopoda*) and carabids (*Coleoptera: Carabidae*). Total number of each species caught is given for each sampling distance and type of field edge (tree row vs treeless edge). “T+”: field edge with tree row, “T-“: treeless field edge.

Isopoda	**T+**				**T-**			
Species	**0**	**1**	**5**	**30**	**0**	**1**	**5**	**30**
Armadillidium vulgare (Latreille, 1804)	358	20	2	0	0	0	2	0
Oniscus asellus Linnaeus, 1758	1	0	0	0	0	0	0	0
Philoscia muscorum (Scopoli, 1763)	26	7	5	2	0	9	6	4
Porcellio scaber Latreille, 1804	19	10	1	0	3	3	2	0
Trachelipus rathkii (Brandt, 1833)	18	1	0	0	2	1	1	3

Diplopoda	**T+**				**T-**			
Species	**0**	**1**	**5**	**30**	**0**	**1**	**5**	**30**
Brachyiulus pusillus (Leach, 1815)	17	12	16	6	11	3	4	9
Brachydesmus superus Latzel, 1884	0	0	1	0	0	0	0	0
Cylindroiulus caeruleocinctus (Wood, 1864)	105	120	77	47	98	73	64	94
Cylindroiulus punctatus (Leach, 1815)	2	3	0	1	2	3	0	1
Julus scandinavius Latzel, 1884	0	0	1	1	0	1	0	0
Melogona gallica (Latzel, 1884)	0	0	0	0	0	1	0	0
Polydesmus coriaceus Porath, 1871	5	1	1	0	5	1	0	2
Polydesmus inconstans Latzel, 1884	10	6	12	3	6	6	4	9
Proteroiulus fuscus (Am Stein, 1857)	0	1	0	0	0	0	0	0

Carabidae	**T+**				**T-**			
Species	**0**	**1**	**5**	**30**	**0**	**1**	**5**	**30**
Agonum muelleri (Herbst 1874)	0	0	0	0	1	0	0	1
Amara aenea (DeGeer, 1774)	32	2	1	0	5	4	0	1
Amara communis (Panzer, 1797)	0	0	0	0	0	1	0	0
Amara familiaris (Duftschmid, 1812)	0	0	0	0	1	0	0	0
Amara lunicollis Schiødte, 1837	0	1	0	0	0	0	0	0
Amara similata (Gyllenhal, 1810)	0	0	0	0	1	1	0	0
Anchomenus dorsalis (Pontoppidan, 1763)	5	6	18	18	17	22	23	22
Anisodactylus binotatus (Fabricius, 1787)	1	0	1	2	1	0	0	0
Asaphidion flavipes (Linnaeus, 1760)	0	0	0	2	0	1	0	0
Bembidion lampros (Herbst, 1784)	1	0	0	4	3	1	0	1
Bembidion obtusum Audinet-Serville, 1821	0	3	5	0	2	4	4	9
Bembidion properans (Stephens, 1828)	0	0	0	0	0	1	0	0
Bembidion quadrimaculatum (Linnaeus, 1760)	0	0	0	0	0	0	0	1
Bembidion tetracolum Say, 1823	0	5	2	4	7	3	3	1
Calathus fuscipes (Goeze, 1777)	0	0	0	0	0	1	0	0
Calathus melanocephalus (Linnaeus, 1758)	0	1	0	0	0	0	0	0
Demetrias atricapillus (Linnaeus, 1758)	0	1	0	0	2	1	0	4
Harpalus affinis (Schrank, 1781)	5	0	0	0	4	0	1	0
Harpalus rufipes (De Geer, 1774)	1	1	0	0	0	0	0	0
Loricera pilicornis (Fabricius, 1775)	1	4	2	6	3	6	4	9
Nebria brevicollis (Fabricius, 1792)	5	2	1	0	6	1	2	2
Nebria salina Fairmaire & Laboulbène, 1854	16	34	10	3	2	6	2	1

Notiophilus biguttatus (Fabricius, 1779)	2	0	1	0	0	0	2	0
Notiophilus quadripunctatus Dejean, 1826	1	0	2	3	0	0	2	3
Parophonus maculicornis (Duftschmid, 1812)	4	0	0	0	0	0	0	0
Poecilus cupreus (Linnaeus, 1758)	0	0	0	0	8	1	0	0
Poecilus versicolor (Sturm, 1824)	2	0	0	2	13	4	3	5
Pterostichus diligens (Sturm, 1824)	0	0	0	0	1	0	0	0
Poecilus cupreus (Linnaeus, 1758)	0	0	1	0	0	0	0	0
Pterostichus melanarius (Illiger, 1798)	61	117	112	394	48	68	76	244
Pterostichus strenuus (Panzer, 1796)	0	1	0	0	0	0	0	0
Pterostichus vernalis (Panzer, 1796)	0	0	1	0	0	0	0	0
Tachyta nana (Gyllenhal, 1810)	1	22	19	13	1	12	5	25
Trechus quadristriatus (Schrank, 1781)	10	41	12	31	5	11	12	30

6. General discussion and conclusion

In this research, the impact of tree row presence on soil characteristics (chapter 2), the abundance and diversity of potentially beneficial arthropods (chapter 3) and the yield and quality of arable intercrops (chapter 4) was quantified as a function of distance to the tree rows and tree age, both on boundary planted fields with poplar (15 to 48 years old) and young alley cropping fields (2 to 7 year old). Distance to the trees and their size strongly affected the magnitude of the observed effects. In addition, most of these effects may further differ according to tree species, as illustrated for walnut in chapter 5. In this final chapter, the results obtained in the previous chapters for an individual crop and year are extrapolated for a full crop rotation during an entire tree growth cycle with poplar (i.e. from tree planting to cutting) (6.1). To do so, a virtual silvoarable field with tree rows of poplar is defined. The growth of the poplar trees is estimated based on the growth characteristics of the tree rows on the boundary planted fields and the simultaneous evolution in SOC, arthropod abundance and crop yield is calculated for this virtual field, taking into account the effect of tree row presence. Subsequently, the research questions and hypotheses defined in chapter 1 are taken up again, discussed and evaluated (6.2). Finally, potential options for optimization of AFS (6.3) and further research (6.4) are suggested.

6.1 Field level impact of tree rows throughout an agroforestry rotation

Based on our results, increases in SOC and changes in abundance of potentially beneficial arthropods in silvoarable agroforestry (SAF) fields are heterogeneous at the field level and strongly affected by the size of the present tree rows. In what follows, the evolution in overall SOC-stock in the plough layer with time was estimated at the field level for a virtual SAF field with poplar trees from tree planting to cutting, based on the experimental data obtained in chapter 2 (Figure 6.1). Similarly, the overall evolution of activity-density of macro-detritivorous and predatory arthropods with time in the arable zone was estimated, based on the experimental data obtained in chapter 3.

Also when considering the effects of tree presence on crop yield, both distance to the trees and tree size again were key determinants for the magnitude of the tree impact, as observed in chapter 4. In addition, substantial variation in crop yield reduction was observed among the different crops under study. Hence, crop yield is increasingly reduced throughout the agroforestry-rotation (i.e. from planting to cutting of trees), with the cumulative reduction differing according to the crops cultivated. However, the tree rows in AFS can be considered as an integral part of the agricultural production and thus, at least partly, compensate for the loss in arable crop yield. The Land Equivalent Ratio (LER, Mead and Willey, 1980) is a common and well adopted measure to quantify the productivity of AFS in comparison to sole cropping conditions of both arable crops and wood (Dupraz, 1999; Smith et al., 2012a). It is typically defined as the ratio of the area under sole cropping to the area under the AFS, at the same level of management, that gives an equal yield (Equation 3) (Graves et al., 2010). As indicated by several authors, LERs of AFS can be larger than one (Dupraz and Newman, 1997; Graves et al., 2010; Tallieu, 2011). In what follows, the evolution in tree growth, crop yield and the resulting LER was calculated for one rotation of the tree component for a virtual SAF field. Several models exist to estimate crop yield in AFS based on a set of boundary conditions, of which Yield-safe and Hi-safe are probably the best-know. As indicated by Luedeling et al. (2016), implementation of such models may be prone to difficulties such as insufficient flexibility or extensive needs for parameterization. Therefore, in this research, LMM were used to calculate the crop yield throughout an agroforestry rotation based on the crop yield data obtained in chapter 4 and the height and the diameter of the poplar tree rows on the experimental fields.

6.1.1 Assumptions & methods

Virtual SAF field with poplar

As indicated before, forms of AFS whereby trees are organized in rows can well be combined with the use of modern farming techniques and machinery for growing agricultural crops in the intercropping zone between the tree rows. One such form which is increasingly receiving attention in temperate Europe is alley cropping, whereby the tree rows are located in-field (Quinkenstein et al., 2009; Tsonkova et al., 2012). In addition, the agricultural landscape in Flanders, as in large parts of temperate Europe, has longtime been characterized by tree rows and hedges bordering the fields, amongst others for the production of fuelwood and timber (Baudry et al., 2000; Van Den Berge et al., 2018). This historical familiarity with boundary planted tree rows, combined with the relatively small average agricultural field size in Flanders of 1.34 ha (Coudyser, 2016), may favor the plantation of tree rows on field boundaries.

In what follows, a virtual SAF field with poplar tree rows located in-field and at its field boundaries was designed (Figure 6.1). The following assumptions were made: i) Since it is generally recommended to orient tree rows north-south (see also chapter 4), all of the present tree rows on the virtual field were required to meet this recommendation. ii) In the preceding chapters, experimental plots were located up to 30 m distance from the tree rows in the arable zone. At this distance, tree effects generally appeared to be either non-significant or very limited. To evaluate the entire zone where substantial tree influence may occur, distance to the two nearest tree rows was set at 30 m in the center of the arable intercropping zone. As a result, the interrow distance equals 60 m. iii) The surface area of the rectangular field was assumed to equal 1.34 ha, which is the average size of agricultural fields in Flanders (Coudyser, 2016). iv) The trees are planted at an intrarow distance of 8 m which is similar to the tree rows on the experimental fields in our research. v) All trees are of the same species (*populus x canadensis*) and of homogeneous age. vi) Similar to the alley cropping fields in our research, an arable zone of 12 m wide was preserved on the northern and southern field edge for use as headland.

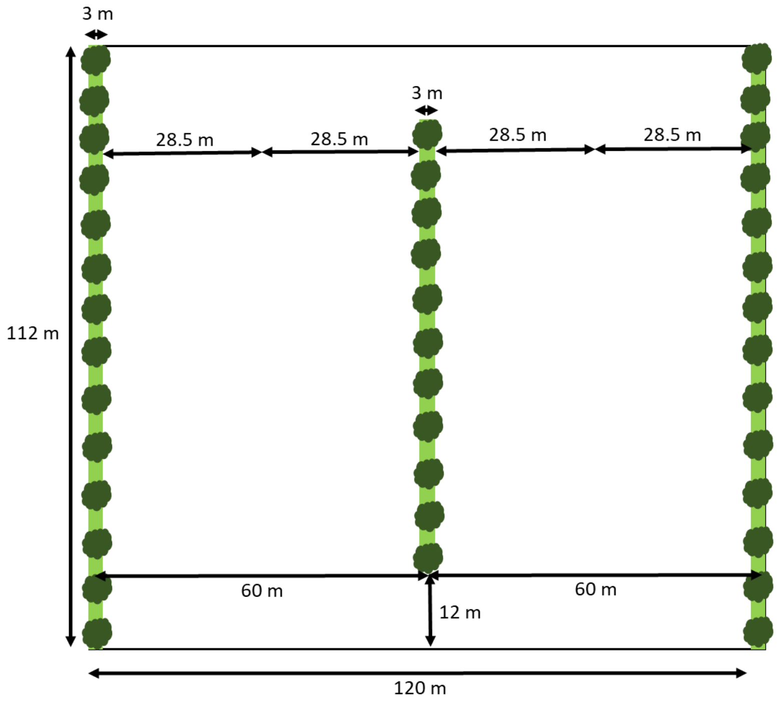


Figure 6.1: Virtual SAF field with poplar trees on which the evaluation of SOC in the plough layer, arthropod presence and biomass production was conducted.

Evolution of height and DBH of poplar trees

Based on the height and the diameter of the poplar tree rows on the experimental fields (Table 1.1, except the field in Landen), the evolution of tree height and DBH of poplar in SAF fields as a function of tree age was estimated using the gnls function in the nlme package in R. Subsequently, the age at which poplar trees reach the maximum diameter for optimal industrial processing (64 cm) was deduced to estimate the duration of one rotation of the poplar trees in AFS. As shown in (Figure 6.3), this value equals 25 years.

The tree stem volume (V) was calculated based on the estimated tree height (h) and diameter (DBH) using equation 2. For the form factor “$f_{1.30}$“ of poplar, values according to Jansen et al. (1996) were used.

Eq 2.: $V = f_{1.30} \times h \times DBH_{1.30}$

The production of woody stem biomass on the virtual field was compared to a poplar forest stand of identical surface and shape. Since only the impact at one side of both tree rows affects the virtual SAF field, the woody stem biomass of only one of both boundary planted tree rows was included in the estimated production of the virtual SAF field. Because no measurements of tree growth and/or wood production in control forest stands were conducted in our research, the estimations of Jansen et al. (1996) were used for a forest stand with bonity 2 (the second highest bonity of forest in Flanders, bonity 6 being the lowest). Estimations for bonity 1 & 3 are given in Appendix 6.1.a. The forest stand was assumed to have the same intrarow distance as the virtual SAF field (8m) and no thinning was done. Since in Jansen et al. (1996) a time step of 5 years is used to describe increments in DBH, the evolution of the DBH during in between years was estimated using the gnls function in the nlme package in R. For the estimation of tree stem volume in the forest stand, the same methodology was used as for the virtual SAF field (see equation 2). Reported densities of poplar wood often vary between 0.3 and 0.35 ton m^{-3} (Beaudoin and Hernández, 1992; Johansson and Hjelm, 2012; Slopiecka et al., 2012), therefore, in our research a value of 0.325 ton m^{-3} was used to convert stem volume to stem biomass (ton).

Evolution in SOC, arthropod abundance and crop yield

The estimated evolution of SOC, biodiversity and crop yield throughout time and the resulting overall effects on the virtual field were compared to an arable treeless sole cropping field of identical surface area and shape, and with the same arable crop rotation (Figure 6.2). The evolution and overall effect on crop yield was quantified for a crop rotation including winter wheat, winter barley, grain maize, forage maize and potato (Table 6.1). Thereby, it was not the focus of this research to present the optimal sequence of these crops in an agricultural rotation but to simulate the expected yield for a crop rotation with a relative share of each of the abovementioned crops as described in Table 6.1. As indicated in chapter 4, cultivation of winter cereals may be preferable as trees mature. Therefore, in our simulation, the share of winter cereals was increased at the expense of grain maize and potato during the last 5 years of the life cycle of the tree component (Table 6.1). Although at least one additional crop should be used in an actual crop rotation, an additional simulation was done for a crop rotation comprising solely winter barley and winter wheat to illustrate the importance of using adapted tree-crop combinations.

In order to estimate the evolution of abovementioned tree-effects with time, the experimental data obtained in chapters 2-4 were expressed as function of tree height. We therefore use H, which is the ratio of the distance from the tree row of each measuring point to the height of this tree row. For example, for a tree height of 20 m and experimental plots on a distance of 10 m from these trees, H equals 0.5. Each of the abovementioned variables (SOC, biodiversity, crop yield) was modelled using a LMM with H as fixed effect in case of tree row presence. In case no trees were present, the distance to the field edge was used as fixed effect. Both H and distance to the field edge were transformed logarithmically to linearize the response variables in case of tree row presence and treeless field edges, respectively. The following random effects were included: “field”; “transect” nested within the field and, if applicable, “year”. Modeling was performed using the lmer function in the lme4 package in R (Bates et al., 2015; R Development Core Team, 2016).

For the assessment of the field-level effects, four zones were distinguished in the SAF field and the sole cropping field, based on the position relative to the nearest tree row or (eastern/western) treeless border (Figure 6.2). Zone A: variables were estimated using the LMM relations obtained for the measuring locations near the mature boundary planted poplar tree rows. Zone B: variables were estimated using the LMM relations obtained for the measuring locations near the treeless field edges on the boundary planted fields. Zone C: in-field conditions were assumed to equal values at 30 m from the treeless field edge, as estimated using the LMM relations obtained for the measuring locations near the treeless field edges on the boundary planted fields. Thereby, three assumptions were made: i) For both fields (SAF and sole cropping), no edge effect was taken into account for the upper (northern) and lower (southern) field border. ii) Tree impacts often reach sole cropping levels at limited distances from the field edge in case of small tree sizes. Beyond this point of interception between the estimated yield levels nearby the tree rows and the control levels, values in the SAF field (zone A) were assumed to equal the control level. iii) As argued higher, observed effects were either not significant or limited at a distance of 30 m to the nearest tree row. As a result of the large interrow distance on the virtual field, overlapping effects of neighboring tree rows were assumed to be negligible beyond a distance of 30 m.

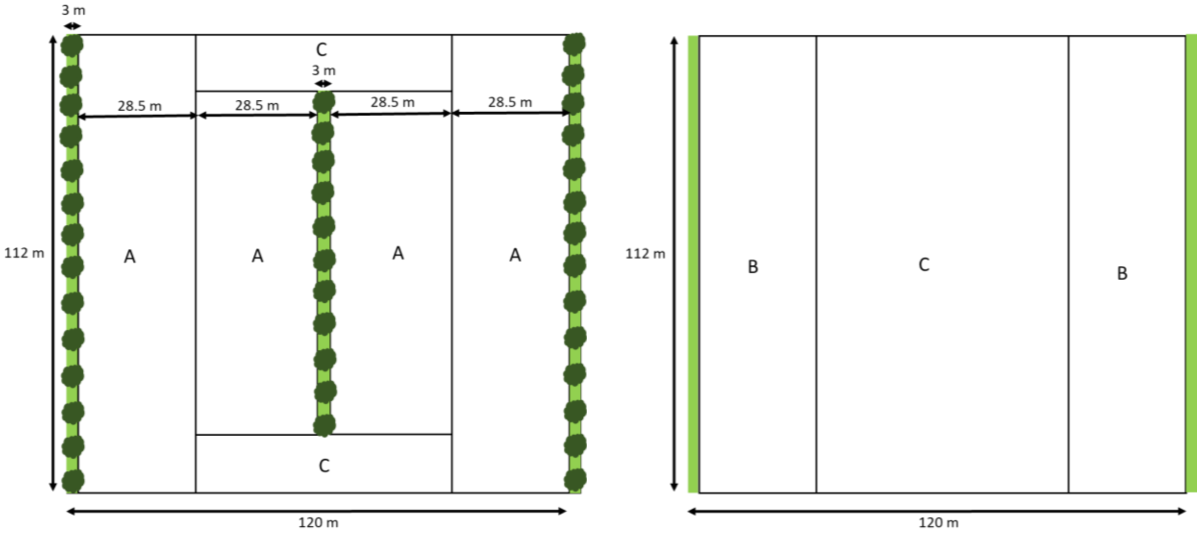


Figure 6.2: Modelling approach: division of the virtual SAF field (left) and sole cropping control field (right) in zones based on distance to the nearest tree row and/or treeless border. Zone A: variables estimated using the LMM relations obtained for the measuring locations near the mature boundary planted poplar tree rows. Zone B: variables estimated using the LMM relations obtained for the measuring locations near the treeless field edges on the boundary planted fields. Zone C: in-field conditions assumed to equal values at 30 m from the treeless field edge, as estimated using the LMM relations obtained for the measuring locations near the treeless field edges on the boundary planted fields.

Land Equivalent Ratio (LER)

The combined productivity of trees and arable crops per unit of land-use may potentially be enhanced in AFS when compared to sole cropping systems, as a result of synergies between both components. This altered land-use efficiency is often quantified by the Land Equivalent Ratio (LER) (Dupraz and Newman, 1997; Graves et al., 2010; Mead and Willey, 1980; Smith et al., 2012a), which can be calculated for an agroforestry rotation using Equation 3 (Graves et al., 2007; van der Werf et al., 2007).

Eq. 3:

$$\mathrm{LER}_{\mathrm{rotation}} = \mathrm{average}\left(\frac{\text{crop yield SAF year0}-\text{i}}{\text{crop yield control field year0}-\text{i}}\right) + \frac{\text{cumulative wood production SAF year0}-\text{i}}{\text{cumulative wood production forest stand year0}-\text{i}}$$

A value of 1 indicates there is no advantage of intercropping over sole cropping. When the LER is larger than 1, the production in the mixed system is higher than in sole cropping. Analogously, an LER <1 indicates reduced production (Ong and Kho, 1996).

For the calculation of the LER, the crop yield and woody stem biomass production in the virtual SAF field were compared to the crop yield in the sole cropping field and the stem biomass production of the control poplar forest stand.

6.1.2 Results and discussion

Evolution of height and DBH of poplar trees

In Figure 6.3, the simulated height and diameter curves are displayed together with the height and diameter curves of poplar in forestry stands as described by Jansen et al. (1996) for the Netherlands. When compared with the estimates of Jansen et al. (1996), the increase in height diminishes more rapidly with time in case of SAF than in case of forestry conditions. Reduced height and diameter growth of poplar trees in AFS has been described in past research (Burgess et al., 2004), where this was assumed to result from competition with the agricultural crop, for example for water. In contrast, other authors have observed increases in diameter growth up to 25% in young AFS with hybrid poplar (Kouakou et al., 2016; Rivest et al., 2009), and up to 26 and 65% in case of wild cherry and walnut, respectively (Chifflot et al., 2006). The authors attributed these increases to the higher availability of light and soil nutrients in AFS, the latter resulting from fertilization practices. Also in our research, the reduced height growth of the trees is, at least partly, compensated by a substantially increased diameter growth in comparison to the estimates of Jansen et al. (1996). As indicated higher, the boundary planted tree rows have reached a diameter of 64 cm after 25 years, whereas this value equals 46.4 cm under forestry conditions (bonity 2, intrarow distance 8 m).

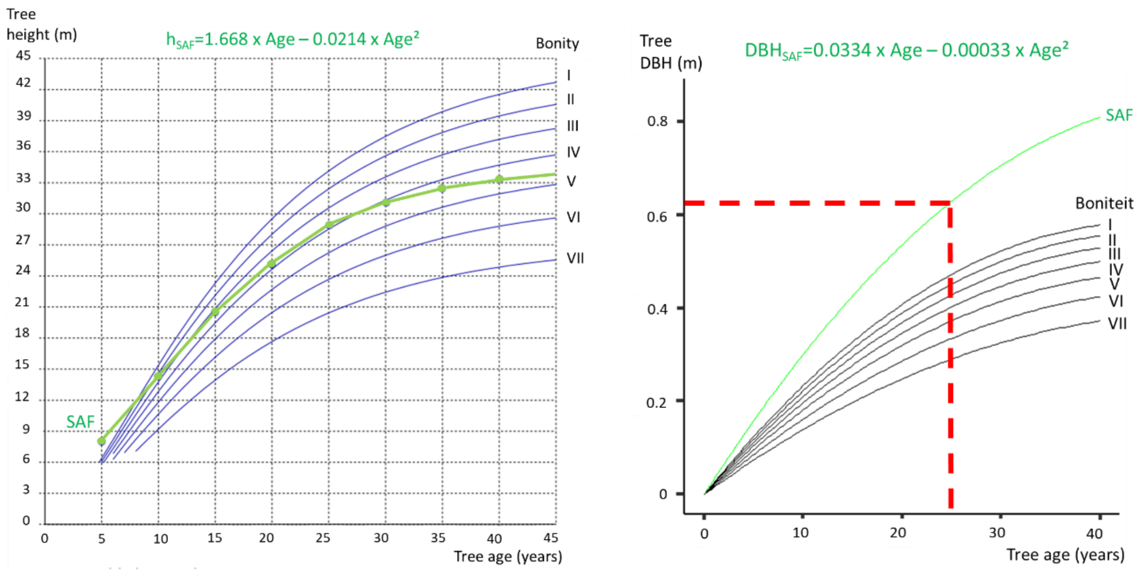


Figure 6.3: Tree height "h_{SAF}" (left) and DBH "DBH_{SAF}" (right) as function of tree age in an arable agroforestry field (green, "SAF") and a forest stand (adapted from Jansen et al. (1996)).

Evolution in SOC and arthropod abundance

It is important to note that for both SOC and arthropod abundance, only the arable zone was considered and increases or decreases in the tree rows and/or treeless field edges were not taken into account. A continuous increase in SOC was found in the arable zone of the SAF field when compared to the constant level of 50.5 ton SOC per 1.34 ha (or 37.7 ton ha^{-1}) in the sole cropping field (Figure 6.4). The overall SOC stock in the plough layer of the SAF field equaled 57.5 ton SOC per 1.34 ha (or 42.9 ton ha^{-1}) at the end of the agroforestry rotation, which corresponds to a total increase of 7 ton (or 5.2 ton ha^{-1}) and an average yearly rate of 209 kg ha^{-1}. As can be seen in Figure 6.4a, the rate of SOC increase appears to diminish towards the end of the agroforestry rotation, which is assumed to result from the similar decrease in tree growth rate in our simulation (Figure 6.3). Although a different methodology was used to estimate the SOC stock for the virtual SAF field (with SOC expressed as function of H), the result is similar to the value obtained in chapter 2 where an increase of 5.3 ton ha^{-1} in SOC stock at a yearly rate of 208 kg ha^{-1} was observed in the arable zone between 2.5 and 30m of the boundary planted tree rows (of which the estimated average age equaled 25.5 years).

For ease of interpretation, the changes in overall arthropod activity-density in the AFS were expressed relatively to the constant overall activity-density levels in the sole cropping fields (set at 100%). Similar to SOC, a continuous increase in macro-detritivore abundance was calculated in the arable zone of the AFS when compared to the sole cropping field (Appendix 6.1). Although less pronounced, the rate of increase again appears to diminish towards the end of the agroforestry rotation. At the end of the agroforestry rotation, the total relative increase amounted to 451%. This effect was however not confirmed for the predatory arthropods, where simulated activity density values were 0.8% lower after 25 years in the SAF when compared to the sole cropping field (Appendix 6.1). The absence of a beneficial effect on activity-density of carabids and rove beetles has also been described for agricultural fields nearby hedgerows (Van Vooren, 2018). These results should, however, be interpreted with caution since the absence of a significant tree effect does not exclude an undetected early season colonization out of the tree rows, as also mentioned in chapter 3. As a result of the often high mobility of these predatory arthropods, colonization may have taken place before the start of the sampling period by the end of May, leading to an overall increase in activity-density values in the arable zone of the experimental fields.

Yield of arable crops and tree stem biomass

The yearly decreased crop yield in the virtual SAF field results in an overall cumulative reduction of 15.5% (340.0 ton versus 402.5 ton) after 25 years in comparison to the sole cropping field (Table 6.1, Figure 6.4b). The strong variations in crop yield losses as a function of crop type are clearly demonstrated in Table 6.1, where the decrease in yield (ton DM) of e.g. forage maize in year 19 and of potato in year 20 of the agroforestry rotation equals more than threefold the decrease observed for winter barley in year 25.

As indicated higher, the woody biomass produced by the poplar trees in AFS can be considered as an integral part of agricultural production. As such, it may at least partly compensate for the observed reductions in crop yield. The woody biomass stem^{-1} at the end of the agroforestry rotation is 60% higher in the SAF field when compared to the forest stand. However, the low number of trees (# 25) when compared to the forest stand (# 210) results in a substantially lower wood production (Figure 6.4c) with the total stem wood yield (ton) in the virtual SAF field equaling 19.1% of the production of the forest stand at the end of the agroforestry rotation.

Table 6.1: Evolution in tree height and DBH on the virtual SAF field. Crop rotation and crop yield on the virtual SAF and the sole cropping control field. Stem wood yield on the virtual SAF and the control forest stand (bonity 2).

SAF field characteristics				Crop yield (ton DM 1.34 ha^{-1})			Woody (stem) biomass production (ton 1.34 ha^{-1})		
Tree age	**DBH**	**Tree height**	**Crop**	**SAF**	**Control**	**SAF:Control (%)**	**SAF**	**Forest stand**	**SAF:Forest (%)**
1	0.03	1.65	Winter wheat	10.7	11.0	97.9	0.01	0.02	27.0
2	0.07	3.25	Winter barley	11.9	12.2	97.7	0.04	0.14	29.2
3	0.10	4.81	Grain maize	11.8	12.3	96.0	0.14	0.49	29.1
4	0.13	6.33	Forage maize	23.8	25.5	93.6	0.29	1.20	24.4
5	0.16	7.81	Potato	19.6	21.7	90.1	0.49	1.97	24.7
6	0.19	9.24	Winter wheat	10.5	11.0	95.9	0.83	3.56	23.2
7	0.22	10.63	Winter barley	11.7	12.2	95.9	1.29	5.14	25.1
8	0.25	11.97	Grain maize	11.0	12.3	89.0	1.89	8.42	22.4
9	0.27	13.28	Forage maize	21.7	25.5	85.1	2.41	11.10	21.7
10	0.30	14.54	Potato	17.4	21.7	80.0	3.10	16.02	19.3
11	0.33	15.76	Winter wheat	10.2	11.0	93.1	4.18	21.18	19.7
12	0.35	16.93	Winter barley	11.5	12.2	94.1	4.96	24.84	20.0
13	0.38	18.07	Grain maize	10.1	12.3	82.1	6.12	33.12	18.5
14	0.40	19.16	Forage maize	19.7	25.5	77.2	7.03	39.88	17.6
15	0.43	20.21	Potato	15.9	21.7	73.2	8.81	43.47	20.3
16	0.45	21.21	Winter wheat	9.9	11.0	90.5	10.10	52.78	19.1
17	0.47	22.17	Winter barley	11.3	12.2	92.6	11.45	64.85	17.7
18	0.49	23.09	Grain maize	9.2	12.3	74.9	13.12	69.38	18.9
19	0.52	23.97	Forage maize	18.2	25.5	71.3	14.26	79.20	18.0
20	0.54	24.80	Potato	15.0	21.7	69.0	16.01	88.80	18.0
21	0.56	25.59	Winter wheat	9.7	11.0	88.1	17.95	93.75	19.2
22	0.58	26.34	Winter barley	11.2	12.2	91.5	19.48	105.66	18.4
23	0.59	27.04	Forage maize	17.4	25.5	68.1	21.41	117.81	18.2
24	0.61	27.71	Winter wheat	9.5	11.0	87.1	22.97	127.35	18.0
25	0.63	28.33	Winter barley	11.1	12.2	91.0	24.91	130.75	19.1

Land Equivalent Ratio (LER)

LER-values of temperate silvoarable AFS, obtained either through modelling or experimental research, often vary between 1 and 1.4 in literature (Borrell et al., 2005; Graves et al., 2010, 2007; Sereke et al., 2015; van der Werf et al., 2007). Also in our simulation, LER-values fell within this range throughout the agroforestry rotation (Figure 6.4 d). An LER$_{rotation}$ value of 1.06 was obtained for the virtual field after 25 years. This relatively low value may result from the integration of crops in the rotation that may be advised against for use in AFS (e.g. maize, potato) as argued in chapter 4. In Appendix 6.2, results of a simulation for a crop rotation comprising solely winter barley and winter wheat are shown. Although at least a third crop with a similar response to tree row presence should be integrated in an actual agricultural rotation, the obtained LER$_{rotation}$ value of 1.12 illustrates the importance of using adapted tree-crop combinations to optimize the production potential, and hence land-use efficiency. In addition, increasing LER-values with increasing tree density have been reported (Graves et al., 2010; Tallieu, 2011). Hence, the low LER$_{rotation}$ value may result from the low tree density (number of trees ha^{-1}) on the virtual SAF field, which may indicate potential synergies are not maximized at the limited tree densities of the virtual SAF field.

In our simulation, the boundary planted tree rows were assumed to be established in existing grassy field edges of 3 m wide. However, the width of existing grassy field edges of actual arable fields will generally be smaller than 3 m, or a grass strip may even be completely absent in between two neighboring agricultural fields. Therefore, an additional simulation was done whereby the tree rows are planted in newly established grass strips (i.e. the area of the grassy strips used for tree planting is entirely used for arable crop production in sole cropping conditions). As shown in Appendix 6.2 c, the resulting $LER_{rotation}$ varies between 1.01 and 1.04, depending on the scenario of crop rotation and bonity of the control forest stand. Although land-use efficiency is still increased when compared to sole cropping fields, the magnitude of the effect is small. This value, however, represents the extreme situation without any pre-existing grassy edge. In addition, the width of the established tree strips of 3 m is relatively high and the use of smaller dimensions may be possible to further increase land-use efficiency.

To evaluate the effect of harvesting the trees earlier in time, additional $LER_{rotation}$ values were calculated for an agroforestry rotation whereby trees are cut when they reach a diameter of 50 cm (after 19 years) (Appendix 6.2 c). This results in a limited increase in $LER_{rotation}$ with values ranging between 1.01 and 1.16, versus 1.01 and 1.15 when trees are cut at 25 years. However, harvesting at smaller diameters may result in lower selling prices per m^3 (e.g. 30 € m^{-3} at diameter of 0.50 m versus 45 € m^{-3} at diameter of 0.64 m (kbbm, 2018)), as a result, the small increase in $LER_{rotation}$ may not correspond with an increase in financial revenues.

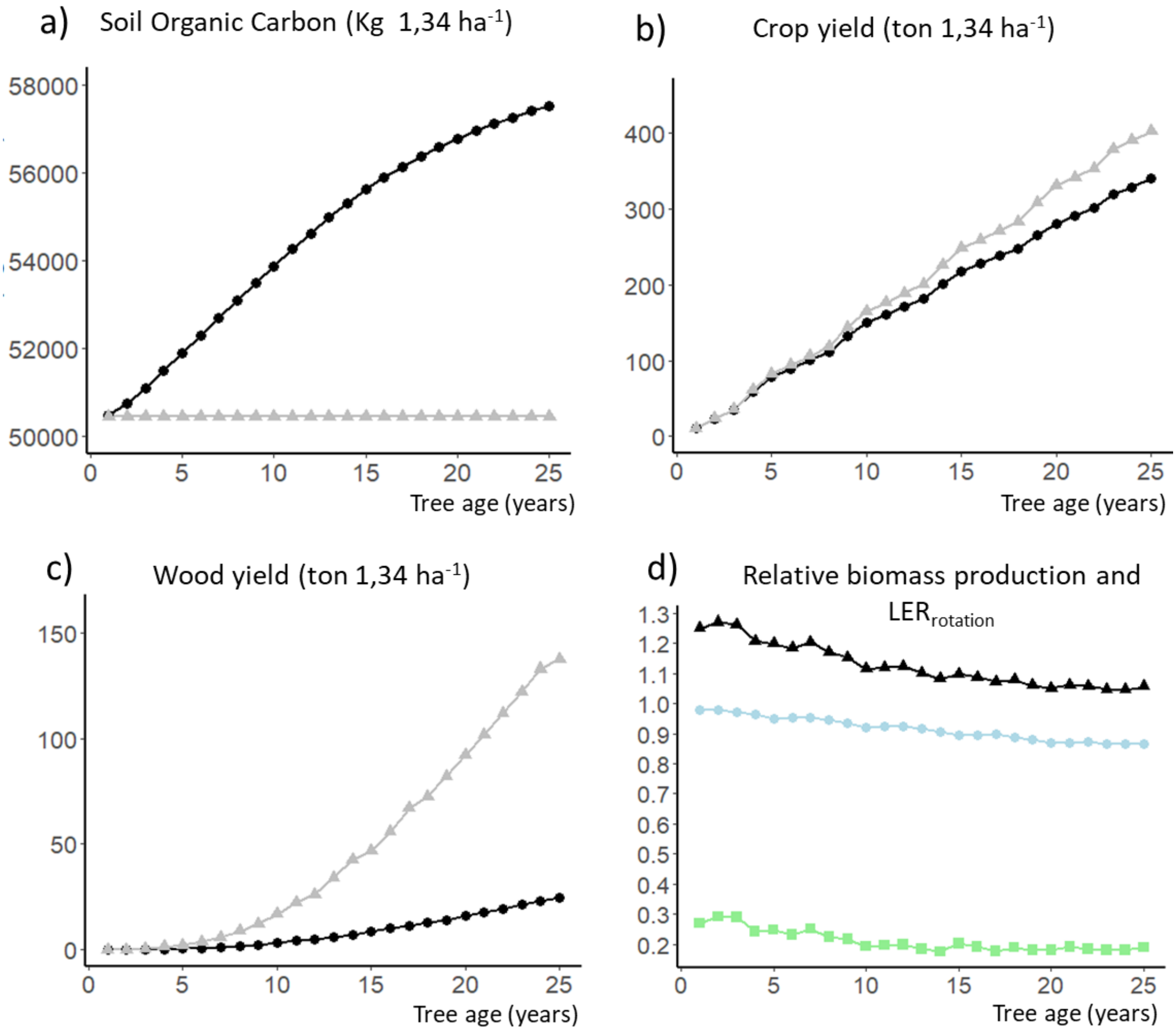


Figure 6.4: (a) Evolution of SOC and (b) crop yield in the virtual SAF field (black dots) and the sole cropping control field (grey triangles) throughout one rotation of the tree component. (c) Evolution of stem wood yield in the SAF field (black dots) and the control forest stand (grey triangles). (d) Average relative crop yield in the virtual SAF when compared to the sole cropping control field from year 1 to i (blue dots), cumulative relative wood yield in the virtual SAF when compared to the control forest stand (green squares) and LERrotation from year 1 to i (black triangles).

6.2 Feedback to hypotheses and research questions

6.2.1 Hypothesis 1: Tree row presence significantly affects soil characteristics in arable fields. The magnitude of these effects is dependent on both distance to the trees and their size.

RQ1.1: *How large is the increase of SOC and soil nutrient concentrations near tree rows?*

In between a distance of 2 to 30 m from the poplar trees, total SOC stock in the 0-23 cm soil layer equaled 45.1 ton ha^{-1}, which corresponds to an increase of 5.3 ton ha^{-1} when compared to the control zone. In the virtual SAF poplar field, a total increase of 7 ton SOC (5.22 ton ha^{-1}) was realized at the end of the life cycle of the trees (i.e. 25 years). Similarly, an increase in soil nutrient stock of 556 kg total N ha^{-1}; 108 kg K ha^{-1}; 45 kg Mg ha^{-1}; 86 kg P ha^{-1} and 16 kg Na ha^{-1} was observed in the experimental zone near the poplar trees when compared to the control zone. The potential of tree row presence to increase SOC and soil nutrient concentrations was confirmed on the boundary planted fields with walnut trees (see RQ 4.1).

RQ1.2: *To what extent does the magnitude of the observed effects vary with decreasing distance to the field edge and increasing size of the trees?*

SOC and soil nutrient concentrations exponentially increased as distance to the tree rows became smaller. At 2 m of the poplar tree rows, SOC concentration equaled 16.8 g kg^{-1}. At 30 m of the tree rows, this value had decreased to 12.2 g kg^{-1}. Similarly, concentrations of total N, K, Mg, P and Na at 2 m of the tree rows equaled 1613.4; 290.0; 215.8; 247.7 and 27.8 mg kg^{-1}, respectively. At 30 m of the trees, these values equaled 1218.0; 201.3; 190.3; 210.8 and 15.3 mg kg^{-1}, respectively.

No significant effects were observed near the young tree rows on the alley cropping fields. On the boundary planted fields, the increase in concentration of SOC, total N, K, P and Na was significantly related to the size of the present poplar tree rows. The increase of effects with tree-size was also shown in case of SOC for the virtual SAF field in 6.1.2, where a consistent increase with time of SOC was observed throughout the lifecycle of the tree component.

Conclusion: H1 is supported

6.2.2 Hypothesis 2: Tree row presence significantly increases the abundance and diversity of potentially beneficial arthropods in arable AFS.

RQ2.1: *How large are the increases in abundance and diversity of arthropods in and near the tree rows when compared to treeless field edges and further locations (30 m) in arable fields? Are the observed trends similar for macro-detritivorous and carnivorous arthropods?*

A fivefold increase in activity-density of isopods and a 71% and 72% increase in species richness and Shannon-Wiener diversity, respectively, was observed in the boundary planted tree rows when compared to the treeless grassy borders. This effect extended into the nearby arable zone at distances 1 and 5 m of the (larger) boundary planted trees. A similar, although smaller, trend was observed for the activity-density of millipedes with values being 42% higher in the boundary planted tree rows when compared to the treeless field edge and threefold higher when compared to sampling locations at 30 m into the arable zone. Species richness and Shannon-Wiener diversity of millipedes in the field edges of the boundary planted fields were 127 and 177% increased, respectively, when compared to sampling locations at 30 m in the arable zone. However, no significant difference in diversity of millipedes was found when comparing the boundary planted tree rows to the treeless field borders. In the tree rows on the alley cropping fields, both species richness and Shannon-Wiener diversity were 64% higher when compared to values in the treeless control part of these fields.

Contrasting effects were observed in case of carnivorous arthropods. Activity-density values were generally lower in the tree rows when compared to the arable zone. Species richness and Shannon-Wiener diversity of carabids on the boundary planted fields were 41% and 52% higher, respectively, at a distance of 1 m in the arable zone when compared to the values observed in the tree rows. When compared to sampling locations at 30 m into the field, these increases in species richness and Shannon-Wiener diversity equal 29% and 37%, respectively.

RQ2.2: *How strongly does the crop type affect the observed effects?*

Activity-density values of woodlice (in both alley cropping and boundary planted fields) and of millipedes (in alley cropping fields) were lower in the tree rows/field edges in fields with winter cereals when compared to fields with maize (up to 36% and 51% decrease for woodlice and millipedes, respectively). A contrasting effect was observed in the arable zone were values in fields with winter cereals were higher when compared to fields with maize. No consistent effect of crop type on activity-density and/or diversity was observed for the carnivorous taxa under study.

Conclusion: H2 is only partially supported

6.2.3 Hypothesis 3: Tree row presence significantly alters crop yield and quality.

RQ3.1: *How much is the yield of arable crops enhanced or deteriorated as a result of tree row presence and to what extent do the effects differ according to crop type and tree size?*

In between a distance of 2.5 to 12 m, relative yield near the trees when compared to the treeless control zone varied between 85 and 35% for maize, 89 and 54% for potato, 94 and

61% for winter wheat and 93 and 86% for winter barley, depending on the size of the trees. The relatively strong yield penalties in maize and potato, when compared to winter wheat and barley, were assumed to result primarily from the larger overlap in growing season (and hence in resource needs) between the former crops and the tree component. An overall relative yield loss of 15.5% was simulated for the virtual SAF field after 25 years of intercropping when compared to a sole cropping field. This loss in crop yield is partly compensated by this woody biomass, resulting in an LER varying between 1.01 and 1.12 for the virtual SAF field (depending on the system characteristics).

RQ3.2: *How much is the quality of arable crops enhanced or deteriorated as a result of tree row presence?*

The strongest effects were observed on the fields with longstanding trees. The average dry matter and starch concentration of forage maize samples near the treeless field edge in between a distance of 2.5 to 12 m equaled 35.0±4.0% and 36.1±6.2%, respectively. Near the trees this values had decreased to 26.9±3.3% and 22.1±7.1%. In contrast, crude protein concentration was increased, with values equaling 9.2±0.8% in between a distance of 2.5 and 30 m of the trees and 7.2±1.0% near the treeless field edge. In potato, both dry matter concentration and UWW were decreased near the long-standing trees. In between a distance of 2.5 to 12 m to the trees the average values equaled 17.5±1.9% and 310.0± 27.5, respectively. Near the treeless field edge, these values equaled 20.7±1.4 and 367.7±21.3%, respectively. Decreases in average dry matter concentration from 83.7±2.5 to 80.2±2.1% and from 90.7±1.1 to 86.4±2.5% were observed for winter wheat and winter barley, respectively, in between a distance of 2.5 to 12 m to the long-standing tree rows when compared to the zone near the treeless field edge. In contrast, increases in average CP concentration were observed near the trees from 13.5±0.8 to 15.8±1.1% and from 10.1±2.0 to 11.2±1.2% in case of winter wheat and winter barley, respectively.

RQ3.3: *How strongly does the magnitude of the observed effects increase with decreasing distance to the field edge?*

Distance to the tree rows significantly affected crop yield. This relationship was exponential: the closer to the tree row, the lower the yield. This was most obvious on the fields with long-standing trees where the relative yield at 2.5 m of the tree rows equaled 4, 27, 26, 59 and 80% of the yield at 30 m of the trees in case of forage maize, potato, grain maize, winter wheat and winter barley, respectively. Similar exponential trends were observed for the abovementioned effects on crop-quality near the long-standing tree rows, resulting in spatial heterogeneity of crop quality at the field-level. In contrast, an overall increase up to 30 m into the arable zone was observed for dry matter concentration of winter cereals and crude protein concentration of winter barley.

Conclusion: H3 is supported

6.2.4 Hypothesis 4: The effects of tree presence differ according to tree species.

RQ4.1: *To what extent are the observed effects of tree row presence on soil characteristics in the arable zone different near tree rows of walnut when compared to tree rows of poplar?*

Similar to the observations near poplar trees, SOC and soil nutrient concentrations near walnut trees were significantly increased when compared to further locations in the field or to the arable zone near treeless field edges. These increases followed similar exponential trends as function of distance to the tree rows. However, the magnitude of the effects differed when compared to the effects near poplar trees, with respective increases equaling 2.3 versus 5.3 ton SOC ha^{-1}; 156 versus 108 kg K ha^{-1}; 23 versus 45 kg Mg ha^{-1} and 157 versus 86 kg P ha^{-1}. In addition, a significant increase of Ca (168 kg ha^{-1}) was observed in between a distance of 3 to 30 m of the walnut trees when compared to the treeless control zone, whereas no such effect was observed near the poplar trees.

As shown in chapter 2, the observed effects of tree row presence on soil characteristics were strongly related to the size of the present trees. Despite their older estimated age (69 years versus 26 years), the walnut trees are of smaller size and hence presumably produce less litter which may explain the smaller increase in SOC. However, similar effects would be expected for the soil nutrients under study. In addition, smaller crop yield reductions were observed nearby the walnut trees. Hence, a smaller impact of reduced crop uptake would be expected. This contradicts the stronger increases of K and P (and Ca) near the walnut trees when compared to the poplar tree rows. However, as indicated in chapter 2 in case of poplar, substantial site-specific differences of (the magnitude) of observed effects may occur which appear to result from other factors besides the size of the trees. Therefore, the differences in observed effects between walnut and poplar trees should be interpreted with caution since only two fields bordered by walnut trees were sampled and it cannot be excluded that site-specific factors affect these differences in addition to a tree-species effect. Hence, further research would be necessary to disentangle the (interactions between) factors responsible for these species-related differences in magnitude of the observed effects.

RQ4.2: *To what extent are the observed effects of tree row presence on the abundance and diversity of potentially beneficial arthropods different near tree rows of walnut when compared to tree rows of poplar?*

Winter cereals were grown on the fields with walnut trees during the two consecutive years in which arthropod-presence was monitored. Hence, no inferences can be made for fields cropped with maize. In case of winter cereals, similar contrasting effects between macro-detritivorous and carnivorous arthropods were observed on the fields with walnut trees when compared to the fields with poplars. Activity-density and species richness of woodlice and activity-density of millipedes were significantly increased in the tree rows when compared to the treeless field edges or to sampling distances at 30 m in the field. Activity-density of carabids and rove beetles was significantly reduced in the tree rows when compared to sampling locations at 30 m in the arable zone, which is similar to the observations near poplar trees. No significant effect of tree row presence on species richness of carabids was found near walnut trees, whereas species richness near poplar trees was highest at a distance of 1 m in the arable zone.

RQ4.3: *To what extent are the observed effects of tree row presence on the yield and quality of arable crops different near tree rows of walnut when compared to tree rows of poplar?*

Similar exponentially decreasing crop yields were observed as distance to the walnut trees decreased. However, these decreases did considerably differ from the decreases observed near poplar tree rows. Crop yield reductions near walnut trees in between a distance of 3 to 30 m to the field edge, when compared to the arable zone near the treeless field edge, equaled 5%; 10.6%; and 7.8% in case of winter wheat, winter barley and grain maize, respectively. These values equaled 27. 9%; 8.6%; and 26.2%, respectively, in between a distance of 2.5 to 30 m to long-standing poplar tree rows. Considering the smaller size of the walnut trees, the smaller impact on crop yield of winter wheat and grain maize is assumed to result from reduced competition for light (and potentially for water and nutrients). The similar magnitude of the observed effects in case of barley may indicate the relatively limited impact of tree species choice on the yield of this crop, potentially because it displays the shortest overlap in growing season with the tree component when compared to the other crops studied in this research. However, the measuring data of crop yield near walnut trees concern a single field and hence should be interpreted with caution.

Similar to the observations near poplar trees, average dry matter concentrations of cereals were decreased as a result of tree row presence and average crude protein concentrations were increased. In the arable zone in between a distance of 3 to 30 m, average values were decreased from 78.5±2.9 to 75.5±3.7% in case of grain maize, from 87.7±1.1 to 86.8±1.4% in case of winter barley and from 83.3±1.0 to 82.7±0.7% in case of winter wheat. Average crude protein concentration of winter cereals were increased from 13.6±2.3 to 14.8±2.0% and from

11.6±1.8 to 12.5±2.3% near the walnut trees in case of winter wheat and winter barley, respectively.

Conclusion: H4 is partially supported

6.3 Suggestions for optimizing the delivery of ES and biodiversity in SAF fields

6.3.1 Provisioning services

Humans value agricultural systems in particular for their provisioning services (Power, 2010). Our results confirm the theorem that the implementation of silvoarable AFS may simultaneously enhance multiple ES whilst maintaining productivity of land (Quinkenstein et al., 2009; Torralba et al., 2016; Tsonkova et al., 2012). As shown higher for poplar, the integration of trees in agricultural systems may be an effective way to increase SOC and beneficial biodiversity in arable fields. Although values vary according to the system characteristics, the calculated $\mathrm{LER}_{\mathrm{rotation}}$ values for the virtual SAF field consistently exceed 1. As a result, the abovementioned beneficial effects are realized without compromising biomass production and even increasing the land use efficiency. The simulated gains in land use efficiency are, however, small when compared to values obtained in other research. Several measures can be taken to further enhance land use efficiency and delivery of provisioning ES (although not all of them may apply to the virtual SAF in our simulation).

One key aspect to increase the productivity of mixed cropping systems is the selection and use of well-adapted tree crop combinations. This was clearly illustrated in our research where observed reductions in crop yield strongly differed according to the crop type, which in turn strongly affected the simulated $\mathrm{LER}_{\mathrm{rotation}}$ values of SAF fields. In general, the cultivation of crops with a reduced overlap in growing season with the tree component (e.g. winter cereals) can be considered an effective way to increase compatibility between trees and crops, in particular if crops using the C3-pathway of photosynthesis are grown (Dufour et al., 2013; Reynolds et al., 2007). In addition, during the process of agricultural intensification, the selection of crops and cultivars has generally been conducted in absence of trees and/or shrubs. As a result, most of the currently cultivated crop species and/or cultivars are probably poorly-adapted for growth in AFS. For instance, when considering shade-tolerance, most crops and cultivars have been selected for growth in full-light conditions, whereas in AFS, shade tolerant cultivars and/or species may actually be preferable (Artru et al., 2016; Burner and West, 2010; Mu et al., 2010).

In AFS, such better adapted cultivars could be cultivated in the whole of the intercropping zone. However, the magnitude of tree-crop competition is often strongly dependent on the distance to the trees (Liu, 1991; Montero et al., 2008). For instance, as shown by Leroy et al. (2009) and Gillespie et al. (2000), the lowest light availability is observed in the immediate vicinity of the trees whereas reductions in the center of the intercropping zone may be relatively small. As a result, subdividing agroforestry fields in different zones as a function of potential resource-competition between trees and crops, and adapting cultivation patterns accordingly (e.g. shade tolerant cultivars near the trees and shade intolerant cultivars in the center of the intercropping zone) may offer the highest potential to maximize productivity. This may entail difficulties regarding crop management as a result of heterogeneities in crop development at the field-level, owing to cultivar-related differences in e.g. ripening stage. However, as shown in chapter 4 and 5, such heterogeneities do also occur when only one cultivar is used and zoning the intercropping area, and the cultivars used, might even offer potential to mitigate or overcome these issues. In addition to using multiple cultivars, also the cultivation of different crop species may be envisaged. The actual feasibility of using different crops is however questionable, considering the complicated agricultural management as a result of e.g. strongly differing harvest times, (timing of) soil management and plant protection activities or issues related to accessibility of the different cropping zones. Similar to the selection of crop species and cultivars, also the past process of technological improvement of cultivation methods has mainly been conducted for sole cropping conditions. In AFS, however, adapting management might be beneficial, for example: experimenting with different sowing densities nearby trees (Gaba et al., 2015), or, as suggested higher, harvesting cereals at later times during the day to allow sufficient vaporization of nocturnal humidity or postponing the harvest to a later time during the growing season to overcome delayed ripening stages.

Further optimization of productivity may be achieved by focusing on the tree component. Firstly, this may be realized by the selection and use of tree species and cultivars with characteristics suitable for growth in AFS. For example, preference can be given to tree species and/or cultivars characterized by a low number of interior leaves (Peng et al., 2009; Reynolds et al., 2007), a late budburst (Dufour et al., 2013), good litter quality (Mafongoya et al., 1998), etc., to minimize resource-competition with the intercrop and maximize potential synergies. Although improvement of trees is lagging behind when compared to agricultural annual crops (Peña and Séguin, 2001; Simons and Leakey, 2004), if available, using cultivars specifically selected for more open field situations may be preferable in AFS as a result of the different growing conditions and the absence or strong reduction of several key processes occurring in forestry conditions (for example limited light availability in the understory which promotes self-pruning) (Leakey and Page, 2006). Secondly, trees in AFS often only occupy part of the grass strips, which leaves opportunities for the production of other agricultural goods and the potential realization of early revenues. Potential options may, for example, include the integration of animal production (e.g. poultry, rabbits) in fenced off areas of the grass strips, shrubs or low-stemmed fruit trees for the production of nuts and/or fruits or the cultivation of vegetables (Figure 6.5). Besides potentially increasing productivity, this may aid farmers in bridging the large timespan until the harvesting of the trees and the associated revenues which is often considered to be a discouraging factor for the establishment of AFS (Borremans et al., 2018; Merwin, 1997; Yates et al., 2007).

Suboptimal productivity of AFS may also be the result of inadequate management. Although farmers are generally highly skilled with respect to crop cultivation, this may not be the case regarding the management of the tree component, or awareness of the importance of the latter may be lacking (Jäger et al., 2017). In addition, as observed on some of the experimental fields in this research, leafless trees in their early age may even be neglected during crop management activities and severely damaged by heavy agricultural machinery which can strongly impact the tree growth and ultimately their economic value (Figure 6.5). Nonetheless, adequate management of the trees is of key importance throughout most of their lifecycle (e.g. heading back of fruit trees, high pruning) to maximize their production potential (i.e. fruits, nuts, high quality wood). In addition, this may further reduce negative interactions between trees and crops, for instance by the pruning of branches whereby light availability for the intercrops increases (Leroy et al., 2009) and pruning of roots to reduce the competition for water (Inurreta-Aguirre et al., 2018). Besides awareness, this requires sufficient knowledge and labor force for a proper performance, which may necessitate the provision of technical guidance and/or assistance (e.g. workshops) and continued financial governmental incentives throughout the entire agroforestry rotation.

Figure 6.5: Contour planting combined with swale structures and the cultivation of vegetables in the tree strips (left). Damaging of trees by agricultural machinery at early age (middle). Planting of "signaling" coniferous trees to increase visibility of the young (leafless) trees (right).

6.3.2 Supporting and regulating ES and biodiversity

The observed increases in SOC in the sampled soil layer (0-23) might be maximized and consolidated by the use of conservation tillage or zero tillage, whereby intensity and frequency of soil tillage is reduced and higher levels of soil cover (e.g. cover crops, crop residues) are maintained (Baker et al., 2007; Govaerts et al., 2009; Lal and Kimble, 1997). As indicated by Freibauer et al. (2004), the strongest beneficial effects of reduced tillage on carbon sequestration are found where relatively high soil carbon contents occur simultaneously with relatively high decomposition rates, for example in North-Germany and the Netherlands. Other ES attributed to AFS are the reduction of runoff water and erosion (Quinkenstein et al., 2009; Tsonkova et al., 2012). Although actual comparative research with other spatial configurations of the tree rows in AFS appears to be limited, AFS on sloped parcels wherein tree rows are spatially organized along the contour lines of elevation, whether or not combined with ditch-ridge structures (Figure 6.5), might show particular potential to reduce runoff and erosion (Adhikary et al., 2017; Anderson et al., 2009; Palma et al., 2007; Paningbatan et al., 1995; Schoeneberger et al., 2017). The use of cover crops and application of crop residues in AFS, as suggested higher, might further enhance water retention (Dabney, 1998; Unger and Vigil, 1998), thereby further reducing runoff of nutrient-enriched water and flood risks (Cerdà et al., 2016; Gómez et al., 2009). Although the fields in our research were conventionally farmed, faunal and floral diversity (and the associated ES) might be further enhanced in agricultural systems were crop protecting agents are omitted or strongly reduced (Geiger et al., 2010; Pickett and Bugg, 1998). In addition, parts of the grass strips can be designed in such a manner to optimize habitat conditions for potentially beneficial species whilst being unsuitable for pests (Gaba et al., 2015). For example, establishment of features with diverse wildflower mixtures in farmland might provide refuge and a diverse range of food sources (a.o. nectar, pollen, honeydew, alternate prey, litter) that benefit pest predators (Pfiffner and Wyss, 2004), pollinators (Haaland et al., 2011; Korpela et al., 2013) and detritivorous arthropods (Hopkin and Read, 1992; Smith et al., 2008b). As shown by Jones and Sieving (2006), the integration of sunflowers in a vegetable cropping system can be an effective habitat modification to increase the foraging activity of pest predatory bird species. Another example may be the establishment of “beetle banks” in the grassy strips, i.e. within-field ridges that act as overwintering refuges in sole-cropping fields, which are known to improve pest control in the neighboring arable zone (Collins et al., 2002; Macleod et al., 2004).

As a result of potential synergies between different agro-ecological practices, the highest success in maximizing ES-delivery in AFS may be expected if several of the above-mentioned measures are combined. For example, the beneficial effect of tree rows on water quality (e.g. by reducing erosion and nutrient leaching) may be further enhanced in AFS where crop protection agents are omitted to maximize the potential for biological pest control. As indicated in the meta-analysis of Pittelkow et al. (2015), implementing no-tillage alone may lead to reductions in crop yield, whereas the combination of no-tillage, soil cover and crop rotation may increase yields. In addition, several of the beneficial effects of AFS on ES-delivery concern the landscape rather than the field level and the success of implemented measures may strongly depend on the local context. For example, the mere presence of wildflower strips may not suffice to increase natural pest control, because colonization of these strips by pest predators may depend on the presence of other nearby semi-natural habitats in the agricultural matrix (e.g. permanent grassland, woodlots) (Jonsson et al., 2015; Tscharntke et al., 2005). Hence, although based on our results, tree rows can successfully be integrated in conventional agricultural systems, realizing the full potential of AFS for ES-delivery supposedly necessitates a more substantial shift to integrated agro-ecological production methods, whereby farmers develop tailor-made practices, adapted to the local context and applied at farm and/or landscape level.

In addition to the marketing of the agricultural goods produced, multiple options exist for farmers to valorize the abovementioned benefits of implementing agroforestry (Borremans et al., in preparation). On the one hand, farmers can directly benefit from this enhanced delivery of ES in such cropping systems without additional changes in management or marketing. For example, in Mediterranean regions, the sheltering effect of the trees has been found to reduce evapotranspiration, resulting in higher soil water content under arid conditions (Campi et al., 2009; Sánchez et al., 2009; Smith et al., 2012a). Such effect may potentially also occur under temperate conditions when periods of prolonged summer drought occur, as was the case during 2018 in several parts of north-western Europe. The creation of an attractive landscape may stimulate agro-tourism, both on the landscape scale (cf. fruit orchards in Haspengauw) and on the farm-level where agricultural production is combined with e.g. B&B or restauration activities. Other examples are the potentially increased crop yields as a result of the abovementioned increase in SOC (which, together with reduced soil erosion, may contribute to enhanced soil structure and soil fertility). On the other hand, farmers may actively utilize the opportunities provided by AFS to increase financial valorization. For example, enhanced natural pest control may allow the reduction or omission of pesticides and the associated costs for their purchase and application. Requesting higher tenancies from hunters may be justified because of the increased species richness and structural diversity of the vegetation. Nonetheless, at present, several opportunities remain to further valorize the benefits of AFS, in particular via initiatives launched on a regional or (inter)national scale and/or supported by the government or other stakeholders such as retail, landscape –and environmental organizations. For example, at present, consumer awareness and demand for environmentally friendly production methods with attention for animal wellbeing is increasing. However, consumers may not be aware that this demand can partially be met by production systems where agroforestry is implemented or it may not always be clear when products originate from

AFS. Therefore, increasing visibility and recognizability, for example by the establishment of an agroforestry-label (cf. BIO, Fairtrade, MSC) may aid in valorizing these aspects of AFS. In addition, whereas farmers can currently benefit from subsidies to recover 80 % of the establishment costs of an AFS and agroforestry is considered an official measure to fulfill the greening requirements, these incentives launched by the government may not be in proportion to the ES realized by implementing agroforestry and the consecutive benefits for society. In Austria, for example, farmers can apply for a payment of 30 € ton^{-1} CO_2 sequestered in the plough layer of their fields. This payment for ES is facilitated by the local eco-region via the *Humusaufbau* project and is funded by local companies to compensate for their CO_2 emissions (Ökoregion Kaindorf, 2018). Expanding such initiatives to other regions while focusing on agroforestry and the development of similar incentives with regard to other ES provided such as erosion reduction and the enhancement or conservation of biodiversity should be evaluated to remunerate famers for the ES provided to society as a whole.

6.4 Further research

6.4.1 Carbon sequestration and soil nutrient conditions

In our assessment of SOC and soil nutrient conditions in temperate SAF fields, we have focused on the soil layer of highest agricultural relevance (0 – 23 cm). However, the observed effects may extend to deeper soil layers. In particular when evaluating the C-sequestration potential of SAF, the results of this research only represent a limited fraction of the total C sequestered, since no quantification of the total above –and belowground woody biomass was done, nor of SOC in deeper soil layers or in the grassy tree strips. Hence, assessment of the total woody biomass and of soil characteristics in deeper soil layers, in the arable zone as well as in the tree rows, would be necessary to quantify the full potential for C-sequestration. The assessment of rooting patterns of both trees and crops and root biomass may furthermore aid in the evaluation of tree-crop competition and the selection of adapted tree-crop combinations (see below).

The observed increases in soil nutrient concentrations in the plough layer (see chapter 2) may indicate that competition for nutrients is not the main cause for the observed reductions in crop yield. Hence, reduced fertilization may be possible in SAF as suggested by (Cardinael et al., 2015a; Jose et al., 2000a; Rivest et al., 2009; Zhang, 1999). However, confirming this hypothesis would require actual field trials whereby the growth response of arable crops, submitted to competition with tree rows, on various fertilization regimes is evaluated. In addition, since the tree component in AFS constitutes an integral part of the agricultural production, also the simultaneous effect of altered fertilization regimes on tree growth and/or productivity should be assessed.

6.4.2 Agro-biodiversity

The monitoring of arthropod abundance in chapter 3 and 5 has shown the potential (beneficial) effect of SAF on communities of macro-detritivorous arthropods. However, in the particular in case of carnivorous taxa, a more extended monitoring campaign would be required to interpret the observed trends. As also suggested by Van Vooren (2018), where a similar experimental setup was used as in our study, starting the monitoring early in season may reveal potential colonizing movements which may remain undetected when sampling is not started until the end of May. In addition, in this research, a field-level approach was used to assess gradients in abundance and diversity in and near tree rows when compared to treeless conditions and in-field locations at several distances to the tree rows. Alternatively, considering the high mobility of several arthropod taxa, the effect of AFS on arthropod presence may be evaluated using a landscape level approach whereby agroforestry fields are compared with similar fields without trees, or where comparison is made between agricultural landscapes with high versus low presence of AF. The combination of these sampling approaches can be considered complementary, in particular when considering both mobile and less mobile taxa and/or species. In addition, not all carabid species are strictly carnivorous and further differentiation and analysis as function of their feeding characteristics may further increase knowledge regarding their potential for pest control in AFS. Furthermore, combined monitoring of both pest predators, pest species and/or crop damage may be necessary to evaluate the actual impact on crop yield. Finally, the implementation of agroforestry may affect several other aspects of biodiversity which were not assessed in this research but may be of (economical) importance for farmer and society. This includes for example other functional arthropod groups such as pollinators, endangered farmland birds or mammals (European hamster, *Cricetus cricetus*), several game species, mychorrizae and plants.

6.4.3 Crop yield and quality

The magnitude of the observed effects on yield and quality of arable crops appeared to be strongly related to both the crop and tree species under study. Selection of adapted tree-crop combinations appears to be of prior importance to optimize the production potential of SAF. This may be achieved by assessing crop yield in AFS for various crops types/species (e.g. hemp, *Cannabis sativa*; soybean, *Glycine max*; vegetables) and crop cultivars (e.g. regarding shade tolerance), either under artificial conditions (e.g. shading nets) or field trials in actual SAF systems, as well as varying species and cultivars of the tree component. In addition, knowledge about tree growth and quality of wood in SAF is limited. Hence, selection of adapted tree species and cultivars may focus on both limiting competition with arable crops and, unless trees are grown for fruits and/or nuts, producing high-quality wood (e.g. limited development of side branches). Finally, in this PhD-research, focus was on the assessment of bio-physical effects. Thereby, the tree and crop components of highest importance were considered (e.g caryopsis, tree stem wood, etc.). However, the assessment of biomass production in AFS may be further enhanced by including other potentially less valuable components such as straw and tree branches.

6.4.4 Financial valuation

As shown by other authors and confirmed in our research, LER values of AFS can exceed 1, indicating an increased biomass production in AFS when compared to sole cropping conditions. However, assessing the profitability of AFS requires the translation of biophysical LER's to economical LER's whereby the observed effects (e.g. decreased crop yield and altered crop quality) are financially valuated to estimate the related economic benefits and disadvantages ultimately determining the economic viability of integrating AFS at the farm level. Although this was not the focus of this particular research, a first rough attempt was made to translate the $LER_{rotation}$ values obtained for the virtual SAF field with poplar to financial revenues. This was done both for the standard crop rotation and for the crop rotation with solely winter cereals, based on the estimations of costs and revenues of agricultural crops and wood production as described by Van Vooren et al. (2016) (see Appendix 6.2). Not taking amortization of revenues and/or costs into account, implementation of agroforestry appears to result in a simulated loss in net revenues of around 7 000 – 7 500 € ha^{-1} after 25 years in case of the standard crop rotation. In case of a rotation with winter cereals, this values decreases to around 500 € ha^{-1}. this would imply that an additional financial revenue of approximately 290 and 20 € ha^{-1} $year^{-1}$, respectively, would be necessary to obtain similar financial revenues in AFS when compared to sole cropping fields. These estimates are, however, prone to several assumptions and simplifications and, as also indicated by Borremans et al. (2018, 2016), several additional factors should be considered such as the increased uncertainty and financial risks for the farmer associated to the long rotation time of the tree component and the discrepancy between the long rotation time of the trees and the often short-time horizon on which farmers have to operate.

As indicated before, several options may exist to reduce or compensate the abovementioned loss of income such as the integration of other production functions, further optimization of selected tree-crop combinations, reduced use of pesticides or remuneration for ES delivery. For example, based on the increase of 5.3 ton C ha^{-1}, and the payment in the *Humusaufbau* project of 30 € ton CO_2 sequestered, an additional revenue of 23 € ha^{-1} would be realized, thus compensating for the abovementioned net loss in the cropping rotation with winter cereals. As argued higher, potential options for (financial) compensation for the delivery of supporting and regulating ES and the enhancement of biodiversity for farmers implementing AFS should be further evaluated.

6.4.5 Research on mature alley cropping fields

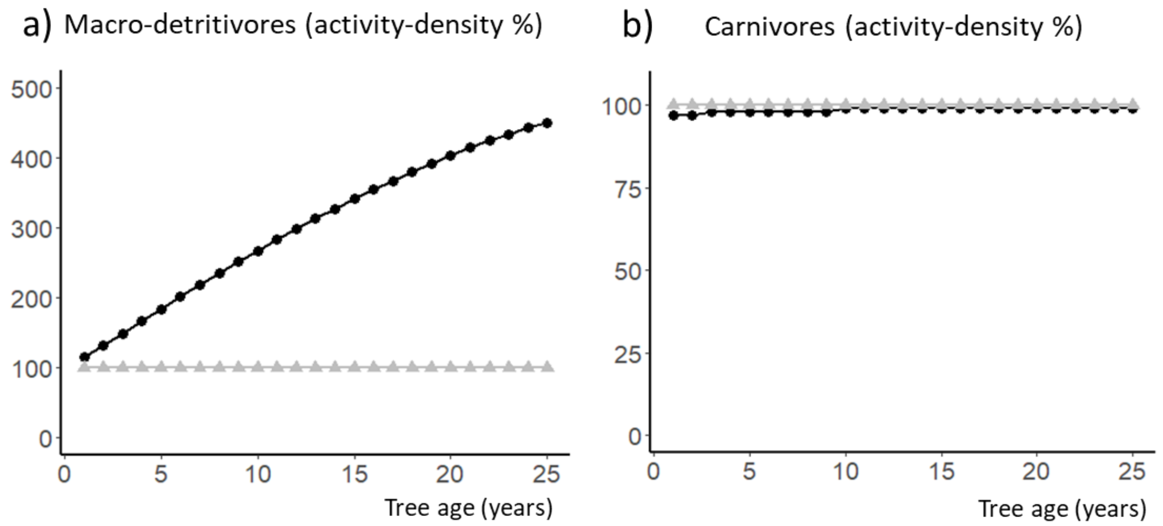
In this research, the main reason for using boundary planted fields as a proxy for mature alley cropping fields was the current absence of actual arable alley cropping systems in Flanders with tree rows of intermediate or older age. As argued in chapter 1, the selected boundary fields had to comply to several conditions (e.g.: NS orientation, high pruning, etc.) to most closely resemble alley cropping fields. Nonetheless, some factors should be taken into account when extrapolating the observed effects to actual alley cropping systems. For example, in contrast to in-field located tree rows, boundary planted trees may be characterized by a different management or land–use on the other side of the tree row such as meadow or a dirt road. This may, amongst others, affect the colonization of the tree rows by arthropods, or the growth and rooting patterns of the trees as a result of differing fertilization practices or soil management activities, respectively, which may in turn affect resource competition between trees and crops. Furthermore, at present in Flanders, the interrow distance of newly-established fields on conventional farms is often set to equal the width of the spraying boom used in field management. However, considering the observed effects near mature trees extended up to 30m into the arable zone, our observations are assumed to be valid for alley cropping fields with an interrow distance of 60m or more (cf. virtual SAF field in 6.1.1) because overlapping tree effects are expected at smaller distances in actual alley cropping fields. Nonetheless, as also indicated by several authors (Cleugh, 1998; Nuberg, 1998), tree rows may reduce wind speed up to distances equaling several times the tree height. Therefore, even when planted at larger interrow distances, different microclimatic conditions can be expected in alley cropping systems with multiple parallel tree rows when compared to boundary planted fields, which may for example lead to altered crop yields or tree leaf deposition patterns.

As mature alley cropping fields will become more abundant in the near future, these potential limitations may be overcome by continuing and extending the research presented in this thesis in actual alley cropping systems, including fields with limited interrow distances. Ideally, this would be conducted in a controlled environment under standardized conditions. Besides the advantage of having control of field and crop management activities (e.g. crop type sown, crop variety, harvest date, etc.), this may aid in avoiding some of the challenges of selecting and studying on-farm fields. Examples of the latter may for example include the selection of fields with homogeneous soil conditions for the establishment of such experimental sites, the use of specific tree varieties at the time of tree planting, avoid uncertainties about tree age, the establishment of a standardized management of the grass strip or communication of conducted management activities. Although this was avoided as much as possible, these factors may be hampered when selecting existing on-farm fields whereby (limited) heterogeneities in soil conditions may become apparent, taking tree variety into account as a selection criteria may be very difficult or even infeasible, or differences in management and herbaceous composition of the grass strip may be present.

6.5 Appendix

6.5.1 Appendix 6.1

Figure 6.4: (a) Evolution of SOC and (b) crop yield in the virtual SAF field (black dots) and the sole cropping control field (grey triangles) throughout one rotation of the tree component. (c) Evolution of stem wood yield in the SAF field (black dots) and the control forest stand (grey triangles). (d) Average relative crop yield in the virtual SAF when compared to the sole cropping control field from year 1 to i (blue dots), cumulative relative wood yield in the virtual SAF when compared to the control forest stand (green squares) and LERrotation from year 1 to i (black triangles).

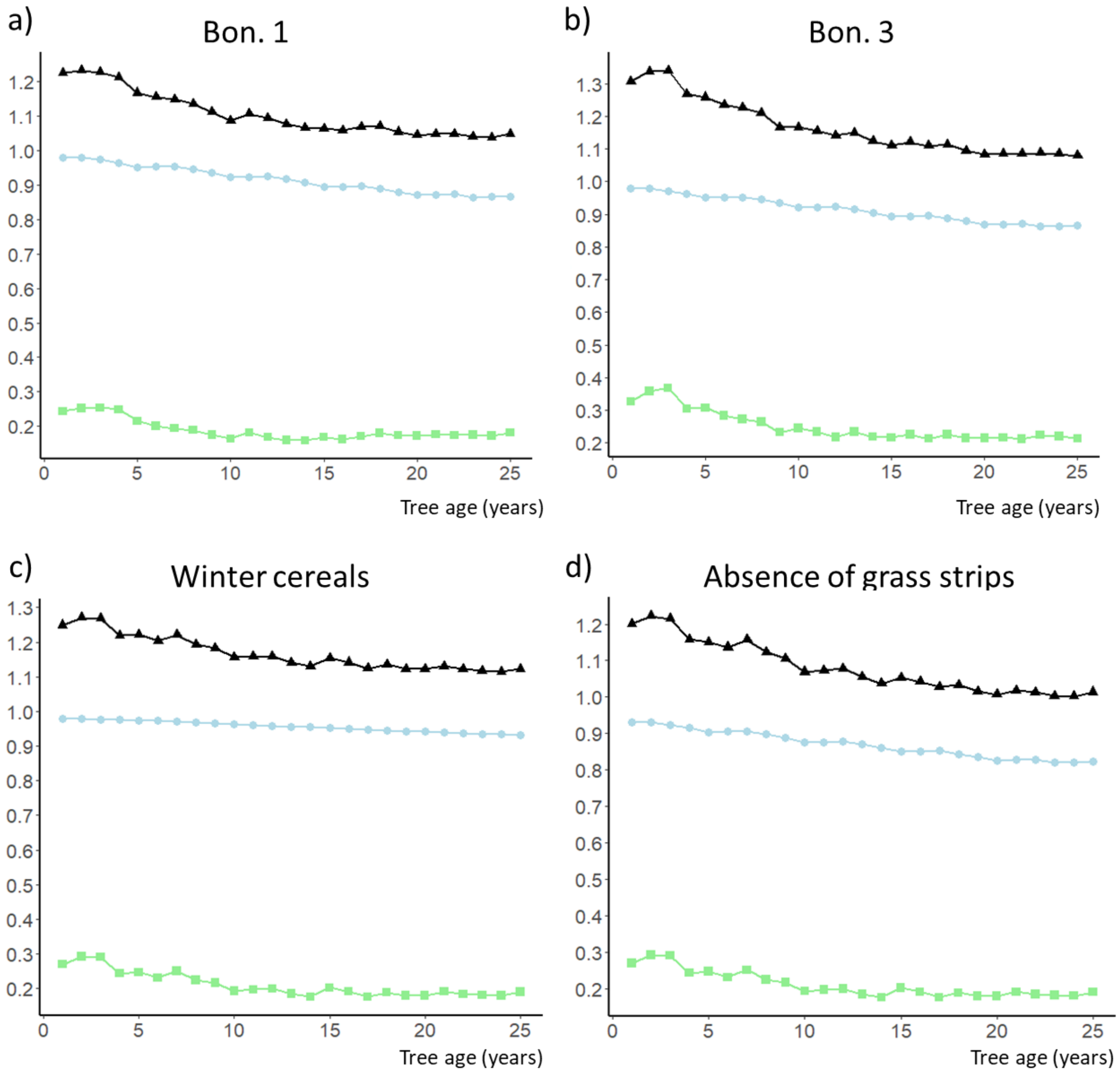


6.5.2 Appendix 6.2

a) Alternative scenarios for wood and crop yield: stem wood yield in the virtual SAF field relative to the stem wood yield in the control forest stands of bonity 1 & 3. Crop yield in the SAF field relative to the yield in the sole cropping control field in case no grassy edges are present and in case only winter cereals are grown.

	Wood (stem) biomass production (ton 1.34 ha^{-1})					Crop yield: scenario no grassy edges (ton 1.34 ha^{-1})			Crop yield: scenario Winter cereals (ton 1.34 ha^{-1})		
Tree age	**Virtual SAF**	**Forest stand Bon 1**	**SAF:Forest (%)**	**Forest stand Bon 3**	**SAF:Forest (%)**	**SAF**	**Control**	**SAF:Control (%)**	**SAF**	**Control**	**SAF:Control (%)**
1	0.01	0.02	24.4	0.02	32.7	10.7	11.5	93.1	10.7	11.0	97.9
2	0.04	0.16	25.2	0.11	35.9	11.9	12.9	92.9	11.9	12.2	97.7
3	0.14	0.56	25.4	0.39	36.8	11.8	13.0	91.2	10.7	11.0	97.4
4	0.29	1.17	24.9	0.95	30.5	23.8	26.8	89.0	11.9	12.2	97.0
5	0.49	2.26	21.5	1.58	30.8	19.6	22.8	85.6	10.6	11.0	97.0
6	0.83	4.09	20.2	2.91	28.4	10.5	11.5	91.2	11.8	12.2	96.3
7	1.29	6.63	19.5	4.74	27.3	11.7	12.9	91.2	10.4	11.0	95.4
8	1.89	10.00	18.9	7.13	26.5	11.0	13.0	84.6	11.7	12.2	95.5
9	2.41	13.77	17.5	10.37	23.2	21.7	26.8	80.9	10.3	11.0	94.4
10	3.10	18.84	16.4	12.63	24.5	17.4	22.8	76.0	11.6	12.2	94.8
11	4.18	22.86	18.3	17.88	23.4	10.2	11.5	88.5	10.2	11.0	93.1
12	4.96	29.37	16.9	22.85	21.7	11.5	12.9	89.5	11.5	12.2	94.2
13	6.12	38.22	16.0	26.17	23.4	10.1	13.0	78.0	10.1	11.0	92.0
14	7.03	44.16	15.9	32.15	21.9	19.7	26.8	73.4	11.4	12.2	93.5
15	8.81	52.17	16.9	40.69	21.7	15.9	22.8	69.6	10.0	11.0	91.0
16	10.10	62.12	16.3	44.62	22.6	9.9	11.5	86.0	11.4	12.2	92.9
17	11.45	66.89	17.1	53.72	21.3	11.3	12.9	88.1	9.9	11.0	90.0
18	13.12	72.64	18.1	58.17	22.5	9.2	13.0	71.2	11.3	12.2	92.4
19	14.26	81.92	17.4	66.38	21.5	18.2	26.8	67.8	9.7	11.0	89.0
20	16.01	92.25	17.4	74.60	21.5	15.0	22.8	65.6	11.2	12.2	91.9
21	17.95	101.55	17.7	82.98	21.6	9.7	11.5	83.8	9.7	11.0	88.1
22	19.48	111.75	17.4	91.71	21.2	11.2	12.9	87.0	11.2	12.2	91.5
23	21.41	121.97	17.6	95.55	22.4	17.4	26.8	64.8	9.6	11.0	87.4
24	22.97	132.82	17.3	104.03	22.1	9.5	11.5	82.8	11.1	12.2	91.2
25	24.91	137.29	18.1	116.60	21.4	11.1	12.9	86.6	9.5	11.0	86.8

b) Alternative scenarios for estimation of $LER_{rotation}$: a) control forest stand of bonity 1 and standard crop rotation, b) control forest stand of bonity 3 and standard crop rotation, c) control forest stand of bonity 2 and crop rotation with solely winter cereals, d) control forest stand of bonity 2 and no grassy edges present. Average relative crop yield in the virtual SAF when compared to the sole cropping control field from year 1 to i (blue dots), cumulative relative wood yield in the virtual SAF when compared to the control forest stand (green squares) and $LER_{rotation}$ from year 1 to i (black triangles).



c) Estimation of $LER_{rotation}$ values for varying scenarios of stem wood and crop yield: tree cutting at 25 or 19 years of age; control forest stand of bon 1-2-3; a standard crop rotation or a rotation comprising solely winter cereals and in case no grassy edges are present.

25 y		**Crop yield scenario**	
Bonity	**No grassy edges**	**Standard crop rotation**	**Winter cereals**
Bon. 1	1.005	1.048	1.113
Bon. 2	1.014	1.057	1.122
Bon. 3	1.037	1.080	1.145

19 y		**Crop yield scenario**	
Bonity	**No grassy edges**	**Standard crop rotation**	**Winter cereals**
Bon. 1	1.010	1.053	1.117
Bon. 2	1.016	1.059	1.123
Bon. 3	1.051	1.094	1.158

6.5.3 Appendix 6.3

Financial evaluation for the agroforestry rotation on the virtual SAF when compared to a sole cropping field for a standard crop rotation and a crop rotation comprising solely winter cereals (the latter not being good agronomical practice but shown here for illustrative purposes as argued in 6.1.1). Costs and revenues are based on the estimation by Van Vooren et al. (2016) (i.e. not taking into account fixed costs), with addition of the estimated costs for crop harvest. No discounting of revenues is included (i.e. the specific timing of revenues is not taking into account). A net loss in crop revenues in the SAF (1.34 ha) is observed equalling approximately 12 900 and 3 800 € in case of a standard crop rotation and a crop rotation with winter cereals (or around 9 600 and 2 850 € on a hectare basis, respectively). This loss is only partially counterbalanced by the net revenues of stem wood wich equal around 3 100 € (or 2300 € ha^{-1}). This results in a total reduction of net revenues of approximately 9 800 and 700 € in case of a standard crop rotation and a crop rotation with winter cereals (or 7 300 and 500 € on a hectare basis, respectively).

Arable crop	Winter wheat	Winter barley	Silage maize	Grain maize	Potato
Price per ton	200	178	145	79.6	100
Seed and propagating material (€ ha^{-1})	96.60	99.9	167.6	167.6	621.1
Fertilizers (€ ha^{-1})	190.5	153.3	125	125	341.6
Crop protection (€ ha^{-1})	196.2	138.5	101.2	101.2	591.3
Contract work (€ ha^{-1})	83.1	78.4	87.6	87.6	168.5
Other costs (€ ha^{-1})	12.5	11.2	19.6	19.6	73.5
Harvest (€ ha^{-1})	250	250	300	300	350

Net revenues (€ 1.34 ha^{-1})	Standard crop rotation	Winter cereals
SAF	38 973	34 204
Sole cropping	51 877	38 020
Difference	-12 906	-3 816

Wood		
Plant purchase (€ tree^{-1})	2.0	Year 1
Planting (€ tree^{-1})	1.52	Year 1
Plant protection (€ tree^{-1})	0.94	Year 1
Formation pruning (€ tree^{-1})	10 trees hour^{-1} 30€ hour^{-1}	Year 4, year 7, year 10

Net revenues (€ 1.34 ha^{-1})	
SAF	3 111
Control forest stand	15 277

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8. Curriculum vitae

Personal data

Name: Paul P. F. Pardon

Date of birth: 22 June 1987

Place of birth: Siegburg (Germany)

Nationality: Belgian

Education

2005-2012: MSc. Bioscience Engineering: Land and Forest Management, KU Leuven (Belgium).

1999-2005: Modern languages-science. Sint-Catherina College, Grammont (Belgium).

Professional experience

December 2014 - present: PhD student at Ghent University (Department of Environment & Department of Plant and Crops) and the Flanders research institute for agriculture, fisheries and food (ILVO)

October 2014 – December 2014: Scientific researcher at Gent University - Department of Environment

August 2012 – October 2014: Junior tender engineer at Envisan - Jan De Nul Group

Scientific publications

Coussement, T., Maloteau , S., **Pardon, P.**, Artru, S., Ridley, S., Javaux, M., Garré, S., 2018. A tree-bordered field as a surrogate for agroforestry in temperate regions: where does the water go? Agric. Water Manage. 210, 198-207. https://doi.org/10.1016/j.agwat.2018.06.033

Pardon, P., Mertens, J., Reubens, B., Reheul, D., Coussement, T., Elsen A., Nelissen V., Verheyen, K., Juglans regia in temperate arable agroforestry systems: effects on soil characteristics, arthropod diversity and crop yield. Submitted to Renew. Agric. Food Syst.

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Scientific reports

Nelissen, V., Coussement, T., **Pardon P.**, Reubens B., 2018. Effect van agroforestry op organische stof en nutriënten. Agroforestry Vlaanderen.

Nelissen, V., Van Daele, S., Verdonckt, P., Reheul, D., **Pardon, P.**, Reubens, B., 2017. Teelttechnische impact agroforestry. Agroforestry Vlaanderen.

Nelissen, V., Van Gossum, P., Reubens, B., Ruysschaert, G., D'Hose, T., **Pardon, P.**, Van Vooren, L. 2016. Maatregelen om het ESD-aanbod van landbouw te verhogen. Natuurrapport – Aan de slag met ecosysteemdiensten. Technisch Rapport. INBO, Brussels, Belgium.

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Pardon, P., Reubens, B., Mertens, J., Verheyen, K., De Frenne, P., De Smet, G., Nelissen, V., Van Waes, C., Reheul, D., 2018 Biomassaproductie en kwaliteit van landbouwgewassen en bomen in lijnvormige agroforestry systemen. Agroforestry Vlaanderen.

Participation in congresses, symposia or workshops

Oral presentations

International congresses

25-05-2016 "Ecological interactions between tree, crop, soil and environment in alley cropping systems in Flanders". 3rd European Agroforestry Conference. Montpellier.

03-05-2017 "Agroforestry in Flanders". Alter-net conference Nature and society: synergies, conflicts and trade-offs. Brussels

30-05-2018 "Gradients in abundance and diversity of ground-dwelling arthropods in temperate silvoarable fields". 4th European Agroforestry Conference. Nijmegen.

National congresses, symposia or workshops

20-09-2016: “Silvoarable agroforestry: yield, soil characteristics and agricultural biodiversity”. 5th Belgian Agroecology Meeting. Ghent.

24-03-2017: “Silviculturele agroforestry: bodemkarakteristieken, functionele biodiversiteit en gewasopbrengst”. Starters in het bos- en natuuronderzoek. Ghent.

05-10-2017: “Bomen op de akker? Over de zin van agroforestry voor boer, klimaat en omgeving.” 3de studienamiddag CriNglooP collectief. Melle.

08/11/17 Introductionary course “Agroforestry of boslandbouw”, Agro- and biotechnology, Greenery Management. HoGent.

19/03/18 Introductionary course “Agroforestry of boslandbouw”. Institut Montjoie.

Poster presentations

27-03-2015: “Interacties tussen boom, bodem, gewas en omgeving in een agroforestry-systeem in Vlaanderen”. Starters in bos- en natuuronderzoek. Brussels.

13-12-2016: “Silvoarable agroforestry: yield, functional biodiversity and soil characteristics”. BEES X-mas market. Ghent.

14-11-2017: “Silvoarable agroforestry: soil characteristics, functional biodiversity and yield”. 6th Belgian Agroecology Meeting. Gembloux.

30-05-2018: “Temperate agroforestry: yield of five key arable crops near tree rows of Populus x canadensis”. 4th European Agroforestry Conference. Nijmegen.

(co-)Supervision of thesis students and internships

Martens, Corneel. Masterthesis. 2016. Invloed van een agroforestry-systeem op de regenwormenpopulaties in de zandleemstreek van België. Master of Science in Bioscience Engineering Technology: Agriculture and Horticulture. Promotor: Prof. dr. ir. Jan Mertens. UGent.

Di Coco, Marion. Internship (January 2016). Master in agricultural engineering. Institute for life, food and horticultural sciences and landscaping (Agro Campus Ouest).

Van der Hoeven, Rico. Internship (April 2017). Bachelor Secondary education Geography & Biology. Artevelde hogeschool.

van Riet, Emiel. Internship (April – August 2018). Bachelor of forestry and nature management. Hogeschool Van Hall Larenstein.

Peer reviewing for scientific journals

European journal of agronomy (2017)

Agriculture, ecosystems and environment (2018)