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First-rotation tree growth of organic and conventional short-rotation agroforestry systems in southern Germany

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II Summary

Introduction

Agroforestry systems (AFS) are land use systems that combine trees and shrubs with agricultural crops and/or livestock on the same land. To produce wood for energy, fast-growing tree species are planted in short rotation agroforestry systems (SRAFS). AFS offer both ecological and socio-economic benefits. They provide a variety of environmental services such as protection of biodiversity, climate, water, and soil. In addition, tree cultures diversify agricultural production and thus the farmers' incomes. Also, synergies between trees and crops can lead to increased overall productivity in AFS. For example, windbreak effects can increase the yields of adjacent arable crops. Over the past decades, the size of arable fields has been significantly increased in many agricultural regions and trees, hedges, and other structural elements have been partially removed. Traditional extensive AFS that still exist, such as orchards, are particularly worthy of protection and ecologically valuable. But modern SRAFS can also enrich an agricultural landscape and increase diversity of use. Due to the many advantages of AFS and SRAFS, interest in these systems has recently grown. AFS can be established in many locations with different soil/climate conditions. Since policy makers and farmers are not aware of the ecological and economic benefits of AFS and lack experience with corresponding farming methods, AFS are hardly promoted and established.

One economic success factor for the cultivation of trees on agricultural land is the development of the stand. Tree yields at the end of the rotation period determine the sales value, but also the efficiency of resource use and, to a large extent, carbon storage. Farm managers need to take into account tree species-specific differences in terms of growth rate, intraspecific competition and response to environmental influences and management measures. Therefore, the design of the system and the selection of suitable tree species determine the success of AFS and SRAFS. SRAFS have been insufficiently studied under conditions in southern Germany (or comparable site conditions). Few studies investigated organic farming systems at all and none compared organic with conventional SRAFS on the same location. Therefore, research on the suitability and growth dynamics of different tree species as bioenergy crops in SRAFS is essential.

Material and methods

The present work focused on the development of biomass estimation functions and the analysis of tree and stand development of five tree species (black alder, black locust, poplar clone Max 3, poplar clone Androscoggin, willow clone Inger) and a mixture of native trees (black alder, goat-willow, common hazel, common hornbeam, sycamore maple). With the aim to investigate silvoarable SRAFS in long-term field experiments, strips of trees were planted on organically and conventionally managed fields of the research station Scheyern (southern Germany). On two organic and two conventional fields, three tree strips were planted at a distance of 30 meters from each other. Each tree strip consisted of six rows. Within the strips, different tree species alternated in 30 meter long blocks.

From 2009 to 2012, stem base diameter (SBD), tree height (H) and the number of shoots were measured. Next to describing the stand development, these variables also formed the basis for the development of allometric biomass estimation functions and thus for the modelling of aboveground tree biomass within the four-year rotation. To validate the estimation functions at the end of the rotation, the yields of the harvested middle tree rows were compared to those of the biomass functions.

Organic and conventional farming systems offered the possibility to study species-specific tree growth under two conditions. Since in SRAFS, unlike in short rotation coppices, trees are planted in strips, edge effects on trees play an important role. Therefore, a further focus was placed on the differences between the border and inner rows of a tree strip.

Results and discussion

For the first time a system comparison of organic and conventional SRAFS was carried out. Allometric biomass functions serve as a practical and non-destructive application for estimating biomass of trees in SRAFS. Tree species-specific functions are required for an accurate estimation of yields. The inclusion of tree height as an additional parameter to SBD significantly improved estimation accuracy and kept the deviation between yields measured by allometric funtions and those by harvesting below 10%. Deviations without tree height were 8–31%. The integration of the ratio between SBD and H, which can change intraspecifically due to environmental conditions and the ontogenetic stage, also increases the transferability to other stands. The same functions were used for border and inner rows, and no differences were found between the management systems.

Species-specific stand growth determines biomass yield and influences management decisions like planting density and harvest requirements. The poplar clones were well adapted to the conditions of the study area, developed an equal population and achieved the highest growth of 10–11 t ha^{-1} yr^{-1} at a survival rate of 99%. Black locust reached 9 t ha^{-1} yr^{-1} – the third highest biomass production of all investigated species. Strong self-thinning (10% mortality) and SBD inhomogeneity caused by intraspecific competition were observed, which can lead to impairments in harvesting and quality of the wood. Lower plant densities are thus recommended. Alders showed a moderate growth of 8 t ha^{-1} yr^{-1} with a mortality of 8% and developed like black locust an unequal stand. Willow and the native mixture had the lowest yields (5 t ha^{-1} yr^{-1}), which was up to 50% lower than that of poplar. The willow stands had no crown closure after four years and consequently showed no mortality. Even though a reduction in the number of shoots occurred in the second year, several new shoots sprouted in the following years. The common practice of early coppicing is thus recommended for willow in order to promote the regrowth of multiple shoots and thus a quicker crown closure. The low yields of the native wood mixture can be attributed to the low to no growth of individual tree species, with the exception of black alder. Overall, longer rotations would have led to higher growth rates for all tree species, as after four years the maximum growth rate was probably not reached for any of the tree species. However, the higher tree diameters due to longer rotations may require more expensive harvesting techniques, the cost of which must be weighed against the higher yields.

Previous and current organic land management has not affected tree growth. When edge effects are excluded, the organically managed fields produced the same tree biomass as the conventionally managed ones. If, however, the border rows are considered, a positive effect of fertilizer application in the conventional system, especially for poplar and willow, was observed. Black locust and alder seem to have been less influenced by the fertilizer due to their symbiosis with nitrogen-binding bacteria. But there were also positive edge effects in the organic system, with the exception of willow. The border rows achieved larger tree diameters and higher numbers of shoots and thus more yield than inner rows. If it is assumed that 1/3 of the strip consists of border rows, the yield of the SRAFS increases by 6 to 37% depending on the tree species. This means that edge effects, which are normally bypassed in studies on short rotation coppices, have a considerable effect on the yields of SRAFS.

Conclusion and outlook

The focus of the work was the measurement and modelling of the biomass development of trees in SRAFS with fast-growing species for energetic use. The determination of the yields and the yield dynamics of the different tree species and clones as accurate as possible is of outstanding importance for the assessment of the economic and ecological performance of SRAFS (economic efficiency compared to SRC and arable use, C storage, energy efficiency, etc.). All the factors tree species, site, system design, and management as well as their interactions determine the tree yields and the overall performance of a SRAFS. For the first time, experimental data on biomass development could be presented for the cool and humid conditions of the Bavarian tertiary hills. For the first time, it was proven that after many years of organic farming, the same wood biomass yields can be achieved in organic SRAFS as in conventional SRAFS. SRAFS are therefore also suitable for organic farming and can be recommended in practice. However, the application of fertilizer to conventional arable crops had a yield-increasing effect on the border rows and thus on the total yield of the tree strips. Since the first rotation is not always representative of the growth potential of tree species, subsequent rotations should be investigated before general recommendations are given on yield and stand development. In addition, gene-environment interactions may affect the performance of tree species at other sites.

III Zusammenfassung

Einleitung

Agroforstsysteme (AFS) sind Landnutzungssysteme, die Bäume und Sträucher mit landwirtschaftlichen Kulturen und/oder Nutztieren auf einer Fläche kombinieren. Zur Erzeugung von Energieholz werden in AFS schnellwachsende Baumarten mit kurzer Umtriebszeit gepflanzt (short rotation agroforestry systems, SRAFS). AFS können sowohl ökologische als auch sozioökonomische Vorteile bieten. Im Bereich der Umweltdienstleistungen können sie zum Schutz von Biodiversität, Klima, Wasser und Boden beitragen. Zudem diversifizieren Baumkulturen die landwirtschaftliche Produktion und damit das Einkommen der Landwirte. Zusätzlich können AFS durch Synergien zwischen Bäumen und Kulturpflanzen zu einer gesteigerten Gesamtproduktivität beitragen. Windschutzeffekte können z.B. die Erträge der angrenzenden ackerbaulichen Nutzpflanzen erhöhen. In den vergangenen Jahrzehnten wurden die Ackerschläge in vielen Agrarregionen deutlich vergrößert und hierbei Bäume, Hecken und andere Strukturelemente dezimiert. Noch vorhandene traditionelle extensive AFS, wie z.B. Streuobstwiesen, sind besonders schützenswert und ökologisch wertvoll. Aber auch moderne SRAFS können eine Agrarlandschaft bereichern und die Nutzungsdiversität erhöhen. Aufgrund der vielfältigen Vorteilen von AFS und SRAFS ist das Interesse an diesen Systemen jüngst gewachsen. AFS können auf sehr vielen unterschiedlichen Standorten mit differenzierten Boden/Klimabedingungen etabliert werden. Da politische EntscheidungsträgerInnen und LandwirtInnen jedoch die ökologischen und ökonomischen Vorteile der AFS oft nicht kennen und zu wenig Erfahrung mit den Anbaumethoden haben, werden AFS wenig gefördert und kaum etabliert.

Ein wirtschaftlicher Erfolgsfaktor für die Kultivierung von Bäumen auf landwirtschaftlichen Flächen ist die Entwicklung des Bestandes. Baumerträge am Ende der Umtriebszeit bestimmen den Verkaufswert, aber auch die Ressourcennutzungseffizienz und weitestgehend die Kohlenstoffspeicherung. BetriebsleiterInnen müssen baumartenspezifische Unterschiede hinsichtlich Zuwachsrate, innerartlicher Konkurrenz sowie Reaktion auf Umwelteinflüsse und Bewirtschaftungsmaßnahmen berücksichtigen. Der Erfolg von AFS und SRAFS hängt damit in hohem Maße von der Gestaltung des Systems und der Auswahl geeigneter Baumarten ab. SRAFS wurden unter den Bedingungen in Süddeutschland (oder vergleichbaren Standortbedingungen) nur unzureichend analysiert. Wenige Studien untersuchten Systeme im ökologischen Landbau und keine stellten einen direkten Vergleich von ökologischen und konventionellen SRAFS an. Daher ist die Erforschung der Eignung und Wachstumsdynamik verschiedener Baumarten als Bioenergiepflanzen in SRAFS unerlässlich.

Material und Methoden

Forschungsschwerpunkte der vorliegenden Arbeit sind die Erstellung von Biomasseschätzfunktionen sowie die Analyse der Baum- und Bestandsentwicklung von fünf Baumarten (Schwarzerle, Robinie, Pappelklon Max 3, Pappelklon Androscoggin, Weidenklon Inger) und einer Mischung einheimischer Bäume (Bergahorn, Gemeine Hasel, Hainbuche, Sal-Weide, Schwarzerle). Mit dem Ziel silvoarable SRAFS langfristig in Dauerfeldexperimenten zu untersuchen, wurden auf ökologisch und konventionell bewirtschafteten Feldern der Versuchsstation Scheyern (Süddeutschland) Gehölzstreifen angelegt. Auf je zwei ökologischen und konventionellen Feldern wurden jeweils drei Gehölzstreifen in einem Abstand von 30 Metern gepflanzt. Jeder Streifen bestand aus sechs Baumreihen. Innerhalb der Streifen wechselten sich alle 30 Meter verschiedene Baumarten blockweise ab.

Von 2009 bis 2012 wurden jährlich die Stammbasisdurchmesser (SBD), Baumhöhen (H) und Triebzahlen gemessen. Diese Variablen dienen der Beschreibung der Bestandsentwicklung und bilden auch die Grundlage für die Erstellung allometrischer Biomasseschätzfunktionen und damit der Modellierung der oberirdischen Biomasse innerhalb der Umtriebszeit. Um diese Funktionen am Ende der Umtriebszeit zu validieren, wurden die Erträge der geernteten mittleren Baumreihen mit den Erträgen der Biomasseschätzfunktionen verglichen.

Die ökologischen und konventionellen Bewirtschaftungssysteme boten die Möglichkeit das artenspezifische Baumwachstum unter zwei unterschiedichen Bedingungen zu untersuchen. Da in SRAFS, anders als in Kurzumtriebsplantagen, Bäume in Streifen angelegt werden, spielen hier Randeffekte auf die Bäume eine erhebliche Rolle. Deshalb wurde ein weiterer Fokus auf die Unterschiede zwischen äußeren und inneren Reihen eines Gehölzstreifens gelegt.

Ergebnisse und Diskussion

Erstmalig wurde ein Systemvergleich ökologischer und konventioneller SRAFS durchgeführt. Allometrische Biomasseschätzfunktionen dienen als praktische und zerstörungsfreie Anwendung zur Ertragsschätzung von Bäumen in SRAFS. Für eine genaue Bestimmung der Erträge sind baumartenspezifische Funktionen nötig. Die Einbeziehung der Baumhöhe als zusätzlicher Parameter zum Stammdurchmesser verbessert die Schätzgenauigkeit erheblich. Sie hält die Abweichung zwischen berechneten und durch Ernte gemessenen Erträgen unter 10%. Ohne Berücksichtigung der Baumhöhe lagen die Abweichungen je nach Baumart bei 8–31%. Durch die Integration des Verhältnisses von SBD zu H, welches sich durch Umweltbedingungen und mit dem ontogenetischen Stadium verändern kann, erhöht sich auch die Übertragbarkeit auf andere Bestände. Für Rand- und Innenreihen können jedoch die gleichen Funktionen verwendet werden und auch zwischen den Bewirtschaftungssystemen wurden keine Unterschiede festgestellt.

Das artenspezifische Bestandswachstum bestimmt den Biomasseertrag und beeinflusst das Management der Systeme wie Pflanzdichte und Erntetechnik. Die zwei Pappelklone waren gut an die Bedingungen des Untersuchungsgebiets angepasst, enwickelten einen gleichmäßigen Bestand und erzielten bei einer Überlebensrate von 99% das größte Wachstum von 10–11 t ha^{-1} a^{-1}. Die Baumart Robinie erreichte mit 9 t ha^{-1} a^{-1} die dritthöchste Biomasseproduktion unter allen untersuchten Arten. Aufgrund intraspezifischer Konkurrenz zeigte sich eine starke Selbstausdünnung (10% Mortalität) und SBD-Inhomogenität, was zu Beeinträchtigungen bei Ernte und Qualität des Holzes führen kann. Daher sind niedrigere Pflanzdichten zu empfehlen. Erlen zeigten ein moderates Wachstum von 8 t ha^{-1} a^{-1} bei einer Mortalität von 8% und entwickelten wie die Robinie einen ungleichen Bestand. Die Weidenflächen und die einheimische Mischung hatten die niedrigsten Erträge (5 t ha^{-1} a^{-1}), die bis zu 50% niedriger waren als die der Pappel. Die Weidenbestände zeigten nach vier Jahren noch keinen Bestandsschluss und folglich auch keine Mortalität. Auch wenn sich im zweiten Jahr vorerst eine Reduktion der Triebzahlen einstellte, kam es in den Folgejahren zu einem erneuten Austrieb der Stöcke. Für die Weide wird damit die übliche Praxis des frühen Zurückschneidens empfohlen, um das Austreiben mehrerer Triebe und damit einen schnelleren Bestandsschluss zu fördern. Die niedrigen Erträge der einheimischen Gehölzmischung sind auf das geringe bis gar kein Wachtum einzelner Baumarten, mit Ausnahme der Schwarzerle, zurückzuführen. Insgesamt hätten längere Umtriebszeiten zu höheren Wachstumsraten aller Baumarten geführt, da die maximale Zuwachsrate mit großer Wahrscheinlichkeit bei keiner der Baumarten nach vier Jahren erreicht war. Die durch längere Umtriebszeiten stärkeren

Baumdurchmesser könnten jedoch teurere Erntetechniken erfordern, deren Kosten mit den höheren Erträgen abzuwägen sind.

Die vorausgegangene und aktuelle ökologische Bewirtschaftung der Flächen beeinträchtigte das Baumwachstum nicht. Unter Ausschluss der Randreihen erzeugten die ökologisch bewirtschafteten Felder die gleiche Baumbiomasse wie die konventionell bewirtschafteten Felder. Bei Hinzunahme der Randreihen zeigte sich allerdings ein positiver Effekt der Düngergabe im konventionellen System, vor allem für Pappel und Weide. Robinie und Erle scheinen durch ihre Symbiose mit stickstoffbindenden Bakterien weniger vom Dünger beeinflusst worden zu sein. Doch auch im ökologischen System gab es, die Weide ausgenommen, positive Randeffekte. Die Randreihen erzielten größere Baumdurchmessers und höhere Stammzahlen und damit mehr Ertrag als innere Reihen. Wenn davon ausgegangen wird, dass 1/3 des Streifens aus Randreihen besteht, dann erhöht sich der Etrag der SRAFS je nach Baumart um 6 bis 37%. Somit wirken sich Randeffekte, die in Studien zu Baumplantagen meist unberücksichtigt bleiben, erheblich auf die Erträge von SRAFS aus.

Schlussfolgerungen und Ausblick

Der Schwerpunkt der Arbeit war die Messung und Modellierung der Biomassebildung der Bäume in SRAFS mit schnellwachsenden Bäumen zur energetischen Nutzung. Die möglichst genaue Bestimmung der Erträge und der Ertragsdynamik der unterschiedlichen Baumarten und Klone ist von herausragender Bedeutung für die Einschätzung der ökonomischen und ökologischen Leistung (Wirtschaftlichkeit im Vergleich zu KUP und Ackernutzung, C-Bindung, Energieeffizienz, etc.) von SRAFS. Die Faktoren Baumart, Standort, Systemdesign und Bewirtschaftung sowie deren Interaktionen bestimmen die Baumerträge und die Gesamtleistung eines SRAFS. Für die kühl-feuchten Bedingungen des bayerischen Tertiärhügellandes konnten erstmals experimentelle Daten zur Biomassebildung vorgelegt werden. Erstmalig wurde nachgewiesen, dass nach langjährigem ökologischen Landbau gleiche Holzbiomasseerträge in ökologischen SRAFS wie in konventionellen SRAFS erzielt werden können. SRAFS sind daher auch für den ökologischen Landbau geeignet und zu empfehlen. Allerdings hat die Düngergabe auf den konventionellen Ackerkulturen einen ertragssteigernden Effekt auf die Randreihen und damit auf den Gesamtertrag der Gehölzstreifen. Da der erste Umtrieb nicht in allen Fällen für das Wachstumspotenzial von Baumarten repräsentativ ist, sollten nachfolgende Rotationen erforscht werden, bevor allgemeine Empfehlungen zum Ertrag und zur

Bestandsentwicklung gegeben werden. Darüber hinaus können Gen-Umwelt-Interaktionen die Leistung der Baumarten an anderen Standorten beeinflussen.

1 INTRODUCTION

Agroforestry is a land use system, which combines trees and shrubs with agricultural crops and/or livestock on the same land (i.a. European Commission 2013a). Up until the 20th century, trees were widely integrated on agriculural land in Europe. With mechanization, standardization, and intensification of agriculture, farmers gradually removed single trees and structuring woody elements (hedgerows, field boundaries) from their fields. Likewise, traditional agroforestry systems (AFS) disappeared from agrarian landscapes and are still progressively declining. This development was intensified by the shift from small land holdings to larger single farms, the general separation of forestry, agriculture, and nature conservation policy, and because wooded areas were ineligible for subsidy payment for many years in the EU (Dupraz et al. 2005, Eichhorn et al. 2006, Smith et al. 2012, Dhillon and Wuehlisch 2013, Nerlich et al. 2013, den Herder et al. 2017).

While this change in agriculture resulted in higher productivity, it was often accompanied by adverse impacts on the agriculture’s natural resource base, including the loss of biodiversity, water pollution, the decline of soil fertility, and the increase of erosion and soil compaction (Dupraz et al. 2005, Nerlich et al. 2013). Consequently, this ecosystem degradation and the loss of resilient agrarian systems endanger agricultural production, particularly in times of climate change. In addition, the devastating climate impact of using fossil energy resources and their ongoing depletion will further increase land demand for energy crops as replacement, especially on productive agricultural land. This induces competition for land with food and feed production (Smith et al. 2012, Alves et al. 2017). If the world‘s population grow to 10 billion by 2050, demand for food, feed, raw materials, and bioenergy, and thus for productive land, will be pushed up by almost 50% (FAO 2017).

The need for both ressources and environmental protection urges to develop new ecologically, economically, and socially sound and efficient approaches (Alves et al. 2017). Improving land-use efficiency by the sustainable intensification of production is seen to meet this challenge, and agroforestry is regarded as one approach (Smith et al. 2012). It is widely recognized that in AFSs beneficial interactions occur and social, economic as well as environmental needs are balanced (Eichhorn et al. 2006, García de Jalón et al. 2017). These benefits include economic diversification, enhancing energy use efficiency, conserving biodiversity, improving water and soil quality, managing pest and weed, and mitigating greenhouse effects by carbon sequestration (Schoeneberger 2008, Dhillon and

Wuehlisch 2013, Nerlich et al. 2013, Lin et al. 2016a). When the harvested wood substitutes fossil fuels, the carbon dioxide (CO_2) reduction potential of the farming system is further enhanced.

Despite its value and its multifunctional potential, agroforestry remains under-recognized for agriculture in Germany and around the world. The lack of reliable data on agroforestry area, various definitions of agroforestry, and the limited informationbase on management and proper designs explain why agroforestry was disregarded in land use and environmental policy-making (Eichhorn et al. 2006, Zomer et al. 2016, Böhm et al. 2017, den Herder et al. 2017). In the last decades, however, agroforestry researchers started to develop the theoretical principles needed to strengthen the revival of AFS and to incorporate them into sustainable agricultural management. Novel AFS approaches were developed, such as short rotation agroforestry systems (SRAFS). Those systems incorporate fast growing trees with short rotations, typically as rows, on agricultural fields with the aim to produce renewable energy. Planted as single-field system, such short rotation coppice (SRC[1]) are currently in the focus of environmental policies and are more and more implemented and studied, but like AFS and SRAFS still underrepresented on agricultural land (Aust et al. 2014).

Woody energy crops are a good option in low-input and organic farming because of their high nutrient and energy use efficiency (Jørgensen et al. 2005, Lin et al. 2016a, 2017). Astonishingly, organic SRAFS and their distinctive conditions (e.g. nutrient limitations, weed competition) have hardly been studied (Jørgensen et al. 2005, Winterling et al. 2013). So far, no direct comparison between conventional and organic SRAFS has been made.

In the following, an overview of the various designs, objectives and functions of AFS, with a special focus on SRAFS, is given (Section 1.1). A review of ecosystem services and socioeconomic benefits of trees on agricultural land (Section 1.2) as well as of constraints to cultivate them (Section 1.3) follows. Influences and uncertainities on tree and stand development are further identified (Section 1.4).

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[1] Throughout this work, SRC refers to short rotation coppices as single field system, SRC elements to the tree component in short-rotation agroforestry systems (SRAFS).

1.1 DESIGN FOLLOWS FUNCTION: SHORT ROTATION AGROFORESTRY WITH SPECIAL PURPOSES

The aims and motivations to cultivate AFS vary and so do the design of those systems. Some AFS concentrate on biomass production, others focus on regulating mechanism and in some systems focus is on aesthetic landscapes for tourism and recreation (Moreno et al. 2017). Literature classifies AFS in different ways, for example based on structure and components (Moreno et al. 2017) or focus of production (den Herder et al. 2017, García de Jalón et al. 2017, Burgess and Rosati 2018). In this context, the design of the system is adjusted to the use of it, where local, climatic and operational conditions at the respective site further influence the choice of the system and its lifetime. Table 1 gives an overview of existing AFS seperated according to their structure and components, with a brief description of their functions and typical examples. This list is not complete but shows the diversity of AFS in terms of their structure, function, distribution, and even name of practice. In addition, Figure 1 groups the given systems according to their focus of production: arable agroforestry (arable crops + trees), livestock agroforestry (livestock + trees), and agrosilvopasture (crops + livestock + trees).

While forest farming, woodlands or shelterwoods (Table 1) are mostly AFS in forest areas, the other management types are mainly AFS on agricultural land. Hedgerows and buffer strips may not be defined as real AFS, however, scientists often referred to it as AFS when the considered farmland was rich in such structures. This is why they are listed here as well.

The first three practice categories in Table 1 (for example woodlands, homegardens, hedgerows) are rather traditional agroforestry systems and still practiced worldwide, although having decreased dramatically in the 20th century (den Herder et al. 2017, Moreno et al. 2017). They are often attributed high natural and cultural value (Moreno et al. 2017). Recently, den Herder et al. (2017) estimated that agroforestry (with main farming focus and low tree densities included) in the EU 27 is still practiced on at least 15.4 million ha which is equivalent to about 3.6% of the territorial area, and 8.8% of the utilised agricultural area. The area potentially suitable for agroforestry is estimated to be 585-1,215 million hectare globally (Albrecht 2003 in Dhillon and Wuehlisch 2013) and for arable agroforestry at European scale 90 million hectare (Dupraz et al. 2005). The potential for silvopasture might be even higher.

Existing AFS are most frequent in Mediterranean countries and overall dominated by silvopasture (den Herder et al. 2017). Silvopasture include grazed broadleaved woodlands, grasslands with sparse trees, and permanent crops such as olive groves in the Mediterranean. In continental and Atlantic regions, grazed fruit orchards are common as well. Arable agroforestry systems are rarer and usually remnants of once widely distributed systems. Typical practices are mediterrenean broadleaved woodlands with cereal and olive groves sown with cereals, vegetables or fodder crops between the trees (see also Dupraz et al. 2005, Eichhorn et al. 2006). European arable agroforestry generally can be separated in two geographical and climatic zones: Northern Europe and the Mediterranean. In northern Europe light limitations determine the form and structure of the systems, while in the Mediterranean it is water scarcity (Dupraz et al. 2005, Eichhorn et al. 2006).

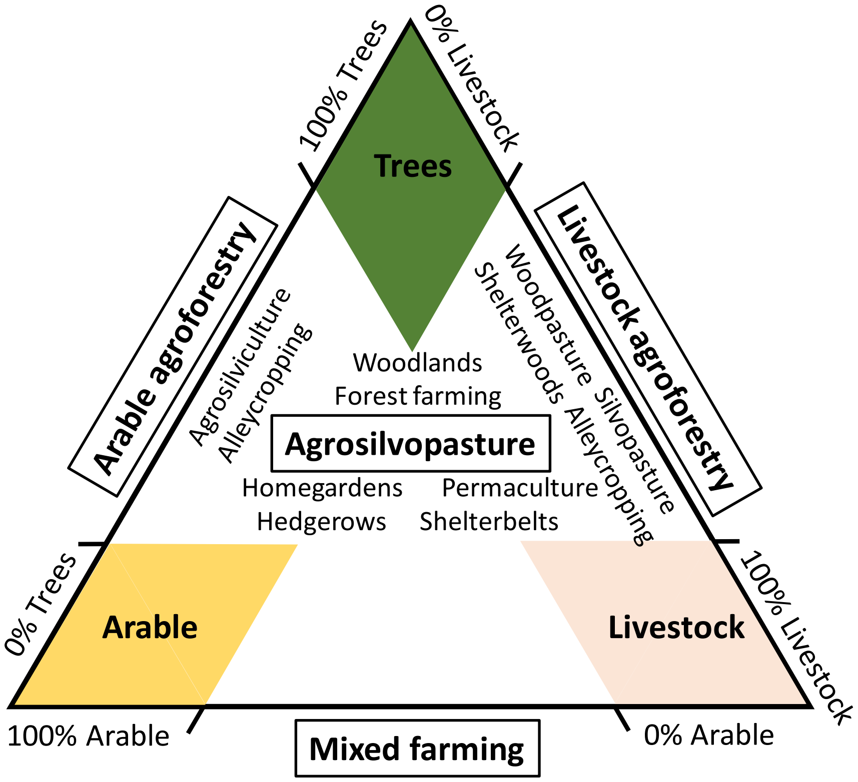

Figure 1: Overview of agroforestry systems grouped by their focus of production: Arable agroforestry, livestock agroforestry, and agrosilvopasture as a combination of both. Mixed farming does not include trees in the management practice. Practices groupd around agrosilvopasture (from woodlands to shelterbelts) can be managed either as arable agoforestry, livestock agoforestry or in combination of both. Figure retrieved and modified from Burgess and Rosati (2018).

Table 1: Overview of agroforestry systems grouped by the structure and composition of the main components. Main functions and examples are given as well.

Practice[1]	**Structure and components**	**Main functions**[2]	**Examples**
Forest farming, woodlands, shelterwoods, silvopasture, woodpasture, agrosilviculture, agrosilvopasture	Natural tree stands (broad-leaved, coniferous or mixed) or arable land and grassland with permanent (scattered) trees or shrubs. Grazing domesticated animals and/or crops in the understory. Mostly two-layered.	• Diversification of production in space and time (Provision of browse and forage, fuelwood, timber and non-timber forest products) • Moderation of microclimate: Reduce animal stress, protect sun- or wind-sensitive crops, enhance moisture • Enhance species and habitat biodiversity • Ecosystem stability, e.g. pest control, decomposition, and pollination provided by hospitality of many organisms • Grazing as control of wildfire • Sequester carbon	• Oak woodlands (e.g. Dehesa/ Spain, Montado/ Portugal) (*Eichhorn et al. 2006, Smith et al. 2012, den Herder et al. 2017, García de Jalón et al. 2017, Moreno et al. 2017*) • High value tree systems: fruit orchards (e.g. Streuobst/ Germany, pré-verger/ France, pomaradas/ Spain), vineyards, olive groves, nut trees, etc. (*Eichhorn et al. 2006, Smith et al. 2012, den Herder et al. 2017, García de Jalón et al. 2017, Nair et al. 2017*) • Reindeer husbandry/ Sweden (*Moreno et al. 2017*) • Wood–pasture remnants/ UK (*Moreno et al. 2017*) • Fodder-trees for cattle and goats/ the Netherlands (*Smith et al. 2012, García de Jalón et al. 2017*) • Shade-grown coffee and cocoa plantations/ Ghana (*Nair et al. 2017*)
Homegardens, multispecies agroforestry, multistrata agroforestry	Multi-storey agroforestry systems that have many diverse species coexisting in ecological niches from the high canopy to bottom story shade-tolerant crops. Non-competitive sharing of growth resources such as light, water, and nutrients.	• Diversification of production in space and time • Enhance species and habitat biodiversity • Ecosystem stability, e.g. pest control, decomposition, and pollination provided by hospitality of many organisms • Sequester carbon • Protect soil and water quality • Control of soil erosion • Nutrient cycling	• Indigenous homegardens in the tropics for food security and welfare (*Jose 2009, Nair et al. 2017, Tiwari et al. 2017)* • Permaculture (*Ferguson and Lovell 2014*)

[1] The here given terms are often used as synonyms.

[2] According to Rockwood et al. 2004, Eichhorn et al. 2006, Schoenberger 2008, Jose 2009, Smith et al. 2012, Dhillon and Wuehlisch 2013, Ferguson and Lovell 2014, den Herder et al. 2017, García de Jalón et al. 2017, Moreno et al. 2017, Nair et al. 2017, Tiwari et al. 2017.

Table 1 (continued)**.**

Practice[1]	**Structure and components**	**Main functions**[2]	**Examples**
Hedgerows, windbreaks, shelterbelts, Riparian buffers	Linear plantings of trees and shrubs to form barriers and protection structures. Often in combination with other vegetative types. The tree component is not the focus of production	• Protect soil and water quality • Reduce non-point pollution from adjacent land uses • Control of nutrient leaching • Stabilize streambanks • Enhance aquatic and terrestrial species and habitat biodiversity • Ecosystem stability • Barrier to wind (control wind erosion, protect wind-sensitive crops, enhance moisture, reduce animal stress), dust, odor, water (control water erosion), snow and pesticide drift • Diversification of production in space and time • Treatment of municipal and agricultural waste, and of stormwater • Sequester carbon	• Spreewald floodplain/ north-eastern Germany (*García de Jalón et al. 2017, Moreno et al. 2017)* • Bocage systems/ France (*Smith et al. 2012, García de Jalón et al. 2017, Moreno et al. 2017*) • Phytoremediation AFS (*Rockwood et al. 2004*)
Alleycropping	Rows of trees or shrubs planted at wide spacings, intercropped or grazed. Arranged with fast growing trees at high densities and short rotation cycles or with high value trees (fruit or timber trees) at longer rotations and low densities.	• Diversification of production in space and time • Reduce non-point pollution from adjacent land usese • Control of nutrient leaching • Control of soil erosion • Protect soil quality • Enhance species and habitat biodiversity • Barrier to wind, dust, odor, water, snow and pesticide drift • Sequester carbon	• Short-rotation agroforestry for bioenergy (*Lamerre et al. 2015, Huber et al. 2016*) • Intercropping of poplar timber trees for the first 2–3 years of a 7–10 cultivation cycle (e.g. France and North Italy) (*Eichhorn et al. 2006, Smith et al. 2012, den Herder et al. 2017*) • Intercropping of fruit or nut trees (e.g. piantata (vineyards)/ Italy) (*Eichhorn et al. 2006*)

[1] *The here given terms are often used as synonyms.*

[2] *According to Rockwood et al. 2004, Eichhorn et al. 2006, Schoenberger 2008, Jose 2009, Smith et al. 2012, Dhillon and Wuehlisch 2013, Ferguson and Lovell 2014, den Herder et al. 2017, García de Jalón et al. 2017, Moreno et al. 2017, Nair et al. 2017, Tiwari et al. 2017.*

The increased interest in agroforestry over the last decades also led to novel silvoarable and silvopastoral designs, which are adapted to modern farming practices, such as alley cropping (den Herder et al. 2017). Alley cropping is defined as strips of woody crops alternating with agricultural or horticultural fields (Table 1). Centuries ago, this ancient technique was already used in certain tropical and temperate regions (Nair et al. 2017). Nowadays, it is designed as short rotation or high value tree agroforestry with spacings of multiple machine widths (Tsonkova et al. 2018). High value tree agroforestry uses tree species to grow fruit or timber on agricultural fields, harvested after several years (den Herder et al. 2017). However, short rotation agroforestry systems (SRAFS) became the major focus of interest. In SRAFS, tree strips are planted with fast-growing tree species capable of stump sprouting such as poplars (*Populus spp*.), willows (*Salix spp*.), black locusts (*Robinia pseudoacacia*) and alders (*Alnus spp*.). As a source for bioenergy, the trees are usually harvested in short 1 to 5-year rotations; their average lifetime is about twenty years. SRAFS are very promising because they show positive ecological effects (e.g. Jose 2009) while achieving an economically competitive production, because SRC (elements) allow to fully mechanize the harvesting and have a high ressource use efficiency (Jørgensen et al. 2005, Lin et al. 2016a, 2016b, Lin and Hülsbergen 2017). Although more and more research on SRAFS is being conducted today (e.g. Grünewald et al 2007, Böhm et al. 2011, Lamerre et al. 2015), there has been little adoption into farming practice yet.

1.2 ECOSYSTEM SERVICES AND SOCIOECONOMIC BENEFITS OF TREES ON AGRICULTURAL LAND

AFS are multifunctional land-use systems which provide both ecological and socioeconomic benefits, which include the protection of climate, water, soil, biodiversity, and crops/lifestock (cp. Table 1) (Dupraz et al. 2005, Jose 2009, Smith et al. 2012, Mbow et al. 2014, Torralba et al. 2016, den Herder et al. 2017). The meta-analysis of Torralba et al. (2016) showed that globally AFS provide more ecosystem services than simple structured crop- or tree-based systems, however, results are dependent from the context and the land-use system selected for the comparison. They explained that diversified systems with great functional and structural diversity have „a tighter coupling of nutrient cycles, soil retention, and increased biodiversity“. Dupraz et al. (2005) identified 80% of the European arable land as potential risk areas for nitrate leaching, soil erosion, and/or landscape diversity. On 56 % (90.6 million hectar) of the European arable land, AFS might solve those major land-use problems whilst offering economically viable wood yield (Dupraz et al. 2005).

Ecosystem services and socioeconomic advantages of AFS are interlinked because ecosystem services are per se also socioeconomic benefits. They help to reach environmental targets, offer public goods, and enhance stability, productivity, and resilience of agrarian systems. From a farmer's perspective, however, the medium to short-term financial profitability may be more important. The product diversification of AFS, that yield foods and tree products and spread labour requirements, can be such a direct economic advantage for farmers (Dupraz et al. 2005, Mbow et al. 2014). In some cases, AFS increase the overall output of goods per unit area through protecting crops and natural ressources as well as through adding new products (Mbow et al. 2014, Dupraz et al. 2005, den Herder et al. 2017). In the following, key functions of AFS are outlined.

1.2.1 Carbon dioxid reduction

Agricultural production (including related forest clearing) is one of the main emitters of greenhouse gases (GHG), accounting for 24% globally (Pachauri et al. 2014). By storing atmospheric carbon dioxid (CO_2) in various aboveground compartments (plant parts of the trees and herbaceous plants), subterranean compartments, and soil pools (roots, soil organisms, humus in different soil horizons), the potential of wood on agricultural land to mitigate climate change is tremendous (Nair et al. 2009, Butler Manning 2015). When the wood is used for energy production, carbon (C) is stored in it only temporarily and released back into the atmosphere (combustion). Still, fossil energy sources are substituted and, hence, the CO_2 increase can be slowed or even reversed.

Carbon sequestration

Carbon sequestration is defined as the removal and storage of C from the atmosphere into a reservoir (such as oceans, vegetation, or soils) (Jose 2009, Stefano and Jacobson 2017). AFS are perceived to sequester more C in the above- and belowground vegetation and in the soil (organic and inorganic C, soil microorganisms) than comparable crop monocultures or open grasslands (Nair et al. 2017, Moreno et al. 2017, Stefano and Jacobson 2017).

Nair et al. (2009) reported C sequestration in above- and belowground biomass in different AFS around the world, which ranged from 0.3 Mg C ha^{-1} yr^{-1} to 15.2 Mg C ha^{-1} yr^{-1}. They concluded that AFS on arid, semiarid, and degraded sites store less C than those on fertile humid sites and temperate AFS store less than tropical systems. C sequestration of soil reported in literature ranges from 1.3 Mg C ha^{-1} to 300 Mg C ha^{-1} (Nair et al. 2009 , Lorenz and Lal 2014).

Soil C sequestration occurs via direct fixation of CO_2 into soil inorganic carbon (SIC) compounds (30% of total soil C) and via indirect fixation by decomposing plant biomass into soil organic carbon (SOC) (70% of totoal soil C) (Batjes 1996 in Nair et al. 2009). Agricultural and degraded soils have a promising C sequestration potential due to the loss of their original SOC pool (Stefano and Jacobson 2017). The meta-analysis from Stefano and Jacobson (2017) revealed significant increases in SOC of 26–40% at various soil horizons and depths (up to 1 m) in the land-use change from agriculture to agroforestry and, although less pronounced, from pasture or grassland to agroforestry. The SOC increase in AFSs stem from the high inputs of above- and belowground organic matter from tree leaves, roots, and rhizodepositions. Furthermore, integrating trees in croplands and pasture can reduce erosion and alter soil processes leading to even higher sequestration rates and stabilized SOC (e.g. translocation of biomass into subsoil by deep tree roots, aggregation, reduced mineralization due to cessation of tillage). Factors influencing these C dynamics are the previous land use, tree species (quality and quantity of litter), soil properties (e.g. clay content, mineral composition), environmental conditions (e.g. climate, water availability), and system management (e.g. fertilization, irrigation, tillage) (Jose 2009, Nair et al. 2009, 2017, Lorenz and Lal 2014, Stefano and Jacobson 2017). Apart from the advantage of higher amount of SOC in AFS, C in deep tree roots can persist for long periods of time and SOC, especially in subsoil horizons, may be even stored for millennia (Lorenz and Lal 2014). Therewith, AFS are a viable and favourble solution for long-term carbon sequestration.

On a global scale, 80% of the C is stored in soil (~2,300 Pg) and only 20% (~610 Pg) in vegetation (Batjes 1996 in Nair et al. 2009). In tree-based land-use systems, however, the vegetation already accounts for 40% of the total C pool (reviewed in Stefano and Jacobson 2017). Zomer et al. (2016) stressed that the importance of above- and belowground vegetation compartment in forests is widely recognized as important C sink. The role of trees in the total C pool of agrarian systems, however, is largely ignored compared to the attention paid to the SOC. To underpin the immense potential, Zomer et al. (2016) combined the IPCC Tier 1 value for the world C storage in above- and belowground biomass on agricultural land (11 Pg C or 5 Mg C ha^{-1}) with their assumption that 2010 over

40% of this area had at least 10% tree cover. They revised the C pool to 45 Pg C, where trees contribute more than 75% (34 Pg C) to this global total (Zomer et al. 2016). This underlines the huge underestimation when neglecting tree components in farming systems.

Recalling the large amount of land suitable for AFS (cp. section 1.1) C sequestration in woody biomass and soil via growing trees on agricultural land is an important strategy to mitigate climate change.

Wood as renewable energy source

The popularity of SRC as source of woody energy, planted as plantations or as elements in SRAFS, have increased in recent years. This was also driven by the European Union's (EU) climate and renewable energy policy targets (cf. UNFCCC and Kyoto protocol). The EU has set a 20% target for renewable sources by 2020 from the overall share of energy (European Commission (EC) 2009). Thereby, the EC requests their member states to achieve between 10% and 72% of their gross final energy consumption from renewable energy; in the case of Germany, the share of non-fossil fuels requires an increase to 18% (EC 2018). In doing so, the EC (2009) states biomass and especially woody biomass as a cornerstone among renewable energy sources. However, technical constraints and ecological restrictions (for example the sustainability principles of forest management) limit the woody biomass potential from forests. The Deutsches Biomasseforschungszentrum (DBFZ) forecasts a wood supply shortfall of approximately 30 million solid m³ in Germany by 2020, which is equivalent to 2.2% of Germany′s primary energy use (PEC) in 2009 (Thrän et al. 2009 in Aust et al. 2014).

SRC systems are an additional source of wood and are furthermore considered to be more sustainable than other bioenergy crops such as rapeseed, maize, and also miscanthus. SRC need less external supply of nutrients and plant protection, avoiding more emissions than annual crops, and are not used for food or fodder production (Schweier and Becker 2013, Butler Manning 2015). Moreover, wood chips have a higher energy density (higher energy yields per unit area) and better fuel properties than for example miscanthus and straw. They create lower CO_2 emissions for electricity generation than straw, although more CO_2 is emitted in comparison to forest residues (Hauk et al. 2014). However, the previous promotion of renewable raw materials in Germany (through the Renewable Energy Law, EEG) has led to a strong expansion of almost exclusively maize for biogas production and rapeseed for biodiesel production to a total of 2.4 million ha. Only 6,600 ha of SRC for solid fuel have been cultivated so far (Fachagentur Nachwachsende Rohstoffe (FNR) 2018). The EEG only funds SRAFS when they are considered as single-field SRC. However, to remain eligible within the Basic Payment Scheme under the CAP Guidelines 2014–2020, SRC elements within SRAFS need to cover a minimum area of 0.3 ha (EC 2013b), an area too large for most SRAFS in Germany.

Using SRC to compensate for the predicted biomass shortfall in Germany, a production area of 1–1.5 million ha with biomass yields between 10 and 15 t ha^{-1} yr^{-1} would be needed (Aust et al. 2014). The study of Nitsch et al. (2012), commissioned by the German Federal Government, developed strategies for the sustainable expansion of renewable energy and conclude that approximately 0.9 million ha of cropland could be used for SRC in the future. Aust et al. (2014) took ecological (water availability, temperature), ethical (no food competition by using only low yielding agricultural areas), political (protected areas, EC regulation 1782/2003 for the conversion of grassland), and technical restrictions (slope) into account. A bit less optimistics than Nitsch et al. (2012), they came to the result that at least 680,000 ha (5.7%) of marginal cropland and 80,000 ha (0.9%) of grassland might be suitable for SRC in Germany. Assuming 14 t ha^{-1} yr^{-1} increment, 11 million t yr^{-1} could be provided, covering 70% of the wood supply shortfall for Germany in 2020 or 1.5% of Germany′s PEC based on 2009 (Aust et al. 2014). SRC potentials on permanent grassland are extraordinarily high in southern Germany due to the high precipitation rates and in north-western Germany due the access to groundwater (Aust et al. 2014). This makes those sites also very suitable considering the aridification caused by climate change (Aust et al. 2014). Considering that the suitable area for grazed or intercropped AFS (cp. section 1.1) could be partly planted with SRAFS, the vast potential to mitigate CO_2 emissions becomes apparent.

1.2.2 Protection and efficient use of ressources

High soil fertility and stability, sustained water supply, and biological diversity are preconditions to keep stable and resilient farming systems, particularly with an eye toward the weather extremes by climate change (e.g. droughts and heavy rainfalls). AFS help to protect and conserve these natural ressources and, thus, balance the ecological system. In doing so, AFS can reduce the need to apply external inputs such as agrochemicals, fertilizers, and irrigation (Jose 2009, Quinkenstein et al. 2009, Carsan et al. 2014, Mbow et al. 2014, Torralba et al. 2016). By suppressing weeds, trees can reduce the need for weed control (Waldron et al. 2012). Furthermore, Dupraz et al. (2005) demonstrated that competition between trees and crops induce adaptation and allows to capture more resources from the environment than pure crop or pure tree systems. They found that silvoarable systems in Europe with high value trees at low tree densities are more productive than growing trees and crops separately (increases to 30% in biomass, and 60% in final products). Such facilitative interactions of trees and crops as well as livestock can increase the economic value of AFS (den Herder et al. 2017). A swiss study indicated as well that combining trees and crops increases the overall farm productivity, although intercrop productivity diminished due to light comptetition with high tree densites or when trees were not pruned (when using fruit trees instead of timber trees) (Sereke et al. 2015). Thus, AFS can also have no effetc or inhibit arable or pasture biomass production due to allelopathy and resource competition for nutrients, light or water (Dupraz 2005, Eichhorn et al. 2006, García de Jalón et al. 2017, Moreno et al. 2017). In South Germany, shadowing by trees led to losses in yields at the adjacent crop rows (Wagener et al. 2013). Still, land use efficieny can be higher through tree biomass compensating for arable crop losses. Regarding SRAFS, the high nitrogen and energy use efficiency of tree components (Jørgensen et al. 2005, Lin et al. 2016a, 2016b) can enhance the overall efficiency values of SRAFS compared to pure arable farming. Resource-use efficiency analyses in South Germany (Lin et al. 2016a, 2016b, Lin and Hülsbergen 2017) showed this for both conventional and organic SRAFS. Other studies with a life cycle assessment approach indicated that for SRC harvesting and transportation are the most critical processes from an environmental viewpoint (Schweier et al. 2016) and that the environmental balances are, despite SOC accumulation, impacted by variances in biomass yields (Hansen et al. 2013). Thus, the environmental balance of SRC (elements) are dependent from tree yield but also from techniques and levels of inputs used.

In the following, some key ecosystem services of AFS are described more detailed.

Conserving and enhancing biodiversity

AFS have beneficial effects on aboveground and belowground biodiversity (species richness and abundance) and are better for habitat for native wildlife compared to conventional agricultural lands or monocultures (Jose 2009, Dupraz et al. 2005, Moreno et al. 2017, Nair et al. 2017). Especially when they are rich in structures, AFS provide food, shelter, habitat, and other resources for multiple species and organisms. Therewith, they can host numbers of insects, avian, mammalian, and plant species including beneficial animals like pollinators, decomposers, herbivores, and predators as well as species of known conservation concern (Carsan et al. 2014, Torralba et al. 2016, Nair et al. 2017). In cleared agricultural landscapes, they serve as refuges for biodiversity and ensure landscape connectivity also with other landscape elements like forests and watersheds (Nair et al. 2017). Soil and litter faunal diversity is crucial to keep soil fertility (cp. section below). In conclusion, high biodiversity in AFS improves the efficiency and functionality of ecosystem services leading to more stability and resilience for the system itself.

Increasing soil fertility and stability

The increased soil fertility and stability in AFS is mostly based on trees adding above- and belowground organic matter (litter, roots) as well as mobilizing and taking up nutrients (Jose 2009, Moreno et al. 2017) (cp. also Section 1.2.1). Diverse microhabitats and heterogeneous litter lead to greater microorganism as well as soil and litter faunal diversity, which increases structural stability and fertility of the soil (Jose 2009). Nitrogen fixing leguminous trees or organic fertilizers can further improve the nutrient status of the system (Jose 2009, Smith et al. 2012, Mbow et al. 2014). Furthermore, the longer growing season of trees enable nutrient capture before and after the cropping seasons, which increases the nutrient-use efficiency in AFS (Jose 2009). However, in SRAFS relatively small trees with large fractions of bark are harvested. This may lead to certain nutrient exports, which are expected to be still lower than those from conventional agriculture (Quinkenstein et al. 2009).

Trees protect the soil from erosion by limiting surface-runoff by acting as barriers to wind or flood. In addition, tree roots enhance water infiltration as well as uptake and stabilize the soil itself. Furthermore, higher levels of soil organic matter (SOM) increase the water storage capacity of the soil and therefore further control water erosion (Dupraz et al. 2005, Torralba et al. 2016, Moreno et al. 2017).

Increasing water availability

Water stored in the SOM under AFS increases water availability for all crops. Furthermore, trees enhance the moisture of the land by intercepting rain or snow and harvesting fog and dew (Quinkenstein et al. 2009). Equally, the deeper rooting systems intercept drainage water and, via hydraulic lift, draw water as well as nutrients from deeper soil layers below the rooting zone of field crops. Released into the upper horizons, water and nutrients are made available to shallower rooted crops (Eichhorn et al. 2006, Jose 2009). In addition, microclimatic modification by tree cover conserve soil moisture. Trees buffer air and soil temperature and atmospheric saturation deficit through shading. Furthermore, trees slow wind velocity widely into the adjacent crop fields and reduce their evaporative water loss (Quinkenstein et al. 2009, Carsan et al. 2014, Mbow et al. 2014). Thus, agroforestry moderates the effects of high temperatures and drought stress on agricultural crops (Torralba et al. 2016). The consequently higher water availability and soil moisture can lead to higher yields (Eichhorn et al. 2006, Nerlich et al. 2013), but may also lead to higher pathogen or slug (personal observation) infestation. In alley cropping systems competition for soil water at the neighbouring crops was also observed, outweghting microclimatic benefits (Quinkenstein et al. 2009).

Reducing soil, water, and air pollution

Trees protect for loss of substances (e.g. nitrate, phosphorous, and plant protection agents) into ground and watercourses by filtering, trapping and bioprocessing surface runoff as well as taking up the excess nutrients or pesticides (Dupraz et al. 2005, Jose 2009, Moreno et al. 2017, Burgess and Rosati 2018). In the study of García de Jalón et al. (2018), the modelled mean annual nitrogen (N) loss in a 14-year-old alley-cropping system with poplar was reduced by 80% compared to the arable control. This was because tree rows (including grass within) took up N whilst they were not fertilized. Tree barriers also reduce noise pollution or mitigate livestock odor (Jose 2009, Moreno et al. 2017).

Sheltering livestock

Tree cover on livestock range increases animal health and welfare by providing protection from hot sun, precipitation, cold temperatures, and birds of prey. Therewith, the energy needed for regulating body temperatures is lowered, increasing feed conversion and weight gain (Broom et al. 2013, García de Jalón et al. 2017). However, farmers need to consider that livestock can damage tree regeneration and cause soil degradation and erosion by overgrazing, browsing, and trampling (Moreno et al. 2017).

1.2.3 Diversification of goods

In addition to the regulating and conserving functions, AFS enable farmers or municipalities to co-produce different goods and services, including timber, fuel wood, medicinal plants, fooder and fruits (Mbow et al. 2014, García de Jalón et al. 2017). Those products diversify and offer additional income to farmers and contribute to the selfsufficiency and the economic equilibrium of the households. The diversification of production in space and time can decrease small-scale farmers‘ vulnerability and increase their resilience to changing market or environmental conditions (Dhillon and Wuehlisch 2013, Carsan et al. 2014, Mbow et al. 2014). The diversification in time constantly offer farm products and spread labor requirements (Carsan et al. 2014). Managing AFS even creates new jobs, as multiple products require additional expertise for harvesting, processing, and selling. However, this may be more advantageous in tropical AFS, whereas farmers in Germany struggle with high bureaucratic and technical burden when establishing and managing AFS (Tsonkova et al. 2018). Often, AFS are mentionad as a solution when marginal land is too poor, or site conditions are too unfavorable for intensive agricultural crop production (e.g. hillside, waterlogging) (Tsonkova et al. 2018). Still, product diversification was the main advantage pointed out in a survey of farmer’s interest in european AFS (Dupraz et al. 2005). For example, producing high quality timber in AFS reduces the need for importing tropical timber (Dupraz et al. 2005). Likewise, SRAFS growing energy wood safeguard energy independence while promoting food security or offers access to new markets. AFS with high natural and cultural value (HNCV) can offer direct income by agritourism and recreation activities such as hunting and fishing, education and leisure (Moreno et al. 2017).

1.3 CONSTRAINTS TO CULTIVATE TREES ON AGRICULTURAL LAND

The area potentially suitable for agroforestry (see Section 1.1) and the expected ecosystem services (see section 1.2) are remarkable. However, various constraints still hinder the (re-)integration of trees on farms on a larger scale. The hesitation stems from the lack of expertise, uncertain economic efficiency, unknown ecological impacts, and political boundaries.

Biological constraints risking the profiterability of agrarian tree systems include negative reactions to climate and weather condition or plant diseases and pests. Also, the introduction of trees into arable fields may reduce crop yields through competing for light, water, and nutrients or enhance pests and desease infestion though higher moisture values (Dupraz 2005, Eichhorn et al. 2006, García de Jalón et al. 2017, Moreno et al. 2017).

Insecurity resulting from economic and technical restrictions are: high investment costs without an annual income, biomass yield that is difficult to predict, little knowledge of timber markets and tree cultivation, as well as high tree management, harvesting, and recultivation costs due to the absence of suitable machines (García de Jalón et al. 2017, Tsonkova et al. 2018). Because mechanization is still underdeveloped for AFS, the design has to be suitable for large farming machines advantaging timber (more space below tree canopies) (Sereke et al. 2015) and alley cropping (large space between tree rows) systems (Tsonkova et al. 2018).

Further uncertainties are caused by political frameworks, including environmental protection regulations (e.g. protection of grassland; Aust et al. 2014), the possible introduction of certification systems (Schweier and Becker 2013) and complexities of subsidy payments by the EU’s Common Agricultural Policy (CAP). The first pillar of the CAP (Regulation 1307/2013) defines agroforesty as agricultural land and as an ecological focus area in the Greening component, however only to a given tree density (100 trees/ha) or a specified level of cover. The second pillar (Article 23 of Regulation 1305/2013) supports the establishment of AFS and covers the maintenance costs for 5 years (Böhm et al. 2017). Although this was a political attempt to promote the implementation of AFS, high administrative burden has disadvantaged AFS relative to annual crops and even contributed to a futher decline of silvoarable AFS across the EU (Eichhorn et al. 2006, García de Jalón et al. 2017). In Germany, agroforestry is still not activated at all in the Rural Development Programme (RDP, pillar II) and therewith not eligible, neither under pillar I nor pillar II (Böhm et al. 2017). Accordingly, in Germany the first establishment of AFS is not financially supported, nor is AFS regarded as a holistic system (Tsonkova et al. 2018). Consequently, alley cropping systems such as SRAFS must be evaluated separately by each tree row and crop, while fulfilling the minimum parcel area of 0.3 ha (Tsonkova et al. 2018). Therewith, establishing AFS on small farmlands is widely hindered (Tsonkova et al. 2018).

SRC is hardly promoted as well, as the focus of the EU bioenergy policy is on liquid fuels (Butler Manning 2015). Although the EU points out the need to exploit the potential of biomass and the CAP recognises SRC as agriculture (permanent crops) eligible for subsidy payments under certain conditions (list of tree species, area minimum 0.3 ha, harvest cycles maximum 20 years; Regulation 1307/2013) (EC 2013b), no or only vague references are given to SRC in several other EU regulations (e.g. The Renewable Energies Directive, Biomass Action Plan). Furthermore, as for agroforestry, administrative burdens hinder the SRC implementation (Butler Manning 2015).

Environmental benefits of AFS and SRC are still not priced and agroforestry farmers in Germany are not or hardly financially compensated for extra costs involved. With an unsure profitability of AFS and high land rental prices, intensive land use systems are still preferred. Although efforts are being made to quantify environmental externalities like the emissions of greenhouse gases (Schoeneberger 2008, García de Jalón et al. 2018), tools first have to be accepted in political frameworks. As long as there is no market for ecosystem services like carbon credits or market premiums or conversely an environmental tax on polluting agriculture, benefits of a healthy agricultural system might only be valued indirectly by enhanced soil fertility or resilience of the agrarian system. Although awareness of the environmental and animal welfare benefits will nonetheless help to promote agroforestry, the uncertain economic efficiency is still a key barrier to establish trees on agricultural land (Schweier and Becker 2013). Hence, sufficient yields, in particular of trees, are mostly a precondition to establish AFS (Dupraz et al. 2005). Also, for SRC, biomass yield and the price of biomass is decisive for the profitability of the system (Hauk et al. 2014). That means that knowledge on the performance of different AFS, SRC, and SRAFS and the dependence of tree growth on biological conditions and farm management becomes critical (Kauter et al. 2003, Schweier and Becker 2013).

With the system becoming more complex, farmers need to consider temporal, spatial, and physical factors. These decisions include the selection of tree combinations and associated arable crops, the orientation of tree rows, the width of the rows, the timing of field operations, and the potential to damage the tree or crop when implementing field operations (García de Jalón et al. 2017). Therewith, the value added by SRC, AFS, and SRAFS highly depends on the specific environmental conditions, the design of the systems and their management (Nair et al. 2017). Still research is required to give recommendations at specific locations.

1.4 INFLUENCES AND UNCERTAINITIES ON TREE AND STAND DEVELOPMENT

Tree and stand development are key elements regarding the economic and environmental value of AFS. Total tree biomass determines the energetic value or carbon stored in the AFS, and thus, forms the basis for economic and several efficiency analyses (energy, land use, carbon etc.). Knowledge of growth dynamics and estimation of biomass gain during the rotation help to forecast the success of the systems and to understand year-to-year development. This is important for planning optimal harvest cycles and technologies

(Böhm et al. 2011) and for assessing the effects of different treatments (e.g. organic versus conventional farming) or environmental influences (Arevalo et al. 2007). Consequently, accurate yield estimates are needed, which are not destructive and less time consuming than harvesting. Knowledge on stand structure and tree size distribution is further needed for decisions on planting design, harvesting methods, and usability of the wood. Factors determining yield and structural characteristics are notably tree species and management interacting with local conditions (Dupraz et al. 2005). The following further outline the four research foci of this work - tree species' (Section 1.4.1), alley cropping (Section 1.4.2), and farming systems' effects (Section 1.4.3) on tree biomass yield and growth performance as well as biomass estimation methods in AFS and SRC (Section 1.4.4).

1.4.1 Tree species

The choice of tree species is one of the major factors influencing the biomass productivity and the structural characteristics of agroforestry tree subsystems. Species-specific growth patterns, ecophysiological mechanisms and interactions influence the performance of individual species under different environments. Hence, the specific site conditions (e.g. climate, soil properties, relief, diseases, insects) and various management treatments (e.g. fertilization, irrigation, planting density, weed control, planting configuration, intercrop rotation choice, tree root pruning) determine wether the chosen species grow successfully (Dupraz et al. 2005). Knowing these mechanisms helps to forecast the total yield at the end of the rotation as well as the growth dynamics during and between rotations. Thus, farmers can identify highest growth rates and optimal harvest cycles (Arevalo et al. 2007, Böhm et al. 2011).

Furthermore, tree species develop different stand structures and distributions of tree dimensions (e.g. of diameter, height, branching pattern, emergence of shoots), thereby species react differently to management and environmental influences. These species-typical expressions as well as the speed of development define the suitability of the specific species for different harvest technologies, wood usages, or sustainability requirements. For instance, tree species developing great stem base diamters (SBD) require adapted rotation lengths so that direct chip harvesting methods are not hampered (Kauter et al. 2003, Hauk et al. 2014). In contrast, tree species growing many low-diameter shoots have a larger share of nutrient-rich bark, which increases the ash contents, therewith lowers fuel quality (Kauter et al. 2003, Jacob et al. 2013) and increases nutrient removal (Morhart et al. 2013).

Also, species developing an unequal stand may have a high tree mortality, affecting total biomass production during later rotations (Tomé and Verwijst 1996).

For SRC or SRAFS, poplar and willow hybrids are the most promising species, because of their rapid juvenile growth, high coppicing ability, adaptation to diverse conditions, and easy vegetative propagation (Bradshaw et al. 2000, Bullard et al. 2002, Kuzovkina and Quigley 2005, Dickmann 2006). Also, black locust and alder recently attracted attention as alternative biomass crop species mainly for less fertile sites, since they benefit from their ability to fix atmospheric nitrogen (Bongarten et al. 1992, Gruenewald et al. 2007, Claessens et al. 2010, Böhm et al. 2011, Carl et al. 2017). Black locust has a high wood density, which reduces transportation costs and facilitates conversion into gaseous fuels (Gruenewald et al. 2007). Black alder can adapt to a wide range of climatic conditions and site qualities (Johansson 1999, Vares et al. 2004). Although in general monoculture plantings are deployed, plantations consisting of multiple species can be an attractive option as well. A species mix improves biodiversity and the habitat for native wildlife, minimizes the risk of disease problems or invading species, and is more resilient to climate change (Dhillon and Wuehlisch 2013).

An enormous number of hybrids have been produced so far and the aforementioned species have been grown in SRC and SRAFS under a wide variety of climatic, site, and management conditions. Therewith, various growth dynamics and yields exist in literature. For poplar, yields in the range of 2–25 t ha^{-1} yr^{-1} were reported (Heilman and Fu-Guang 1993, Al Afas et al. 2008, Fortier et al. 2010, Dillen et al. 2013). High yield ranges of 2–24 t ha^{-1} yr^{-1} exist for different willow clones (Labrecque and Teodorescu 2003, 2005, Stolarski et al. 2011, Sevel et al. 2012, Toillon et al. 2013, Guidi Nissim et al. 2013). Reported yields of black locust lay between 1 and 14 t ha^{-1} yr^{-1} (Gruenewald et al. 2007, Rédei and Veperdi 2009, Böhmet al. 2011, Carl et al. 2017), yields of black alder between 1 and 8 t ha^{-1} yr^{-1} (Johansson 2000). To the author’s best knowledge, no yield results of a species mix exist so far.

Some studies were carried out in Germany. Aust et al. (2014) estimated an average SRC biomass productivity for poplar and willow on the cropland in Germany of 7 t ha^{-1} yr^{-1}, with a range of 3–16 t ha^{-1} yr^{-1}. Hofmann-Schielle et al. (1999) estimated 2–12 t ha^{-1} yr^{-1} for poplar and willow, depending on clone, rotation, and site. Lamerre et al. (2015) estimated 8 t ha^{-1} yr^{-1} for poplar, when edge effects of the alley cropping were included even up to 16 t ha^{-1} yr^{-1}. On reclaimed mine sites, willow (*S. viminalis*), poplar, and black locust produced only 1, 2, and 6 t ha^{-1} yr^{-1}, respectively (Gruenewald et al. 2007). However, black locust achieved 12 t ha^{-1} yr^{-1} on another post-mining area (Böhm et al. 2011) and up to 14 t ha^{-1} yr^{-1} on former agricultural sites (Carl et al. 2017). Only few yield studies were conducted in southern Germany. Here, poplar yielded between 6 and 13 t ha^{-1} yr^{-1} on fertile land (Burger 2010, Morhart et al. 2013) and 6 t ha^{-1} yr^{-1} on marginal land (Schweier and Becker 2013). More research is needed on the species suitability and growth conditions in Germany, particularly in southern Germany, where humid climate and Cambisols offer a high yield potential.

1.4.2 Edge effect of alley cropping designs

In agroforestry and especially in SRAFS with an alley cropping design, edge effects highly influence trees at border rows. As most studies on SRC were performed in plantations, the edge effect on tree growth and yield is not well defined yet. Although barely mentioned, this effect strongly influences yield and tree allometry. Zavitkovski (1981) explained an increased diameter, individual tree dry weight, foliage weight, and leaf area index of border rows by border trees being more exposed to sunlight than inner trees. Lamerre et al. (2015) also found increased yields of border rows in AFS caused by a higher diameter of border trees or a higher number of shoots. They explained the differences to inner rows with an increased plant spacing and light availability and possible higher nutrient availability due to the proximity of the fertilized crop fields. Verwijst and Telenius‘ study (1999), which found a higher biomass at a given diameter for inner stems compared to border stems, suggest that edge effects might affect tree allometry as well.

1.4.3 Farming system: organic vs. conventional

A meta-study on comparing agricultural crop yields of conventional and organic farming globally reveald that overall conventional yields are higher, due to high doses of fertilizers, chemical plant protection products, and crops adapted to these inputs (Seufert et al. 2012). They found that organic farming reaches 75% of the mean global yields for conventional farming, however depending on crop type and growing conditions. Also, at the Scheyern experimental farm in southern Germany, where this study was conducted, differences in structure and production features led to significantly higher agricultural crop yields under conventional than under organic management (Küstermann et al. 2008, 2010, Lin et al. 2016a).

Regarding tree crops, literature showed that, when nutriens or water are limiting, tree yields or early culmination of biomass alike can be improved by fertilization (Heilman and Fu-Guang 1993, Labrecque et al. 1998, Georgiadis et al. 2017) and irrigation (Bongarten et al. 1992, Ceulemans and Deraedt 1999). Even for black locust fertilizers can have a positive effect, in spite of its capabilty to fix atmospheric nitrogen (Bongarten et al. 1992). Furthermore, weed control, mainly in the establishment phase, is essential to ensure survival and high productivity of tree crops (Welham et al. 2007, Hauk et al. 2014). In organic farming annual weeds can be treated only mechanically and, hence, may be difficult to suppress (Jørgensen et al. 2005). Therefore, the question arises whether organically managed trees in SRAFS correspondingly develop lower biomass yields due to restrictions in organic farming (no mineral N, no chemical, synthetic pesticides). Moreover, many AFS worldwide are managed under low-input conditions that are close to organic farming, even if the farm is not certified organic. Short rotation woody crops, especially N_2-fixing species, are already seen as good option to produce bioenergy in low-input organic farming due to the high nutrient use efficiency of trees (Jørgensen et al. 2005). However, organic short-rotation systems have hardly been studied (e.g. Jørgensen et al. 2005, Winterling et al. 2013) and no direct comparison between conventional and organic has been made so far. With this, knowledge on the biomass development of trees under organic and low-input conditions is essential to assess whether SRAFS are a realistic option for farmers.

Regarding structural tree characteristics, fertilization with N, P, and K was proposed to alter willow’s tree allometry by reducing shoot biomass for a given diameter and height (Heinsoo et al. 2002). Also, in a study on black locust on nutrient poorer sites, trees had lower heights, thus, lower biomasses for a given diameter (Carl et al. 2017). Hence, nutrient limitations (and weed competition) in organic farming may also alter wood quality, tree sizes and the structural characteristics of the whole stand. Further research is urgently needed to make recommendations for organic SRAFS.

1.4.4 Biomass estimation

Tree biomass is is directly estimated by harvesting parts of the stand. Nondestructive methods employ regression analysis based on the allometric relationship between tree diameter and/or height and the corresponding biomass or volume of shoots (Muukkonen 2007). Such biomass functions use less destructive harvesting methods or none at all. This saves time and costs whilst providing accurate estimation of biomass gain during the rotation (Al Afas et al. 2008). Accurate yield estimations strongly influence the implementation and management of SRC (Hauk et al. 2014).

Most functions have been developed for tree species grown in mature forest stands (Zianis and Mencuccini 2004, Zianis et al. 2005, Fehrmann and Kleinn 2006, Muukkonen 2007). Because biomass allocation patterns differ with tree age (Wirth et al. 2004), those functions are not applicable to trees with diameters or heights below the range of validity. Furthermore, diameter at breast height (DBH, in 1.30 m above soil) is used as biomass predictor in older stands, which is unsuitable for small trees, because it would be measured in the tapered or branched crown (Sumida et al. 2013). Functions using a standardized SBD instead of DBH as predictor must first be developed. In addition, in SRC trees are planted very densely. Under such crowded condition, competition for sunlight leads to the development of greater height growth relative to growth in diameter (Niklas 1995) and to suppression of lateral branches (Unruh Snyder et al. 2007). Furthermore, due to the afforementiond edge effects in alley cropping systems (Verwijst and Telenius 1999) (section 1.4.2) and fertilization effects (Heinsoo et al. 2002) (Section 1.4.3), biomass equations developed for natural forests may be inadequate for SRC and SRAFS (Tumwebaze et al. 2013). A few equations exist for alder (Hughes 1971, Verwijst and Telenius 1999, Johansson 1999, 2000), black locust (Bongarten et al. 1992, Burner et al. 2006, Böhm et al. 2011), poplar (Laureysens et al. 2004, Zabek and Prescott 2006, Dillen et al. 2007, Vande Walle et al. 2007, Al Afas et al. 2008), and willow (Telenius and Verwijst 1995, Heinsoo et al. 2002, Nordh and Verwijst 2004, Vande Walle et al. 2007, Sevel et al. 2012). However, suitable allometric biomass functions are still lacking for fast-growing and small-diameter trees used in SRC or SRAFS.

In addition, it remains a matter of debate, whether simple allometric models with diameter as single predictor should be preferred to more complex models with e.g. height as an additional predictor (Sileshi 2014, Picard et al. 2015). Trees in SRC span a limited tree size range and stand age, nevertheless the role of height as a reflector of site characteristics (Kobal et al. 2015) and competition (Vanninen and Mäkelä 2000) questions its inclusion. Including H in biomass models may improve the transferability to other stands. However, keeping a model as simple as possible to reduce sampling effort while assuring estimation accuracy is of high economic interest.

2 AIMS AND OUTLINES

To increase the momentum of new agrarian concepts like SRAFS, the sustainability and profitability of those systems has to be proven. The achievement of this goal requires a better understanding of various ecological processes that govern these complex systems. This work provides knowledge on the development of the tree components of SRAFS, which strongly influences profitability and efficiency of the systems. The large amount of carbon and thus energy sequestered in the woody biomass substantially determines the carbon and energy sequestered per unit area in the overall agroforestry system (Schoeneberger 2008). Furthermore, the development of tree dimensions and the survival of individuals influences many management decisions such as the choice of species, planting design, harvest cycles or harvest techniques.

Although some SRAFS and SRC studies investigated the ecological suitability and yield potential of various fast-growing tree species under the environmental conditions of Germany, information about southern Germany is limited. Furthermore, studies still often neglect stand hierarchies, although stand structure, growth dynamics, harvesting methods and wood usage are interdependent (cp. Section 1.4.1). Furthermore, only few studies dealt with the growth performance in SRAFS with an alley configuration, where edge effects highly influence total tree yields (cp. Section 1.4.2). Even less is known about organic SRAFS and no comparative studies of organic and conventional systems have been found (cp. Section 1.4.3). Accurate and practical biomass estimation functions to monitor stand biomass growth in SRC or SRC elements are scarce and influences of farming system and edge effects are little known (cp. Section 1.4.4). Altogether, missing experience and scientific investigations make it difficult to forecast the development of different tree species on agricultural land in Germany and southern Germany, in particular for organic farming.

This study contributes to close the aforementioned gaps. For this, unique long-term field experiments were established at the Scheyern research farm, in southern Germany. Tree strips consisting of different tree species (black alder, black locust, poplar clone Max 3, poplar clone Androscoggin, willow clone Inger, native mix) were planted in fields with both organic and conventional farming to explore species differences and to compare well-established farming systems.

The main objectives of this study and the consequent separation to three publications were

(1) to establish and validate allometric tree biomass models usable in SRAFS,

(2) to analyze the biomass productivity of the first rotation,

(3) to describe the full rotation, stand development, and growth dynamics.

In each publication, influences of tree species, alley structure design, and farming system were evaluated seperately. Throughout this work, the short rotation character of the analyzed systems is emphasized. By excluding the analyzed edge effects, which is always a special investigation point of this work, results may also be transferred to single field SRC.

In the following, the scope of the individual publications is given. The abstracts of the publications along with the particular contributions are given in Chapter 4. The entire articles can be found in Appendix B.

The first study addresses how tree biomass of SRAFS (and SRC) can be estimated with high precision while keeping efforts as low as possible. Biomass estimations were generated for the studied fast-growing tree species, with the following main objectives:

(1) Generate and validate allometric biomass models to estimate the tree biomass of SRAFS and SRC in southern Germany and to put them into the context of allometric theories.

(2) Evaluate the effect of tree height as a second explanatory variable.

(3) Investigate differences in allometry between border and inner rows.

(4) Study the influence of the conventional and organic farming system.

(5) Discuss problems and possibilities when functions are transferred to other sites and stand ages.

In order to assess the productivity of the SRAFS, highlights of the second study were as follows:

(1) Estimate species-specific biomass production and give recommendations regarding species choice.

(2) Analyze differences between trees from border and inner rows.

(3) Evaluate woody biomass production between farming systems.

The third study analyses the complete first-rotation excluding edge effects with respect to

(1) yield and stand structure development of different tree species, and

(2) influences of farming system.

This study was also part of the R&D project ELKE (development of extensive land use concepts for the production of renewable raw materials as possible compensatory measures). This project aimed at mitigating the loss of agricultural land due to sealing and tied compensatory measures by the development of production integrating compensation mechanisms (Wagener et al. 2013). Within this project, several additional scientific investigations were carried out. Such were ressource use efficiency analyses, which were based on the here reported tree yields (Lin et al. 2016a, b, Lin and Hülsbergen 2017) and which are referenced in the previous sections. The influence of the tree strips on quality and yield of the agricultural crops are published in Huber et al. (2013a). In addition, a central question posed by the project was to examine tree species that combine high yields with conservation. Thus, analyses about tree roots and soil carbon sequestration (Huber et al. 2013b) as well as earthworm population (Huber 2013) were carried out. Results are also avalaible via conference papers (see Appendix A). Sun et al. (2016, 2017) studied the microbial community and water extractable organic matter within poplar and black locust tree rows.

3 OVERVIEW OF METHODS AND EXPERIMENTAL SETUP

A brief overview of methods and scientific state of the art is given below. More detailed information can be found in the publications associated with each of the following chapters.

3.1 STUDY SITE AND AGROFORESTRY DESIGN

The study was performed at the Scheyern experimental farm (48°30′N, 11°21′E) in Bavaria, southern Germany. The farm consists of many independent fields in hilly terrain. In 1992, the farm was sudivided into a conventional and organic part and run under both farming systems. The organic one was established as a mixed-farming system with livestock and has been maintained as an organic farm without livestock since 2005. It was based on a seven-field crop rotation with 29% grass-clover-alfalfa, 29% winter wheat, 14% potato, 14% sunflower, 14% winter rye. Mineral nitrogen and synthetic chemical plant protection products were omitted. Tillage was performed with a moldboard plow. The conventional system was a high-input system with synthetic, chemical plant protection, mineral nitrogen input, and a simple structured crop rotation with 50 % wheat, 25 % forage maize, and 25% potato. Conservation tillage was applied (no plowing, crop residue incorporation with a grubber, mustard catch crop). This system had significantly higher agricultural crops yields than the organic one (Küstermann et al. 2010, Lin et al. 2016).

Figure 2: Conventional short-rotation agroforestry system at the Scheyern experimental farm (48°30′N, 11°21′E) in Bavaria, southern Germany. This system was part of a field experiment of the Technical University Munich (© Julia Huber 2010).

The overall purpose of the experimental design was to study the environmental and economic effects of conventional and organic silvoarable SRAFS with an alley-cropping configuration. Furthermore, the influence of different tree species was of special focus. Therefore, in 2009, SRAFS were established in two fields each farming system, covering 1.9–3.7 ha. On each field, three tree strips were planted in a north–south or west–east direction with a spacing of 30 m for the field crops in between (Figure 2 and 3). Although, the tree strips were not manured like the adjacent fields, the two well established systems offered to explore influences of different preconditions on tree development. Weed in the tree strip was controlled by herbicide application (conventional system) and mechanical weeding (organic system) during the first year of establishment.

The tree species were allocated randomly in blocks (30 m × 8.25 m) inside each strip (Figure 3 and 4a). Such a design was chosen because it was impossible to randomize

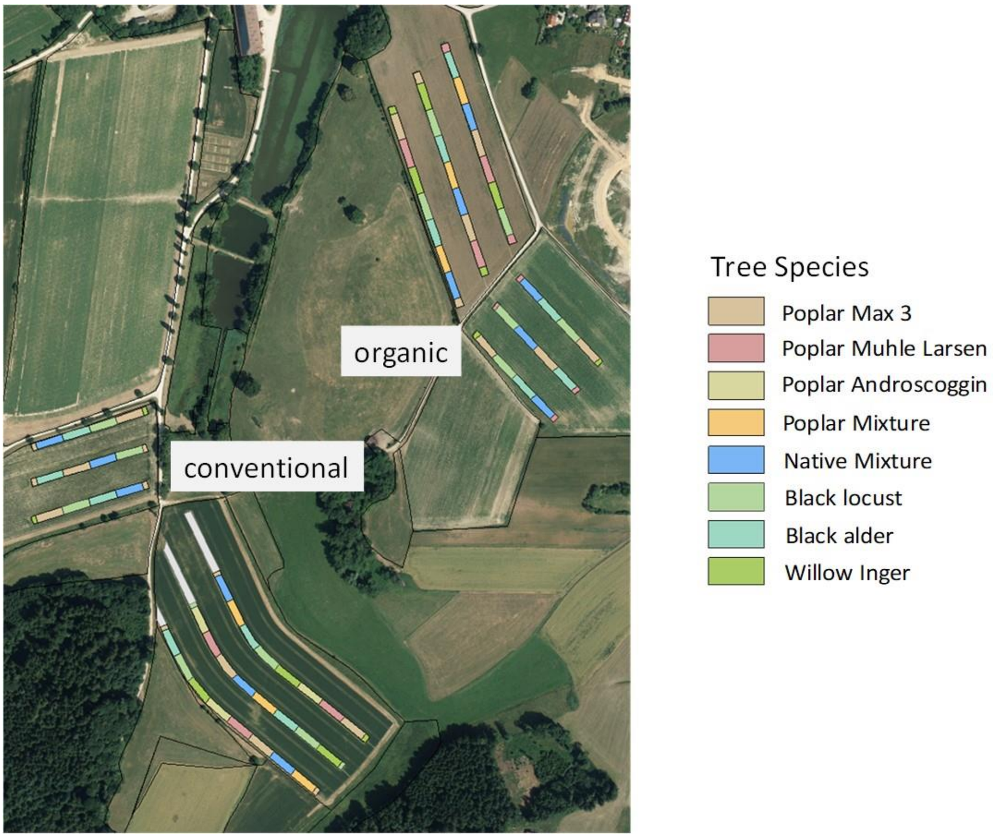

Figure 3: Experimental design of the agroforestry systems at the Scheyern experimental farm (48°30′N, 11°21′E) in Bavaria, southern Germany. Three strips of various species were planted on four fields (two organic, two conventional). Published in Hülsbergen et al. 2012.

farming systems due to the agricultural constraints, and unfeasible not to plant the species in blocks. The studied species were black alder (*Alnus glutinosa*), black locust (*Robinia pseudoacacia*), poplar clone Max 3 (Populus maximowiczii × *P. nigra*), poplar clone Androscoggin (*Populus maximowiczii* × *P. trichocarpa*), and willow clone Inger (*Salix triandra* × *S. viminalis*). Trees were arranged in three double rows (Figure 4b, c). A buffer zone of 0.75 m between crops and trees on each site was established to prevent damage during processing. Effective plot width was 6.75 m, resulting in a total density of 17,778 plants ha^{-1}. Trees were planted manually: poplar and willow as cuttings of 20 cm in length, the other species as bare-rooted saplings of 70–90 cm in length.

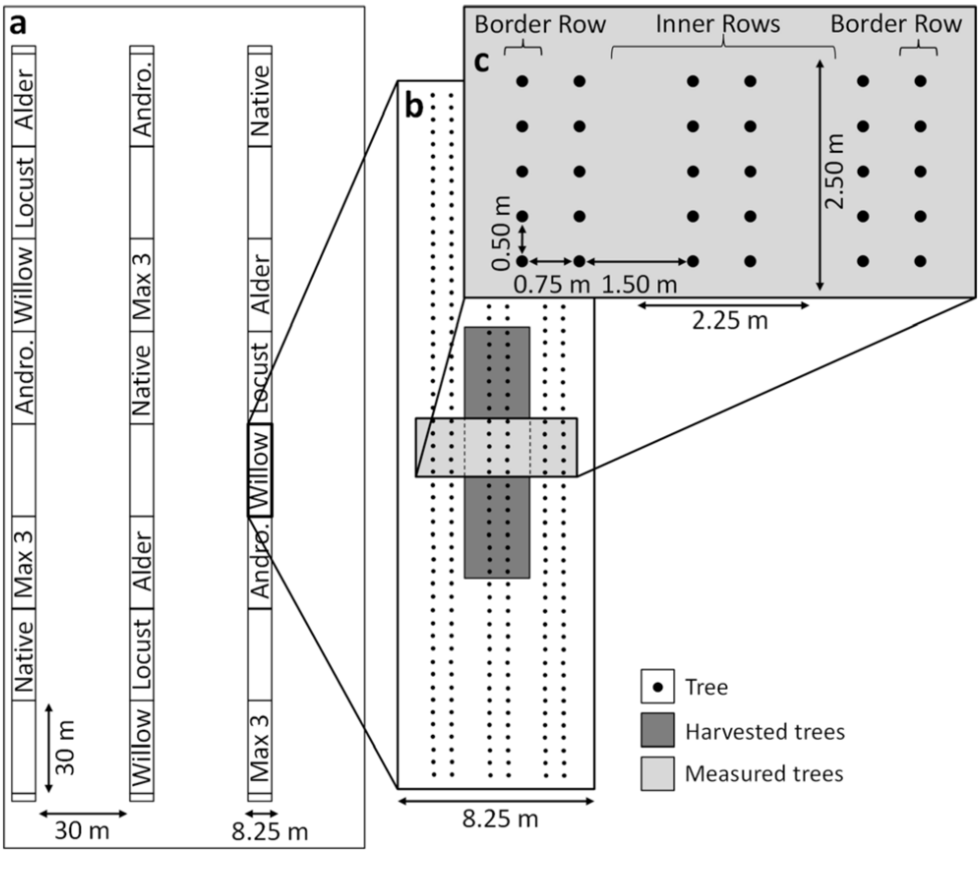

Figure 4: Planting arrangement and data collection of the agroforestry systems, illustrated by the biggest of four fields. Three tree strips of various species were planted (a), resulting in three plots per species and field (gaps within a tree strip are planted with a mixture of different poplar clones and were not part of the study). The inner structure of the tree strips consists of three doublerows (b+c). The study area is highlighted (b+c). This designs repeated on a total of four fields (two organic, two conventional). Published in Huber et al. 2016.

3.2 MEASUREMENTS AND SAMPLING

3.2.1 Meteorological data

Meteorological data were obtained from the nearby Altomünster-Maisbrunn weather station (48°24′N, 11°19′E) of the Deutscher Wetterdienst (DWD). The climate is temperate, with an annual average temperature of 8.7 °C and an annual precipitation of 803 mm between 2009 and 2012. The long-term (1981–2010) averages are 8.3 °C and 887 mm, respectively. Precipitation during the establishment phase in 2009 (May–July) was above average.

3.2.2 Edaphic data

Former literature provided data on altitude and soil types (Scheinostet al. 1993, Schröder et al. 2002). The altitude for the four fields varied between 460 and 490 m above sea level with a 2–10 % slope. Soils mostly have a loamy texture and are classified (WRB soil classification) as either Cambisols or Eutrochrepts with a thin layer of loess, Cambisol with sand and gravel subsoil (sandy-gravelly illuvial horizon), or small-scale clay soils.

At the beginning of the experiment in 2009, soil analyses were carried out in each plot of all four fields at 0–30 cm depth to categorise the soil status of the two farming systems. Organic carbon (C_{org}) and organic nitrogen (N_{org}) were analyzed with the (Dumas 1831) method, available phosphorus (P) and available potassium (K) with the calcium acetate lactate (CAL) method. The pH was also measured.

3.2.3 Tree data

Trees were measured at the end of each growing season on 12 plots for each species (3 strips × 2 fields × 2 systems), except for willow, which was planted only in one field of each system (in total 6 plots) and of poplar Androscoggin, planted only in one conventional field (in total 3 plots). Two datasets were used. One to monitor tree and stand development and a second to develop allometric models on areas different to the monitoring area.

Tree and stand development

Every year of the 4-year rotation, stem base diameter (SBD, at 10 cm above soil) and tree height (H) were measured from all shoots in the middle double row of each species plot (2.25 m × 2.5 m area), on a selection of 10 trees (Figure 4b, c). The shoot number was quantified. In total, 120 individuals were recorded for each year and species (10 trees × 3 strips × 2 fields × 2 systems). Willow was planted on only two of four fields, resulting in 60 indivduals. In the last year, SBDs of the two single border rows were included as well (additional 10 trees × 3 strips × 2 fields × 2 systems). Tree mortality was determined every year. The mixture of native species was not measured, poplar Andoscoggin only in the last year.

At the end of the rotation, 40 trees of the middle double row (Figure 4b) were cut manually 10 cm above soil surface. Harvested plots overlapped measurement plots. The plots with the native mix were harvested as well.

As trees of the inner rows were harvested only in the last year and border rows were not harvested at all, biomass was estimated for all years and rows. This was done by using allometric functions, which were developed during this study (Huber et al. 2017). Table 2 gives an overview of the tree measurements taken from 2009 to 2012.

Table 2: Overview of measurements from 2009 to 2012 to monitor tree and stand development (SBD = Stem base diameter, H = Tree height, Shoot = shoot number, Mort = Mortality, Biom$_E$ = Biomass estimated, Biom$_H$ = Biomass harvested).

Tree species	**Year**	**Row**	**SBD**	**H**	**Shoot**	**Mort**	**Biom$_E$**	**Biom$_H$**
Black alder, black locust, poplar Max 3, willow Inger	2009	inner	×	×	×	×	×	
	2010	inner	×	×	×	×	×	
	2011	inner	×	×	×	×	×	
	2012	inner	×	×	×	×	×	×
		border	×		×	×	×	
Poplar Androscoggin	2012	inner	×	×	×	×	×	×
		border	×		×	×	×	
Nativ mix	2012	inner						×

Allometric functions

In 2011 and 2012, in each species plot (3 strips × 2 fields × 2 systems) 9 leafless single-shoot trees of the border and inner rows were measured and harvested (3 in 2011, 6 in 2012). A total of 108 trees were measured for each species, for willow 54 trees (planted only on 2 fields) and for poplar Androscoggin 18 trees (planted on only 1 field, investigated only in 2012), respectively. Measurements included SBD, H, and single tree biomass. The native mix was not investigated.

Table 3: Overview of measurements from 2011 and 2012 to develop biomass estimation functions (SBD = Stem base diameter, H = Tree height, Biom_S = Single tree biomass harvested).

Tree species	**Year**	**Row**	**SBD**	**H**	**Biom_S**
Black alder, black locust, poplar Max 3, willow Inger	2011	inner and border	×	×	×
	2012	inner and border	×	×	×
Poplar Androscoggin	2012	inner and border	×	×	×

3.3 ANALYSIS

All data were analyzed by generalized linear mixed effects models to account for dependencies within the hierarchical dataset and for heteroscedasticity (Zuur et al. 2009). When the random effects were not significant, generalized linear models were applied. The effects of species (4 to 6 levels), farming system (2 levels: organic and conventional), row position (2 levels: inner and border), year (4 levels: 2009–2012), and their interactions were treated as fixed and those of field and strip as random. The random effect field accounts for the correlation of the three plots within each field. The random effect plot accounts for the autocorrelation of the measurements wihin each plot and also for the spatially dependent measurements of the row positions.

4 PUBLICATIONS: ABSTRACTS AND CONTRIBUTIONS

4.1 ALLOMETRIC TREE BIOMASS MODELS OF VARIOUS SPECIES GROWN IN SHORT-ROTATION AGROFORESTRY SYSTEMS

Julia Alexandra Huber, Katharina May, Kurt-Jürgen Hülsbergen (2017): Allometric tree biomass models of various species grown in short-rotation agroforestry systems. *European Journal of Forest Research. DOI:* 10.1007/s10342-016-1010-7 (Huber et al. 2017).

Abstract: Biomass equations for tree species and the early stages of growth used in short-rotation coppices and agroforestry systems are still lacking. Further, discussion about the structure and parameters of biomass equations are still ongoing. Yield estimations should be precise, while keeping efforts low. To determine the influence of tree species, farming system, and tree position (inner and outer row) on allometric relationships, we derived biomass equations for various tree species from organic and conventional silvoarable agroforestry systems with an alley-cropping configuration. The allometric equations were based on the power relationship between aboveground dry biomass and stem base diameter (SBD) as a single variable or in combination with tree height (H) and were calculated by log-linear mixed-effect regression. Equations span the third and fourth growth year of the first rotation and were validated on the fourth year. Neither farming system nor row position influenced allometric relationship, although biometric variables varied between trees from inner and outer rows. A general model across species explained 95% (R^2_{cond}) of the variation for tree dry weight or 97% (R^2_{cond}) with H as covariate. Yet, for the sake of precision, species-specific equations were necessary. The best fitting equation with only SBD as predictor had species-specific allometric factors and a general exponent across species. However, predicted yields were biased by 8–31%. Thus, functions incorporating H are recommended, as compensation for variances in height-diameter relationships due to the ontogenetic stage, site differences, or social status of the tree reduced the bias of biomass estimation (<10%).

Contributions: I did the data collection, the finalized statistical analysis and wrote the manuscript. *Katharina May* provided statistical analysis and worte on the manuscript. *Kurt-Jürgen Hülsbergen* helped with topical classification and reviewed the draft manuscript before submission. About 45% of the work was done by myself.

4.2 YIELD POTENTIAL OF TREE SPECIES IN ORGANIC AND CONVENTIONAL SHORT-ROTATION AGROFORESTRY SYSTEMS IN SOUTHERN GERMANY

Julia Alexandra Huber, Katharina May, Thomas Siegl, Harald Schmid, Georg Gerl, Kurt-Jürgen Hülsbergen (2016): Yield Potential of Tree Species in Organic and Conventional Short-Rotation Agroforestry Systems in Southern Germany. *Bioenergy Research* 9 (3): 955–968. DOI: 10.1007/s12155-016-9750-2 (Huber et al. 2016).

Abstract: The increasing demand for bioenergy and the combination of agricultural production with conservation has made short-rotation agroforestry systems (SRAFS) a sustainable land-management option. Aboveground woody biomass is a decisive factor in economic and ecological assessment of those systems. To study the yields of organic and conventional SRAFS, the tree species black alder, black locust, poplar clone Max 3, poplar clone Androscoggin, willow clone Inger, and a mixture of different native species were established in an alley-cropping configuration in 2009 and coppiced in 2012. Biomass was determined by harvesting the inner rows of the tree strips and, to investigate row differences within a strip, by an allometric model which estimates tree biomass from stem diameter. Significant variation was observed between species. For inner rows and at the conventional system, highest harvested average annual yield was observed for poplar Androscoggin (10.5 t ha^{-1} yr^{-1}),followed by black locust (9.7 t ha^{-1} yr^{-1}), poplar Max 3 (8.6 t ha^{-1} yr^{-1}), black alder (7.6 t ha^{-1} yr^{-1}), the native mix(4.9 t ha^{-1} yr^{-1}), and willow (3.9 t ha^{-1} yr^{-1}). At the organic system, highest yields were observed for poplar Max 3 (Androscoggin not planted) (10.9 t ha^{-1} yr^{-1}), followed by black locust (8.1 t ha^{-1} yr^{-1}), black alder (7.4 t ha^{-1} yr^{-1}), willow (6.4 t ha^{-1} yr^{-1}), and the native mix (4.7 t ha^{-1} yr^{-1}). Farming system differences were only significant for willow and poplar Max 3; however, the higher yields of the organic system seemed to be a result of varying small-scale site properties rather than a management effect. Border rows showed 18–111 % more yield than inner rows because of greater tree diameters or heights and higher number of stems. This edge effect was emphasized in the conventional systems, possibly indicating that trees benefit from fertilizers applied at adjacent crop fields.

Contributions: I had the idea for row comparison and designed the study. *Katharina May* supported me in data analysis. *Thomas Siegl, Harald Schmid,* and *Kurt-Jürgen Hülsbergen* provided methodological support. All co-authors reviewed the draft manuscript before submission. About 75% of the work was done by myself.

4.3 First-rotation growth and stand structure dynamics of tree species in organic and conventional short-rotation agroforestry systems

Julia Alexandra Huber, Michael Matiu, Kurt-Jürgen Hülsbergen (2018). First-rotation growth and stand structure dynamics of tree species in organic and conventional short-rotation agroforestry systems. *Heliyon* 4 (6). DOI: 10.1016/j.heliyon.2018.e00645 (Huber et al. 2018).

Abstract: Short-rotation agroforestry systems can potentially maintain agricultural production and promote conservation ofsoil and biodiversity, especially if grown organically. Hereby, species-specific stand growth determines woody biomass yield and influences management decisions like planting density and harvest requirements. Studies of longer-term growth dynamics in Southern Germany are scarce and none analyzed differences between conventional and organic systems. Int his study, four tree species (black alder, black locust, poplar clone Max 3, and willow clone Inger) were planted in an alley-cropping configuration in Southern Germany, grown under organic and conventional systems, and monitored from 2009 to 2012. Growth was assessed with stem base diameter, height, aboveground woody biomass, sprouting, and survival. The tree species did not show a uniform ranking in biometric variables and biomass over time. Four-year mean annual biomass increment (MAI) ranged from 7 to 10 t ha^{1} yr^{-1}, with poplar and locust having the highest growth rates. Willow had the lowest MAI, as it had a low diameter growth paired with a low wood density, but it developed the highest number of shoots because of increased sprouting in the last year. Size inequality and skewness of the dominant stems increased for all species throughout the years suggesting asymmetric competition. Size inequality as well as mortality was greatest for black locust. Furthermore, this was the only species, which developed a right skewed SBD distribution and the highest diameter size range. Size inequality was smallest for poplar and willow, with no or only minimal mortality. Alder was in between. For black locust and alder, no difference in growth traits between organic and conventional systems appeared after four years. Organic poplar and willow stands performed better than conventional ones after the second year, leaving unclear whether this can be attributed to management or site effect.

Contributions: I had the idea for and designed the study. *Michael Matiu* supported me in data analysis. *Kurt-Jürgen Hülsbergen* provided input on study design and scope. All co-authors reviewed the draft manuscript before submission. About 80% of the work was done by myself.

5 DISCUSSION

Describing the growth of tree stands (single species stands) is always a combination of considering species-specific physiological and morphological properties, stand dynamics, and reaction to environmental or other external influences (Al Afas et al. 2008, Dillen et al. 2013). In this study, different tree species were grown at the same site, at the same time, with the same planting design, and two longtime established treatments (organic and conventional). Therewith they grew under similar conditions, however with some variations in respect to the heterogeneity of the soil and relief and the plant material (poplar and willow were planted as cuttings, alder, black locust, and the native mix as bare rooted saplings). In the following, the relevant findings of the three presented studies are linked and set in a broader perspective. Furthermore, results are joined to relevance in practice.

This section begins with describing the methodological approach necessary due to the variability of the experiment (Section 5.1). It is further sub-divided into tree species differences (Section 5.2), as well as structural, farming system, and site effects (Section 5.3) on tree development.

5.1 VARIABILITY OF THE EXPERIMENTAL DESIGN AND THE MIXED MODELING APPROACH

The site heterogeneity including soil variability, altitude differences, and microclimatic effects, at the Scheyern research station is typical for the Bavarian Tertiary Highlands. There are many studies on the small-scale variability of soil properties in Scheyern and their significance for the yield of arable crops (e.g. Schröder et al. 2002, Hülsbergen et al. 2012). Influences by organic and conventional management on crop yields at Scheyern were determined as well (Küstermann et al. 2008, 2010, Lin et al. 2016a). With this starting situation, influences of farm management and site heterogeneity on tree biomass were expected as well. The experimental setup of the SRAFS at the research station further increased the complexity of the analyisis. The organic and conventional SRAFS experiments were spatially separated on four fields and tree strips were geographically assigned to each system. On every field, different tree species were planted. All this allowed to study various determinants and their interactions on tree development. However, it was not possible to replicate the farming systems completely randomized. Furthermore, due to limiting field sizes only three replicates each field and tree species were possible.

With the mixed modeling approach, biased estimation of parameters and underestimation of standard errors can be avoided by treating plot and field variations as random errors (Zuur et al. 2009), which are often neglected in literature. The inclusion of random effects always resulted in significant model improvements illustrating that the large between- and within-field variation due to edaphic and micro-climatic differences appeared to have an influence, although no correlation was found between tree data and soil or slope variables (data not shown). Including these random effects enabled to analyze species performance in interaction with the factors time, farming system, and edge effects, less confounded by other influences. Still, the heterogeneity of the site made it difficult to distinguish between farming system and site effects.

5.2 SPECIES DIFFERENCES IN ALLOMETRY, STAND STRUCTURE DEVELOPMENT, AND YIELD

On a single tree basis, growth means dividing energy and material among different structures and activities (Weiner 2004). “The pattern of how trees allocate their net biomass production […] determines their inter- and intraspecific competitiveness and its variability reflects their potential to adapt to different conditions” (Pretzsch et al. 2013). While single tree growth is a primary determinant of individual success, total stand biomass development is often balanced by the growth of dominant and the simultaneously decline of suppressed trees. How single tree allometry (Section 5.2.1) as well as stand structure (Section 5.2.2) interact and determine yield development (Section 5.2.3) discusses this chapter. Furthermore, it draws conclusions about implications for SRAFS management (Section 5.2.4).

5.2.1 Species-specific tree allometry and plasticity

Generalized allometric tree biomass models are species-independent and based on the assumption that all trees follow the same plant structure (Enquist and Niklas 2001). Such models were developed mostly for tropical forests (Brown et al. 1989, 1995, Ketterings et al. 2001, Malhi et al. 2004, Segura 2005) or spanning the globe (Zianis and Mencuccini 2004, Pilli et al. 2006, Muukkonen 2007), induced by the difficulty to estimate single species biomass in such diverse forests. Generalized functions simplify the biomass estimation but are very error-prone. In contrast, species-specific estimations stand for considerable extra work, however, offer more accuracy by quantifying variation in structural traits. The same holds true for the number of tree vaiables (SBD, H, etc.) used to explain tree biomass.

General versus species-specific allometric scaling

The present work revealed that a generalized interspecific allometric scaling with only SBD or with H as predicting variables explained to the largest part the variation of single tree biomass (Huber et al. 2017). However, when functions were applied on a new dataset, species-specific allometric functions were necessary for correct biomass estimation. Species-specific coefficients take into account that species vary in tree architectures, wood densities, annual growth dynamics, and reactions to environmental factors. The demand to differentiate between species is confirmed by other authors (Telenius and Verwijst 1995, Heinsoo et al. 2002, Dillen et al. 2007, Sevel et al. 2012). The equation with only diameter and species-specific allometric factors while constant exponent resulted in a biomass estimation bias of less than 15%, except for willow (31%).

The species-specific allometric factor accounts for the with species varing morphological structure and initial aboveground biomass at a given diameter and includes, inter alia, the differing wood densities, tree shapes, and height growth. Different tree shapes of the two year old species are visible in Figure 5. Poplar and willow had a tightly packed, vertical and pyramidal shoot architecture and shared the greatest height growth, but their allometric

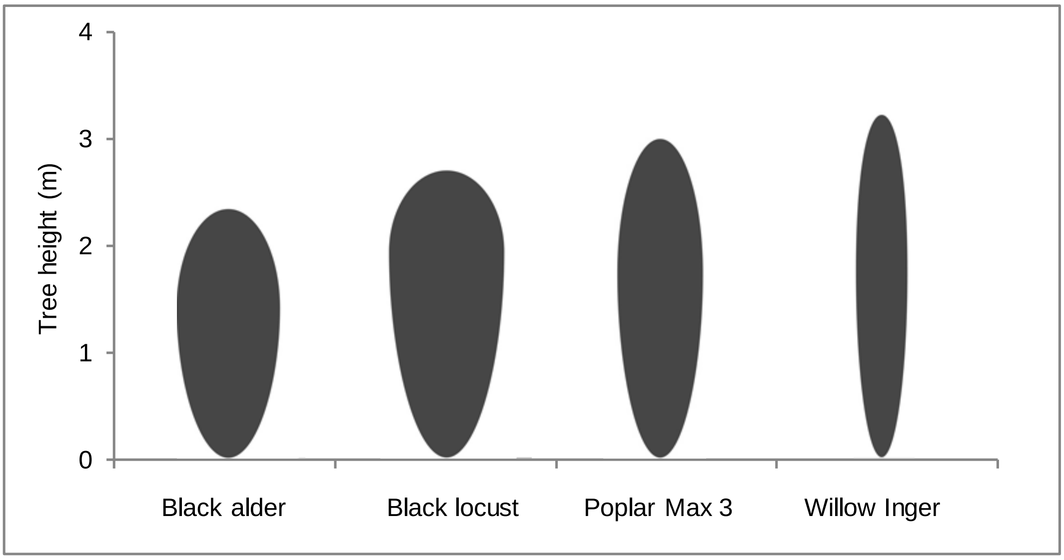

Figure 5: Tree crown shapes of two year old tree species black alder, black locust, poplar Max 3 and willow Inger. Adapted from Huber (2011).

factor was lower than that of black locust. This was maybe because black locust has the highest wood density among secies ($\rho = 0.60$ g cm^{-3}; Klašnja et al. 2013). Alder's wood density is likewise higher ($\rho = 0.40$ g cm^{-3}; Kiaei 2013) than that of poplar ($\rho = 0.34$ g cm^{-3}; Klašnja et al. 2013) and willow clones ($\rho = 0.34$ g cm^{-3}; Klašnja et al. 2013) and the crown is stouter. However, it had the lowest allometric factor, which may be explained by the modest height growth.

The constant exponent across all species assumes the same rate of growth in M and SBD for different species. However, with ageing of the stand or different ecological settings these allometric relationships might change (Niklas 1995, Weiner 2004). This makes the functions less transferable to other stands or the next rotations.

Comparisons of generated allometric coefficients with previously published ones are difficult, owing to different mathematical formulations and corresponding assumptions about growth determinants as well as differences in site, stand density, measurement height of diameter, diameter range, or stand age. Furthermore, most coefficients published for poplar or willow have been derived using other clones, mainly varieties of *P. trichocarpa, P. deltoids*, and T × D crosses, or clonal varieties of *S. viminalis*. A few examples of reported coefficients are compared in Table 4, showing that most reported allometric factors were higher and the corresponding allometric exponents lower than those of our study. The higher allometric factors (higher starting constant) may be due to the inclusion of older or larger trees with higher wood densities (from increased heartwood) (Brown et al. 1995) or higher proportions of branch biomass during aging, at least until canopy closure when the proportion of branch biomass starts to decrease (Pajtík et al. 2008). Another explanation could be the height of diameter measurement. The stem tapers from the ground to the top of the tree. If the measurements are performed at heights greater than in our measurement height (10 cm above soil), diameter decreases and the allometric factor must thereby increase. The visible negative correlation between the allometric factor and exponent has already been recognized in other studies (Zianis and Mencuccini 2004, Pilli et al. 2006, Sileshi 2014). So far no standardized stem base diameter as predictor in biomass functions for SRC exist and must be first developed. In SRC young trees are shorter than 1.30 m and for small trees taller than 1.30 m DBH (diameter at breast height, in 1.30 m above soil), which is normally used for biomass functions in forests, might be a poor biomass predictor (Wirth et al. 2004), as it may be measured at any location in the crown. The trunk is more tapered in the crown than in the region below (Sumida et al. 2013) and some species develop dichotomous branching. Therewith, the measurement height of 10 cm was appropriate in terms of the existing tree heights and consistent with other authors’ approaches.

Intraspecific plasticity of tree allometry and limitations on biomass estimation

Incorporating H into the equation resulted in yields similar to the harvested ones, with a bias less than 10%. H had a significant effect on model performance, although it explained only 2% of the data variance, concordant with previous studies (Joosten et al. 2004, Cienciala et al. 2005, Carl et al. 2017). As the height-diamter (HD) relation decreases with

Table 4: Variability in parameter estimates of recently published species-species equations with tree diameter as predictor (*Biomass* $= \beta_0 * diameter^{\beta 1}$).

Tree Species	β_0	β_1	Height of measurement (cm)	Age (year)	Diameter range (cm)	Author
Black alder	0.026	2.576	10	3–4	1.7–7.6	Huber et al. 2016
	0.017 ^{1}	2.711	10	10	-	Verwijst and Telenius 1999
	0.018 ^{1}	2.748	10	10	-	Verwijst and Telenius 1999
	0.086	2.354	130	-	-	Hughes 1971
	0.153 ^{1}	2.286	130	4–5	2.5–22.5	Johansson 2000
	0.325 ^{1}	2.022	130	-	0–40	Johansson 1999
Black locust	0.050	2.532	10	3–4	1.4–9.9	Huber et al. 2016
	0.024	2.841	10	-	0.5–13.4	Böhm et al. 2011
	0.976	2.293	10	1–8	0.1–20.2	Carl et al. 2017
Poplar Max 3	0.031	2.752	10	3–4	1.6–7.7	Huber et al. 2016
Poplar Andro.	0.037	2.521	10	3–4	2.9–7.9	Huber et al. 2016
Poplar *spec.*	0.072 to	2.633	130	4	-	Laureysens et al. 2004
	0.442	2.155	130	4	-	
	0.180 ^{2}	2.400	22	-	0.9–2.6	Al Afas et al. 2008
	0.295	2.223	30	3	-	Vande Walle et al. 2007
Willow Inger	0.041	2.552	10	3–4	1.2–5.1	Huber et al. 2016
	0.041 ^{1} to	2.612	90	4	-	Sevel et al. 2012
	0.098 ^{1}	1.992	90	4	-	
Willow *spec.*	0.086 to	2.637	30	1–4	0.1–6.5	Arevalo et al. 2007
	0.114	2.624	30	1–4	0.1–6.5	
	0.111 to	2.660	55	4	-	Nordh and Verwijst 2004
	0.435	2.271	55	4	-	
	0.135	2.553	30	3	-	Vande Walle et al. 2007

[1] transformed from mm to cm

[2] model across 17 poplar clones

tree growth (Huber et al. 2017), extrapolating biomass off the appropriable diameter range resulted in high overestimations with only SBD as predicting variable. When H is included, bias was reduced and suggests that H reflects differences in tree shape resulting from ageing, competition, and environmental changes (Joosten et al. 2004, Carl et al. 2017). With height growth being highly sensitive to site quality (Joosten et al. 2004, Kobal et al. 2015) and also to competition or the social status of the tree (Vanninen and Mäkelä 2000), the incorporation of H may be important when the equations are applied to stands with differing site conditions also suggested by Ketterings et al. (2001). In addition, tree growth is expected to be higher in the follwing rotations and more shoots per plant are presumed to resprout. This could lead to deviations in parameters used for estimation, such as relative lower wood density and greater height increase. Therfore, the inclusion of H in biomass estimation is recommended, as it increases the accuracy of estimation and is not complicated to measure in young stands typical for SRC.

Although H as additional variable seem to compensate allometric changes with greater diameters, the lack of old trees still might restrict the applicability of the functions to stands that cover the given range of dimensions. The developed equations including height remain to be tested on independant datasets to proof if they are adequate for estimating biomass of other stands or rotations and therefore serve as a practical tool for farmers.

5.2.2 Stand structure development and competition

Competition is the main driver leading to a divergence of individual tree size dimensions and weight distributions within a stand (Weiner and Thomas 1986). During stand development inequality increases when dominant trees suppress shaded small neighbours while larger trees continue their growth (Long and Smith 1984, Weiner 1990, Laureysens et al. 2005, Coomes and Allen 2007). When stands further develop, self-thinning as a result of the species-specific balance between site and spatial resources occur (Tomé and Verwijst 1996, Bergkvist and Ledin 1998). On the other hand, available space can induce an ongoing sprouting (Long and Smith 1984). The time and density to what competition appears depends on the species-specific time of canopy closure (Long and Smith 1984) as a result of growth rate and plant structure (plant morphology, canopy architecture; Zeide 1985). In SRAFS and SRC competition is enforced by high densities, by the use of species with high growth rates, and by planting mostly one single species competing similarly for resources (Tomé and Verwijst 1996).

In the present study, the SBD and H variability increased for all species indicating intraspecific competition (Huber et al. 2018). After four years of growth, for all species the shoot number was higher than the tree number initially planted. However, sprouting and mortality changed during the rotation. Alder and black locust developed additional shoots in the second year probably due to available space and light penetration. With further closure of the stand, pushed by their spreading crowns (Figure 5 and 6), shoot as well as tree density decreased in subsequent years. Willow and poplar developed many shoots in the first year, mainly at the conventional system possibly due to a higher nutrient availability from previous fertilization. Shoot numbers declined in the second year probably due to competition. Poplar showed a further reduction of shoots in the following years with exception of the organic stands, where small shoots emerged again in the fourth year. However, tree mortality was low. Although, poplar reached canopy closure as well (Figure 3), its straight trunk and narrow crowns allow for more light interception and lower between-plant competition (Laureysens et al. 2005, Amichev et al. 2010). Willow developed further shoots from the third year on. At the end of the rotation none of the planted trees had died and it had the highest number of shoots among species with a bimodal distribution. Willow had not yet reached canopy closure because the trees mostly developed only thin and seldomly branched shoots lowering mutal shading (Figure 5 and 6).

Figure 6: Tree stands of four year old tree species (a) black alder, (b) black locust, (c) poplar Max 3 and (d) willow Inger at the Scheyern research farm. Pictures are not claimed to be correctly scaled.

Black locust showed the most uneven structured stand and was the only species with positive skewed distributions owing to few dominant and many suppressed individuals. For the other species, negative skewness indicates that some small individuals grew under the canopy of many larger trees.

H distributions were more equal than SBD distributions (Huber et al. 2018). Trees of different diameters had partly comparable heights, because subdominant trees enhance their growth in height at cost of their diameter growth „to keep pace with the stand's canopy shifting upwards for a better access to light“ (Pretzsch et al. 2013). This H plasticity is expressed in a variability of the HD ratio, which is limited by the species tolerance to resist low resource levels created by competition (Weiner and Lila 1994). Locust showed a wider H range and a more equal HD ratio in comparison the other species. The strong stand inequality, the positively skewed distribution, the low plasticity of the HD, and the higher tree mortality indicates a lower intraspecific competitiveness for black locust than for all other species.

5.2.3 Tree yield differences

The middle rows of the tree strips were harvested and give the yield without edge effects. The first four-year rotation relvealed a mean annual biomass increment of 7 to 11 t ha^{-1} yr^{-1} (Huber et al. 2016, 2018). Yields were even higher including border rows, which accounted for one third of the tree cultivation area within this experiment (cp. Section 5.3.2).

Poplar clones were superior to any of the other species (Androscoggin exhibited 11 t ha^{-1} yr^{-1} and Max 3 10 t ha^{-1} yr^{-1}, respectively). This can be explained by the high mean SBD, the significantly highest mean H among all species, the development of branched shoots and the high intraspecific competitiveness. These yields are medium ranged in comparison to other studies with similiar rotation lenghts (3–18 t ha^{-1} yr^{-1}; Hofmann-Schielle et al. 1999, Labrecque and Teodorescu 2005).

Black locust yielded a harvested biomass (9 t ha^{-1} yr^{-1}) comparable to poplar. Although its mean SBD was low, mean H even lowest, and mortality highest among all species, stand biomass was high due to some high diameter trees and its highest wood density. Comparing similiar rotation lengths, yields were higher than those reported from marginal land (1–4 t ha^{-1} yr^{-1}; Gruenewald et al. 2007, Böhm et al. 2011) but in the upper area of typical yields under better conditions (3–10 t ha^{-1} yr^{-1}; Bongarten et al. 1992, Rédei and Veperdi 2009, Sixto et al. 2015).

Yield of alder was intermediate among the studied species (8 t ha^{-1} yr^{-1}) owing to its medium values of tree parameters. This species is still rarely studied as biomass crop, although it has a good biomass production potential. Still, the here found yields are in the upper range of biomass production in Sweden with similiar growth periods (1–8 t ha^{-1} yr^{-1}; Johansson 2000).

The harvested biomass of willow was the second lowest among all species (5 t ha^{-1} yr^{-1}). It lays within, but lower range of typical yields achieved without fertilization and/or irrigation and similiar rotation lenghts (2–17 t ha^{-1} yr^{-1}; Labrecque and Teodorescu 2005, Stolarski et al. 2011, Sevel et al. 2012, Toillon et al. 2013, Lafleur et al. 2017). Without weed pressure registered and good site conditions this was probably due to its less developed stand.

The stand structure of the native mix was not analyzed and only biomass was estimated at the end of the rotation. It had the lowest biomass yield (5 t ha^{-1} yr^{-1}). It was planted mainly for nature conservation and risk diversification, as a species mix improves biodiversity and is more resilient to climate change (Dhillon and Wuehlisch 2013). Consequently, for this very reason the stand structure developement of such diverse bioenergy stands in terms of inter-specific competition and single species suitability should be considered in future research. Personal observation indicate that the biomass of the mix could be greater when choosing another species composition, as some species showed a good growth (e.g. sallow), whereas other species hardly grew (e.g. maple).

The first two years, alder and black locust showed the highest biomass growth. Planted as saplings, they might had an advantage over poplar and willow. However, with this planting technique, roots can be bent, and tree development might be affected. Then willow and poplar cuttings might have an advantage since their newly formed root systems developed naturally. Root studies on the same site showed no malformation of the root systems for none of the species (Wagener et al. 2013), however, only single excavations were made. In the third year, black locust and alder showed an overall growth reduction maybe due to frost for black locust and maybe water limitation for alder. Poplar outpaced alder and black locust in this year.

All tree species performed best at the end of the first four-year rotation. They very likely had not yet reached their maximum biomass growth, what was mostly evident for willow that did not yet fully occupy the available space. Heinsoo et al. (2001) already indicated a maximum productivitiy in later years. Furthermore, the yields of all species are expected to be higher in the following rotations (cp. Section 5.2.4).

5.2.4 Management implications

A rotation length and initial plant density attuned to species and site as a function of canopy closure can increase biomass production as long as a competition-induced decrease in plant or stem growth and mortality are taken into account (Bullard et al. 2002, Amichev et al. 2010).

Poplar Max 3 showed a high growth and low size assymmetric competition througout the rotation, demonstrating that the design and the conditions of the study site suited this species. Furthermore, its evenly structured stand is easier to harvest than stands with a high differentiation rate. The same holds true for poplar Androscoggin, although it was only measured in the last year of the rotation.

Mainly black locust but also alder showed a low intra-specific competitiveness and developed an uneven stand. A lower planting density for these species might reduce the size variability and mortality and, thus, would save planting costs. Nevertheless, after four years black locust's biomass production was the second highest among species, although it probably suffered from late-frost in spring, as this species is well adapted to a continental and dry climate. Further investigations on the next rotations and locations with late-frost risk are necessary to be able to make reliable statements. Alder is best suited for wet to humid soils and less suitable for longer dry (Vares et al. 2004). The lack of rain in the third year may have reduced the growth of alder, yet it showed moderate growth among species and its yield was within expected yields.

Willow's stands showed a good growth and no mortality, but biomass was low and only 50% of that of poplar. An increased final yield of willow might be reached either by extended rotation periods or early coppicing, which can promote multiple-shoot regrowth and ealier canopy closure because trees benefit from the already established root system (Laureysens et al. 2003, Laureysens et al. 2005, Guidi Nissim et al. 2013).

The native mixture showed low growth and, like willow, was only 50% of that of poplar. Therefore, the planting of this tree mixture would not be recommended for farmers unless there are other ecological or economic reasons for a tree mixture, e.g. if this variant is recognized as a nature conservation service (Wagener et al. 2013) or remunerated as a social service (cp. Section 1.3).

In Scheyern, the biomass harvest was already carried out after 4 years and this short rotation period was chosen for project planning reasons. Extending rotation cycles would enhance productivity of all species, which very likely had not yet reached their maximum growth rate. For poplar a minimum rotation length of 5–10 years is recommended (Kauter et al. 2003, Hauk et al. 2014). The rotation lengths of black locust and alder need to be carefully considered as well. Alder and black locust are commonly planted in short rotation forestry (SRF) with rotation lengths between eight and 20 years (McKay 2011). Longer rotation lengths further increase wood quality of the wood chips because higher diameters lower the proportion of bark relative to wood (Hauk et al. 2014). This also decreases the removal of nutrients per amount of wood, less impairing site fertility (Hytönen and Saarsalmi 2009). However, the already large diameters within black locust stands (SBDs up to 9.3 cm) might be problematic when harvesting with a mowing cutter. If direct chipping harvesting is nonexecutable due to high SBDs, other harvesting techniques (e.g. forest harvester) may be necessary. As these techniques are more expensive (Hauk et al. 2014), costs have to be compared with profit of the higher biomass.

In the following rotations, biomass development may be even higher, because trees benefit from the already established root system. Hauk et al (2014) reported an average biomass increase of 12.5% for black locust, poplar and willow from the first to the second rotation; Wittwer and Stringer (1985) reported an increase of 29% for alder. Carl et al. (2017) found that on a single tree basis H of black locust was greater for a given diameter in resprouts than in shoots before cutting. In the following rotations, growth may alter in for example resprouting, survival rate, HD ratios and due to weather conditions. Therewith, biomass production and stand structure may differ to the first rotations possibly resulting in a different suitabilty as well as species ranking. Further investigations on subsequent rotation are highly needed. Because of gene-environment interactions, species performances may differ at other locations and management regimes, which hast to be an issue of future research as well.

5.3 ALLEY STRUCTURE, FARMING SYSTEM AND SITE EFFECTS ON TREE AND STAND DEVELOPMENT

This section discusses influences on species growth due to the alley structure (Section 5.3.1) and the farming system including reflections on soil conditions (Section 5.3.2).

5.3.1 Alley structure influences

In the special case of a linear simultaneous agroforestry system with alternating crop strips, trees are exposed to differing growth conditions. On row borders, trees may be more open-grown, and thereby more exposed to sunlight and wind-loading regimes than those of the inner rows. Zavitkovsk (1981) recognized an increased diameter, single tree dry weight, foliage weight, and leaf area index of border rows and primarily explained it by border trees being more exposed to sunlight than inner trees. Likewise, Lamerre et al. (2015) detected a higher diameter at border rows in a 6-year rotation AFS and a higher number of shoots in a 3-year rotation AFS. In line with this, border trees in the present study had a higher mean SBD than inner tress, except for willow. Willow's mean SBD of border rows was lower (organic) or similar (conventional) compared to inner rows (Huber et al. 2016). The positive influence of space and light at border rows was probably less pronounced, because willows canopy was not yet closed. Based on a selection (not the stand average; Huber et al. 2017), for all species H was greater on border rows as well. However, in contrast to Verwijst and Telenius (1999) no differences in the SBD-M allometric relation between trees from border and inner rows could be found (Huber et al. 2017). Therewith the biomass functions were applied on all trees equally. With border trees having higher diameters, a higher tree biomass was estimated. In addition, for all species except organic poplar, border rows had a higher number of shoots. Combining shoot number and SBD, the yield increased at the border rows by 18–111% (except organic willow with -2%) and was most visible for conventional poplar Max 3 and lowest for organic willow (Table 5). Although willow developed more shoots at border rows, the lower or same SBD enhanced its yield to a lower extent. If the average yields of the entire strip are calculated (1/3 border rows, 2/3 middle rows), the average total yield of the trees increases by 6 to 37% (organic willow excluded) in comparison to the yields without edge effects (Table 5).

The yields determined by allometric functions were overestimated for almost all tree species and slightly underestimated only for poplar clones at the conventional system. If this were not the case, conventional poplar Max 3 might have shown a higher total strip yield than conventional black locust. Although willow was overestimated by about 30 %, it still had the lowest biomass production on strip level.

Differences of shoot numbers and mean SBD between row positions were only significant at conventional fields, indicating that the applied fertilizer at the adjacent crop fields may had strengthened the edge effect. Lamerre et al. (2015) also mentioned a higher nutrient availability for border trees. As the unfertilized organic fields showed a positive edge effect as well, light and space might have a main control over growth.

In conlusion, as border rows accounted for one third of the tree strip, the yields are highly increased compared to a single field plantation. Thus, edge effects, which are normally neglected in studies of tree plantations/SRC, strongly influence SRAFS yields. Due to higher yields in SRAFS compared to SRC, it may economically more advantageous for farmers to use SRAFS instead of SRC. Regarding a possible decrease in agricultural crop production in the direct interaction zone next to the trees (Hülsbergen et al. 2012, Wagener et al. 2013) due to competition for light and water, this yield increase must be included in economic calculations.

Table 5: Mean annual biomass increment (MAI) estimated by harvesting (Inner_H) and by using allomtric equations (Inner_E, Border_E, Strip_E; from Huber et al. 2017) after four years of growth for different tree species under organic and conventional farming. The MAI of the differently positioned rows (inner and border rows) as well as the entire strip are presented separately. The strip average is calculated assuming that 1/3 of the strip consists of border rows (two of six rows per strip) and 2/3 of the strip consists of inner rows (four of six rows per strip). The percentage increase over the value of the inner rows is shown in brackets.

Farming system	**Rows**	**MAI ($t\ ha^{-1}\ yr^{-1}$)**				
		Black alder	Black locust	Poplar Androscoggin	Poplar Max 3	Willow Inger
Conventional	Inner_H	7.6	9.7	10.5	8.6	3.9
	Inner_E	8.4	10.4	10.0	8.3	5.1
	Border_E	10.7 (28)	15.1 (41)	16.8 (67)	17.5 (111)	7.2 (41)
	Strip_E	9.2 (9)	11.7 (14)	12.3 (22)	11.4 (37)	5.8 (14)
Organic	Inner_H	7.4	8.1	-	10.9	6.4
	Inner_E	8.5	10.1	-	12.3	8.5
	Border_E	10.4 (22)	15.1 (50)	-	14.5 (18)	8.3 (-1)
	Strip_E	9.1 (7)	11.7 (17)	-	13.0 (6)	8.4 (0)

5.3.2 Influences of farming system and site conditions

At the Scheyern research farm, agricultural crop yields are higher under conventional than under organic farming (Küstermann et al. 2010, Lin et al. 2016). Therewith, system differences in Scheyern were expected to be reflected in tree and stand growth as well, although tree strips were managed extensively without fertilization and weed was controlled on both conventional and organic fields in the first growing season.

Soil analysis revealed a similar nutritional status between the systems, although the previous long-term cultivation differed. Allometric equations did not differ between trees at the organic and conventional system and at the end of the rotation tree yields of middle rows were not enhanced in the conventional farming systems. Indeed, willow and poplar Max 3 inner rows had a significantly higher biomass at the organic system. This was probably a locational rather than a management effect. However, for poplar and willow, tree traits diverged more between border and inner rows under conventional farming. This led to high yields of border rows despite the low biomass of inner rows for this system. This may indicate that border trees benefit from fertilizer of the adjacent crop fields. Also other studies reported that fertilization can promote biomass growth (Heilman and Fu-Guang 1993, Labrecque et al. 1998, Welham et al. 2007, Guidi Nissim et al. 2013, Georgiadis et al. 2017) and alter tree allometry (Heinsoo et al. 2002). Likewise, yields of different willow and poplar clones can differ at local scale due to varying soil properties (Hofmann-Schielle et al. 1999, Boehmel et al. 2008, Fortier et al. 2010, Lafleur et al. 2017).

Border rows of black locust and alder under conventional faming did not show higher values than border rows under organic farming. Generally, black locust and alder responded much lower to farming system and locational variation than poplar and willow, indicating a higher yield stability across different soil and nutrient conditions. Probably this was because they are able to cover the use of nitrogen from their symbiotic fixation. Black locust can adapt to different habitat conditions and symbiotic fixation by Rhizobium bacteria is stated as the most important input for the nitrogen cycle in black locust stands (Vítková et al. 2015). However, sensitivity to locational differences and even an increase in biomass due to N fertilization was also found (Bongarten et al. 1992). Literature confirmed for alder its ability to adjust to differing environment conditions. Alders spend substantial parts of their assimilated energy to its symbiosis with actinomycetes for the self-support with N and to support a favorable rhizosphere which increases nutrient availability

(Dilly et al. 2000, Vares et al. 2004). Vares et al. (2004) argued that due to creating a favorable soil–root interface, productivity of an alder plantation on reclaimed oil-shale mining detritus and stands growing on fertile mineral soils was comparable. Thus, if nutrients are limited, these species may have advantages over poplar and willow, indicating their potential in organic farming or on less fertile sites. Furthermore, since the Bavarian Tertiary Hills differ in site conditions on a small-scale level, yield stability is also an important aspect.

In conclusion, without ongoing fertilization, previously organically managed fields can produce the same tree biomass as previously conventionally managed fields. However, a continuously removement of nutrients through harvesting might lower soil nutrient pools and impair biomass production after several rotations calling for fertilization (mineral or organic) in the longterm (Hofmann-Schielle et al. 1999, Georgiadis et al. 2017). Probably mainly poplar and willow may need additional fertilizers, whereas the drain on site nutrients may less impair black locust and alder.

6 CONCLUSION AND OUTLOOK

The focus of the work was to measure and model the development of fast-growing trees in SRAFS for energetic use. The determination of the yields and the yield dynamics of the different tree species and clones as accurately as possible is of outstanding importance for the assessment of the economic and ecological performance of SRAFS. Allometric models provide cost-effective methods for biomass prediction. Although fitting the data very well, our allometric functions with SBD only were restricted to specific SBD–H relations. Overall estimation accuracy was enhanced considerably by including H. The here developed functions may be applicable to other sites, mainly when tree height measurements are included. However, for trees differing too much from diameters used for parametrization, estimation can be too biased. Further research is needed to validate these functions at other sites.

For the first time, experimental data on biomass development were presented for the cool-humid climate of the Bavarian tertiary hills. The results differ from those at other locations in Germany due to different soil-climatic conditions, e.g. post-mining sites in Brandenburg. Still, the here reported yields of the different tree species fit well into the middle to upper range of values reported in literature, indicating their suitability to the given conditions. However, willow‘s biomass was up to 50% lower than that of poplar, which could be optimized by early coppicing. Therefore, yields are expected to be higher in the following rotations. Generally, higher yields may be achieved in the next rotations due to the already established root system. Furthermore, higher mean annual increment would be probably achieved by extending rotation periods. However, technical restrictions by tree diameter and the late revenues may put a limit to it. The intra-specific competition in black locust, and to a lesser extent in alder, proposes a lower planting density. All these suggestions remain to be tested in future investigations. Finally, the mixed species stand was studied only in their mean biomass production. Their biomass production and environmental benefits demand more research.

The border rows highly increased the overall tree yields of the agroforestry system and probably fertilization on adjacent fields at the conventional system further enhanced this effect for poplar and willow. Nitrogen fixing black locust and alder were less sensitive to farming system or site variability, highlighting their potential on less fertile sites. In general, excluding the edge effect, previous land management did not influence the biomass production in the presence. For the first time it was proven that after many years of organic farming the same tree yields can be achieved in organic SRAFS as in conventional SRAFS. Thus, reducing the need for external inputs such as fertilizer and pesticides, short-rotation agroforestry systems are a promising option in low-input and organic farming. This is underlinded by the high nitrogen and energy use efficiencies found for those systems (Lin et al. 2016a, b).

The shortage of fossil energy sources, the growing conflict between environmental and economic impacts in agriculture, and the threatening climate changes call for methods that combine the protection of natural resources with food and renewable energy production. SRAFS are an integrated land-use system that can combine nature resource protection with food and bioenergy production. Optimally with a facilitating effect on crop and tree yields. Hence, SRAFS would be one way to meet the challenge of limited land availability. Despite its immense potential for ecosystem and socioeconomic balances, agroforestry is still largely ignored in national and international policies. „This has endangered important traditional agroforestry systems, and currently prevents European farmers adopting modern agroforestry innovations“ (Dupraz et al. 2005). Now, the challenge is to shifting policy and investment priorities to support agroforestry practice and their further scientific exploration.

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8 TABLES AND FIGURES

9 LIST OF ACRONYMS

AFS	Agroforestry systems
C	Carbon
C_{org}	Organic carbon
CO_2	Atmospheric carbon dioxid
CAL	Calcium acetate lactate
CAP	Common agricultural policy
DBH	Diameter at breast height (in 1.30 m above soil)
DWD	Deutscher Wetterdienst
EC	European Commission
EU	European Union
FNR	Fachagentur Nachwachsende Rohstoffe
GCA	Grass-clover-alfalfa
GHG	Greenhouse gas
H	Tree height
HD	Height-diamter
HNCV	AFS with high natural and cultural value
IPCC	Internation Panel of Climate Change
K	Potassium
Mg	Megagrams (1 Mg = 10^6 g)
N	Nitrogen
N_{org}	Organic nitrogen
N_2	Atmospheric nitrogen
t	Tonnes; woody biomass is defined as the total amount of woody living organic matter in trees expressed as oven-dry tons
P	Posphorus
PEC	Primary energy use
Pg	Petagrams (1 Pg = 10^{15} g)
R^2_{cond}	Conditional R^2, which describes the proportion of variance explained by both the fixed and random factors
RDP	Rural Development Programme
SBD	Stem base diameter

SIC	Soil inorganic carbon
SOC	Soil organic carbon
SRAFS	Short-rotation agroforestry system
SRC	Short-rotation coppice. In this work SRC referrs to plantations or to SRC elements in AFS

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B. Publication reprints

The next pages show reprints of the publications used in this thesis (see Section 4).

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ORIGINAL PAPER

Allometric tree biomass models of various species grown in short-rotation agroforestry systems

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Abstract Biomass equations for tree species and the early stages of growth used in short-rotation coppices and agroforestry systems are still lacking. Further, discussion about the structure and parameters of biomass equations are still ongoing. Yield estimations should be precise, while keeping efforts low. To determine the influence of tree species, farming system, and tree position (inner and outer row) on allometric relationships, we derived biomass equations for various tree species from organic and conventional silvoarable agroforestry systems with an alley-cropping configuration. The allometric equations were based on the power relationship between aboveground dry biomass and stem base diameter (SBD) as a single variable or in combination with tree height (H) and were calculated by log-linear mixed-effect regression. Equations span the third and fourth growth year of the first rotation and were validated on the fourth year. Neither farming system nor row position influenced allometric relationship, although biometric variables varied between trees from inner and outer rows. A general model across species explained 95% (R^2_{cond}) of the variation for tree dry weight or 97% (R^2_{cond}) with H as covariate. Yet, for the sake of precision, species-specific equations were necessary. The best fitting equation with only SBD as predictor had species-specific allometric factors and a general exponent across species. However, predicted yields were biased by 8–31%. Thus, functions incorporating H are recommended, as compensation for variances in height-diameter relationships due to the ontogenetic stage, site differences, or social status of the tree reduced the bias of biomass estimation (<10%).

Keywords Aboveground biomass · Poplar · Locust · Alder · Willow

Introduction

For the purpose of bioenergy production, short-rotation coppices (SRC) are gaining an increasing interest. In this context, yield potential plays a decisive role in economic viability and in ecological issues, e.g., nutrient and energy balances, carbon sequestration, and CO_2 mitigation (Al Afas et al. 2008; Karp and Shield 2008; Njakou Djomo et al. 2011). Short-rotation agroforestry systems (SRAFS), in which agricultural crop strips alternate with rows of short-rotation woody crops, are not widespread and less studied than SRC. However, their implementation is expected to result in various positive agroecological effects such as conservation of biodiversity, soil protection (Jose 2009), and an increase in biomass (Graves et al. 2007). This distinctive role and potential urges for special focus on SRAFS.

Besides biomass assessments at the end of rotation, knowledge of species-specific growth dynamics during rotation is crucial for identifying optimal harvest cycles and technologies (Böhm et al. 2011) and for assessing environmental influences (Arevalo et al. 2007) and the effects of different treatments (e.g., organic vs.

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conventional farming). Biomass estimation by harvesting is destructive and time-consuming (Al Afas et al. 2008), and therefore, the most common procedure is establishing biomass functions via regression analysis between the volume or biomass of a tree and easily measurable variables such as stem diameter and height (Muukkonen 2007). These relations can be expressed mathematically as allometric power models.

Biomass equations aim at gaining accurate estimates, while keeping a model as simple as possible to reduce sampling effort and assure biological plausibility and interpretability. In the recent literature, it is argued whether simple allometric models with diameter as single predictor should be preferred to more complex models with, for example, height as additional predictor (Sileshi 2014; Picard et al. 2015). A pivotal question is which allometric model holds across the whole ontogenetic development and, thus, across the whole range of tree size (Picard et al. 2015). In SRC trees span a limited tree size range and stand age, nevertheless there is uncertainty which effort (simple or complex allometry) assures accurate estimations and transferability to other stands.

Numerous allometric biomass equations have been developed for tree species grown in managed forest stands (Wirth et al. 2004; Zianis and Mencuccini 2004; Zianis et al. 2005; Fehrmann and Kleinn 2006; Muukkonen 2007), but fewer equations exist for woody species planted in short-rotation coppices in Europe. Only a few allometric studies have dealt with *Alnus glutinosa* (Hughes 1971; Verwijst and Telenius 1999; Johansson 1999, 2000) and *Robinia pseudoacacia* (Bongarten et al. 1992; Burner et al. 2006; Böhm et al. 2011); however, *Populus* (Laureysens et al. 2004; Zabek and Prescott 2006; Dillen et al. 2007; Al Afas et al. 2008) and *Salix* (Telenius and Verwijst 1995; Heinsoo et al. 2002; Nordh and Verwijst 2004; Sevel et al. 2012) species or clones have received more attention owing to their higher yields.

Furthermore, even fewer equations exist for small-diameter trees. Because biomass allocation patterns differ with tree age (Wirth et al. 2004), allometric equations generated from older trees are not applicable to trees whose diameter or height falls below the range of validity of a given model. In addition, functions using a standardized stem base diameter as predictor instead of the diameter at breast height (DBH, in 1.30 m above soil) must first be developed for trees shorter than 1.30 m. DBH might also be a poor biomass predictor for small trees taller than 1.30 m (Wirth et al. 2004), as it may be measured at any location in the crown. Here, the trunk is more tapered than that in the region below the crown (Sumida et al. 2013) or some species develop dichotomous branching.

In SRC or SRAFS, trees are densely planted. Under crowded condition, competition for sunlight leads to the development of greater height growth relative to growth in diameter (Niklas 1995) and to suppression of lateral branches (Unruh Snyder et al. 2007) compared to open-grown trees. Thus, biomass equations developed for natural forests may not be adequate (Tumwebaze et al. 2013) and new functions applicable to dense short-rotation coppices are needed. In the special case of SRAFS with an alley-cropping configuration, trees are also highly influenced by edge effects, which may affect their allometry, resulting in equation parameters differing between those in border rows and those in interior rows (Verwijst and Telenius 1999).

Also fertilization was proposed to influence allometry by increasing tree height and reducing shoot dry weight (Heinsoo et al. 2002). Hence, distinctive conditions in organic farming (e.g., nutrient limitations, weed competition) may alter tree biomass allometry.

Shoots from tree species in their first rotation and soil properties of the investigated organic and conventional silvoarable agroforestry systems were measured in an attempt to fill the gaps described above. The main objective is to evaluate the influence of farming system, row position, and tree species on allometric biomass functions while putting them into the context of allometric theories.

Materials and methods

Study area and plant material

The study was performed in a long-term field experiment with short-rotation agroforestry systems at the Scheyern experimental farm (48°30′N, 11°21′E) in Bavaria, southern Germany. The farm is located 460–490 m above sea level in Tertiary hills. Most soils have a loamy texture and are classified (WRB soil classification) as either Cambisols or Eutrochrepts with a thin layer of loess, Cambisol with sand and gravel subsoil or small-scale clay soils (Scheinost et al. 1993; Schröder et al. 2002). Meteorological data were obtained from the nearby Altomünster-Maisbrunn weather station (48°24′ N, 11°19′E) of the Deutscher Wetterdienst (DWD), 15 km from the experimental site. The climate is temperate, with annual average temperature of 8.7 °C and annual precipitation of 803 mm between 2009 and 2012. The long-term (1981–2010) average is 8.3 °C and 887 mm. Precipitation during the establishment phase in 2009 (May–July) was above average.

In 1992, the experimental farm had been subdivided into an organic (OS) and conventional farming systems (CS). OS is maintained as low-input system and since 2005 as organic arable farming without livestock. It is based on a seven-field crop rotation (with 29% grass-clover-alfalfa). Mineral nitrogen and chemico-synthetic plant protection products are omitted. Tillage is carried out with a moldboard plow. In contrast, CS is a high-input system with chemico-synthetic plant protection use, mineral nitrogen input and a simple structured crop rotation with 50% wheat, 25% forage maize, and 25% potato. Here conservation tillage is applied (no plowing, crop residue incorporation with a grubber, mustard catch crop). System differences in structure and production features led to significantly higher agricultural crops yields in CS (Küstermann et al. 2008, 2010).

In April 2009, agroforestry systems were established in 4 fields, two for each farming system. Using a randomized block design, three strips of different fast-growing tree species were planted on every field with a spacing of 30 m for the field crops in between (Fig. 1). Each strip was divided into plots per species consisting of 360 trees, planted in three 30 m-long double rows (8.25 m wide) accommodating an overall planting density of 17,778 cuttings ha^{-1}. Inter-row spacing was 0.75 m within double rows and 1.50 m between double rows. Intra-row tree spacing was 0.50 m.

The species studied were black alder (*A. glutinosa*), black locust (*R. pseudoacacia*), poplar clone *'Max 3'* (*Populus maximowiczii* × *P. nigra*), poplar clone *'Androscoggin'* (*P. maximowiczii* × *P. trichocarpa*), and willow clone *'Inger'* (*Salix triandra* × *S. viminalis*). All studied species belong to the functional group of pioneers with vigorous juvenile growth (Kauter et al. 2003). Poplar and willow cuttings, approximately 20 cm in length, were planted manually to a depth of 15 cm, leaving one or two buds above the soil surface. The other species, 70–90 cm in length, were planted manually as barerooted saplings. The tree strips were not manured, but weeds were controlled by herbicide application (CS) and mechanical weeding (OS) in the first year of establishment. No further weed control or fertilizer applications were provided.

Measurement and harvest of trees

Two datasets were used for model building and validation. The first was used to develop allometric models, the second to validate them. All measurements were taken on 12 plots for each species (3 plots × 2 fields × 2 systems), with the exception of *S. 'Inger,'* planted only on one field of each system (in total 6 plots) and of *P. 'Androscoggin,'* planted only on one conventional field (in total 3 plots).

In both datasets, stem base diameter (SBD in cm, 10 cm above the soil) was measured in two perpendicular directions using a caliper, and the mean value was used in further calculations. Tree height (H in m) was measured using a Vertex hypsometer. No dead trees were sampled. Sampling numbers and variable ranges are given in Table 1.

First dataset: In winter 2011 and 2012, in each species plot, a total of 9 leafless single-shoot trees of the outer and inner rows were harvested (3 in 2011, 6 in 2012) (Fig. 1; Table 1). For each shoot SBD, H and biomass were measured. *P. 'Androscoggin'* was measured only in 2012. Due to the loss of some trees, sample numbers differed with tree species.

Second dataset: In winter 2012, in each species plot on areas different to dataset 1, all shoots of 10 trees of the middle double row (2.25 m × 2.5 m area) were measured (SBD and H, Table 1). Afterward, all shoots were cut manually 10 cm above soil surface. However, more trees than measured were harvested (40 trees of each species plot, 2.25 m × 10 m area). All shoots from one harvested species plot defined one sample. The fresh weight of these samples was measured on site using a load cell (±50 g) suspended from the fork of a tractor. Yield at stand level (Mg ha^{-1}) was calculated.

All fresh biomass samples were shredded separately into wood chips and mixed thoroughly to get a representative

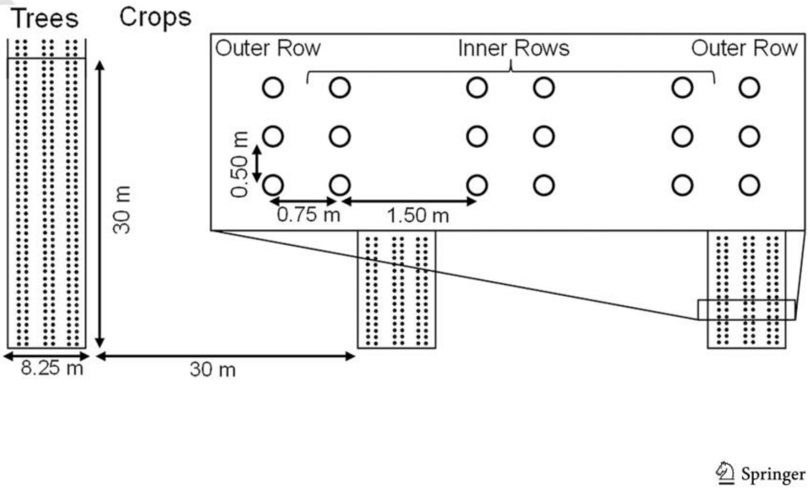

Fig. 1 Plant design of the agroforestry systems, showing the alternating tree and crop rows and the inner structure of the tree rows

Table 1 Summary statistics of the datasets used to develop (1) and to validate (2) allometric biomass equations

Tree species	Dataset	*n*	SBD (cm)			H (m)			HD (cm/cm)			M (kg or Mg)		
			Min	Max	Med	Min	Max	Med	Min	Max	Med	Min	Max	Med
A. glutinosa	1	91	1.7	7.6	4.5	1.3	7.2	4.6	67	153	104	0.1	5.3	1.2
	2	120	1.8	7.4	5.2	1.6	7.0	5.2	64	215	100	24.3	36.1	30.0
R. pseudoacacia	1	87	1.4	9.9	4.9	1.7	7.7	5.7	41	234	106	0.1	17.1	2.3
	2	120	1.1	9.3	4.1	0.5	8.9	4.7	46	217	119	28.3	52.3	32.8
P. 'Androscoggin'	1	18	2.9	7.9	4.9	5.9	8.7	7.9	106	203	159	0.4	5.3	2.7
	2	30	2.2	7.1	4.8	4.0	9.8	7.3	113	257	152	31.9	56.4	36.9
P. 'Max 3'	1	96	1.6	7.7	5.8	1.9	9.7	6.7	96	225	138	0.1	8.0	2.1
	2	120	1.0	7.0	5.0	3.1	9.1	7.5	96	232	159	29.0	50.5	35.8
S. 'Inger'	1	54	1.2	5.1	3.1	2.6	7.7	5.5	116	241	180	0.1	2.7	0.7
	2	60	1.7	5.8	3.9	3.5	7.3	6.1	117	224	161	11.5	28.1	20.7

Range of the variables stem base diameter (SBD), height (H), height:diameter ratio (HD) and aboveground (leafless) tree biomass (M), where *n* number of individual trees in the dataset, *Min* minimum, *Max* maximum, *Med* median. *M* in kg for dataset 1 (single tree level) and Mg for dataset 2 (stand level)

aliquot for the determination of dry matter content. Four 1 L subsamples were taken from each sample and dried in a forced air oven at 105 °C until constant mass was achieved. The mean dry matter content was used for the calculation. All biomass values are given as oven dry mass (M in kg or Mg).

Analysis of factors influencing tree allometry

In order to decide on the inclusion of farming system in the allometric models, it is influence on soil properties was analyzed. Therefore, at the beginning of the experiment in 2009, soil samples were taken of each species plot of each field at 0–30 cm depth (organic, $n = 33$; conventional, $n = 36$). Organic carbon (C_{org}) and organic nitrogen (N_{org}) were analyzed with the Dumas (1831) method, available phosphorus (P) and available potassium (K) with the calcium acetate lactate (CAL) method. The pH was also measured.

To decide on the inclusion of row position and tree species, their influence on biometric variables was also analyzed.

Mean differences of farming system, species, row position, as well as estimation method (harvested or by allometric models) were tested using generalized linear mixed-effect modeling to account for dependencies within the hierarchical dataset and for heteroscedasticity (Zuur et al. 2009). Including the random effect plot ID accounted for correlation of the row positions and for correlation of estimation methods for each species plot.

Model building

On the basis of a power function commonly used in allometric biomass studies (Niklas 1994), a choice of two model assumptions were applied to the dataset: (1) a simple allometric model with stem base diameter (SBD) as predictor of individual tree dry biomass and (2) one including tree height (H) as covariate:

$$M = \beta_0 \, \mathrm{SBD}^{\beta_1} \tag{1}$$

$$M = \beta_0 \, \mathrm{SBD}^{\beta_1} \, H^{\beta_2} \tag{2}$$

wherein M is the aboveground dry mass for a specific stem base diameter SBD and tree height H, β_0 the intercept (allometric factor), and β_1 and β_2 the slopes (allometric exponent). Whereas β_0 accounts for the basic morphological structure and for the initial offset of the tree, β_1 and β_2 describe the ratio of the relative growth rates between M and the explanatory variables (Pretzsch and Biber 2005). The allometric exponents reflect the actual size-dependent scaling of the organism and the necessary adjustment of biomass allocation for optimal physiological functioning (Pretzsch 2009).

Different equations for the inclusion of tree height were found in the literature (reviewed in Zianis et al. 2005), but the best description of our data (goodness of fit and likelihood ratio test, see 'Model building' section) was afforded by Eq. (2). As log-transformed SBD was moderate correlated with log-transformed height (Pearson's correlation coefficient = 0.70) and, consequently, with a low variance inflation factor (VIF = 1.9), the inclusion of H was considered appropriate.

The error structure of the data was analyzed using the likelihood approach outlined by Xiao et al. (2011) and Ballantyne (2013). The information criteria of the normal (additive error) ($AIC_{c\text{-norm}}$) and the lognormal (multiplicative error) ($AIC_{c\text{-logn}}$) regression were computed. The AICc (Burnham and Anderson 2002) is the small-sample-size-corrected Akaike information criterion (AIC; Akaike 1973). The analysis revealed a multiplicative lognormal error structure ($\mathrm{AIC}_{\text{c-norm}} - \mathrm{AIC}_{\text{c-logn}} = 467$) and required a linear regression on log-transformed data:

$$\ln M = \ln \beta_0 + \beta_1 \ln \mathrm{SBD} \quad (3)$$

$$\ln M = \ln \beta_0 + \beta_1 \ln \mathrm{SBD} + \beta_2 \ln H \quad (4)$$

The bias in the biomass estimation due to the retransformation into arithmetic units was corrected by multiplying the intercepts by a correction factor ($\mathrm{CF} = \exp^{\frac{\mathrm{RSE}^2}{2}}$) calculated from the residual standard error of the estimate (RSE) of the regression slope (Sprugel 1983).

To accommodate the hierarchical and clustered dataset and to incorporate among-tree as well as among-plot variation, linear mixed-effects models were fitted (Zuur et al. 2009). Applying restricted maximum likelihood (REML) regression technique, different mixed models based on the fixed variables SBD and H were established. Illustrating only one level of hierarchy for the sake of clarity, the statistical models according to Eqs. (3) and (4) are expressed as:

$$\ln M_{ij} = (\ln \beta_0 + \ln b_{0i}) + (\beta_1 + b_{1i}) * \ln \mathrm{SBD}_{ij} + \varepsilon_{ij} \quad (5)$$

$$\ln M_{ij} = (\ln \beta_0 + \ln b_{0i}) + (\beta_1 + b_{1i}) * \ln \mathrm{SBD}_{ij} + (\beta_2 + b_{2i}) * \ln H_{ij} + \varepsilon_{ij} \quad (6)$$

where β_0 (intercept), β_1 (slope for SBD), and β_2 (slope for H) are the coefficients associated with the fixed effects and b_0, b_1, and b_2 represent random effects. The residuals ε_{ij} are the remaining uncorrelated errors and were assumed to follow $N(0,\sigma^2)$. The additional indices i and j indicate that each observation j is nested within group i.

General allometric functions were fitted to identify a more general allometric pattern. Furthermore, farming system, row position and tree species were treated as fixed effects by adding dummy variables to evaluate differences in the coefficients.

In all steps described above, plot ID (to account for variance between plot means) and field were defined as random effects nested within each other. Each of the models was fitted separately for each combination of random effects on both intercept and slope.

Model selection

The assumptions of homoscedasticity and normality were verified by visual evaluation of residual scatter plots (residual vs. predicted values). The goodness of fit of the models was evaluated by the AIC, the Bayesian information criterion (BIC; Schwarz 1978), the marginal as well as the conditional coefficient of determination (R^2_{marg}, R^2_{cond}; Johnson 2014), the mean absolute percentage error ($\mathrm{MAPE} = \frac{100}{n}\sum_{i=1}^{n}\left(\frac{|\mathrm{M}_{\mathrm{observed}} - M_{\mathrm{predicted}}|}{\mathrm{M}_{\mathrm{observed}}}\right)$; Sileshi 2014), and by the 95% confidence intervals of the linear regression of predicted against observed biomass values. AIC and BIC are both penalized-likelihood criteria, whereas BIC imposes a penalty for additional parameters. R^2_{marg} describes the proportion of variance explained by fixed factors and R^2_{cond} the proportion of variance explained by both fixed and random factors (Johnson 2014). Sileshi (2014) proposes a MAPE >10% as unreliable; however, a cut of point is not yet defined. In the regression of predicted against observed biomass values, prediction errors are not significant if the 95% confidence intervals cover 0 for the intercept and 1 for the slope (Sileshi 2014).

The fixed effects included in the final models were selected using likelihood ratio tests applying maximum likelihood, as comparisons using reduced maximum likelihood are not valid when the fixed effects change. To test whether the random intercept and/or slope were necessary, each in turn was omitted from the model and a likelihood ratio statistic was calculated, contrasting the refitted model with the original model.

All computations and statistical analyses were performed with R software (R Core Team 2015). Linear mixed-effects analyses were performed with the R package 'nlme' (Pinheiro et al. 2014), post hoc analyses (Tukey's HSD test) with 'multcomp' (Hothorn et al. 2008).

Results

Factors influencing tree allometry

The two farming systems showed no significant difference in the initial nutrient status of the soil (Table 2; Appendix

Table 2 Soil properties at 0–30 cm depth in organic and conventional farming systems from the beginning of the experiment in 2009

Component	Unit	Organic farming Mean ± SE	Conventional farming Mean ± SE
C_{org}	%	1.17 ± 0.10[a]	1.11 ± 0.07[a]
N_{org}	%	0.11 ± 0.01[a]	0.11 ± 0.01[a]
pH		5.5 ± 0.2[a]	5.4 ± 0.1[a]
P	kg ha^{-1}	3.5 ± 1.9[a]	5.2 ± 1.4[a]
K	kg ha^{-1}	9.6 ± 2.0[a]	8.8 ± 1.4[a]

Mean organic carbon (C_{org}), organic nitrogen (N_{org}), pH, available phosphorus (P), available potassium (K), and the respective standard errors (SE)

[a] Farming systems sharing the same letter are not significantly different from each other (Tukey HSD, $p < 0.05$)

Table 9), although they were managed differently for more than 20 years. Only soil organic carbon and potassium were slightly higher in the OS, whereas phosphorus was slightly higher in the CS.

The biometric parameters of the trees differed between species and positions (Tables 1, 3; Appendix Table 10). The values were always higher for trees in the outer rows. Also crown shapes were different, with *S. 'Inger,' P. 'Androscoggin,'* and *P. 'Max 3'* having more thin and elongated crowns with monopodial branching, and *A. glutinosa* and *R. pseudoacacia* often developing dichotomous branching and correspondingly greater crown widths.

HD was much greater for the *Salicaceae* family (*P. 'Androscoggin,' P. 'Max 3,'* and *S. 'Inger'*) than for *A. glutinosa* and *R. pseudoacacia* (Table 1). All species showed a decline in H increment with increasing SBD (Fig. 2).

Allometric biomass models

By Eq. (5), which is based only on diameter, farming system did not have a significant influence on allometric relations. With the addition of H and tree species as covariates to the model (Eq. 6), farming system showed only a significant trend ($p < 0.1$). Considering the standard level of significance ($p < 0.05$), farming system was therefore not included as fixed effect. Accordingly, field and plot ID were chosen as random effects (Tables 4, 5) to account for the heterogeneity of the site (with respect to soil, nutritional status, and altitude) and the concomitant variance between the plots.

Tree position did not affect the allometric relations (Fig. 3), and its inclusion into the model revealed no significant improvement.

General models

The simplest allometric model with only SBD as explanatory variable and plot ID as random effect on the intercept (model 1, Table 4) exhibited much higher values for AIC and BIC than all other well-fitting models considering species identity. SBD described 91% of the single-tree dry-weight variance ($R^2_{\text{marg}} = 0.91$) and SBD plus random part explained 94% ($R^2_{\text{cond}} = 0.94$). Adding H as a second predictor (model 5, Table 5), AIC and BIC were highly reduced and the coefficient of determination increased. However, tree height explained only additional 2% of the variance.

Despite the good performance of the general model based on diameter, the estimated biomass for *A. glutinosa* and *P. 'Androscoggin'* was overestimated and underestimated for *R. pseudoacacia, P. 'Max 3,'* and *S. 'Inger'* (Fig. 3; Table 6).

The less biased estimations were obtained for members of the *Salicaceae* family (MAPE $\leq$ 19%), whereas for both *A. glutinosa* and *R. pseudoacacia*, they were biased by 35 and 20%, respectively (Table 7). The prediction error was significant only for *A. glutinosa* (Table 6).

Including H as second explanatory variable improved the biomass estimation of *A. glutinosa, P. 'Max 3,'* and *S. 'Inger,'* but impaired it for *R. pseudoacacia* and *P. 'Androscoggin'* (Table 7). The prediction error was significant for *R. pseudoacacia* (Table 6).

Species-specific models

Adding tree species as a fixed effect on the intercept (model 2 and 6) led to a significant improvement in the general model performances (likelihood ratio test, Eq. 5: $p < 0.001$, Eq. 6: $p < 0.001$), shown in higher R^2_{marg}, lower BIC and AIC (Tables 4, 5), and lower MAPE (Table 7). For the models with only SBD as explanatory variable, plot ID was the random effect that best explained the variance of the slope. This finding implicates that site differences perturbed the allometric exponent for each species more than the allometric factor. In contrast, when H was included, most variation due to site differences was explained by the intercept. This indicates that H explains part of the slope variance.

Table 3 Difference between stem base diameter (SBD), height (H), and aboveground (leafless) biomass (M) of trees grown in the outer and inner rows of a tree strip

Tree species	Mean SBD (cm) ± SE		Mean H (m) ± SE		Mean M (kg) ± SE	
	Inner row	Outer row	Inner row	Outer row	Inner row	Outer row
A. glutinosa	4.5 ± 0.3^{a}	4.6 ± 0.3^{a}	4.9 ± 0.3^{a}	4.6 ± 0.3^{a}	1.4 ± 0.2^{a}	1.5 ± 0.2^{a}
R. pseudoacacia	4.6 ± 0.3^{b}	5.6 ± 0.5^{a}	5.0 ± 0.2^{b}	5.8 ± 0.4^{a}	2.8 ± 0.4^{b}	4.4 ± 0.7^{a}
P. 'Androscoggin'	4.8 ± 0.4^{b}	6.2 ± 0.7^{a}	7.6 ± 0.3^{a}	7.8 ± 0.5^{a}	2.2 ± 0.4^{a}	3.5 ± 0.7^{a}
P. 'Max 3'	4.5 ± 0.2^{b}	5.4 ± 0.4^{a}	6.3 ± 0.3^{b}	7.2 ± 0.5^{a}	2.2 ± 0.2^{b}	3.4 ± 0.5^{a}
S. 'Inger'	2.9 ± 0.2^{b}	3.5 ± 0.4^{a}	5.2 ± 0.3^{a}	5.9 ± 0.5^{a}	0.7 ± 0.2^{b}	1.1 ± 0.3^{a}

^{a,b} Rows sharing the same letter are not significantly different from each other (Tukey HSD, $p < 0.05$)

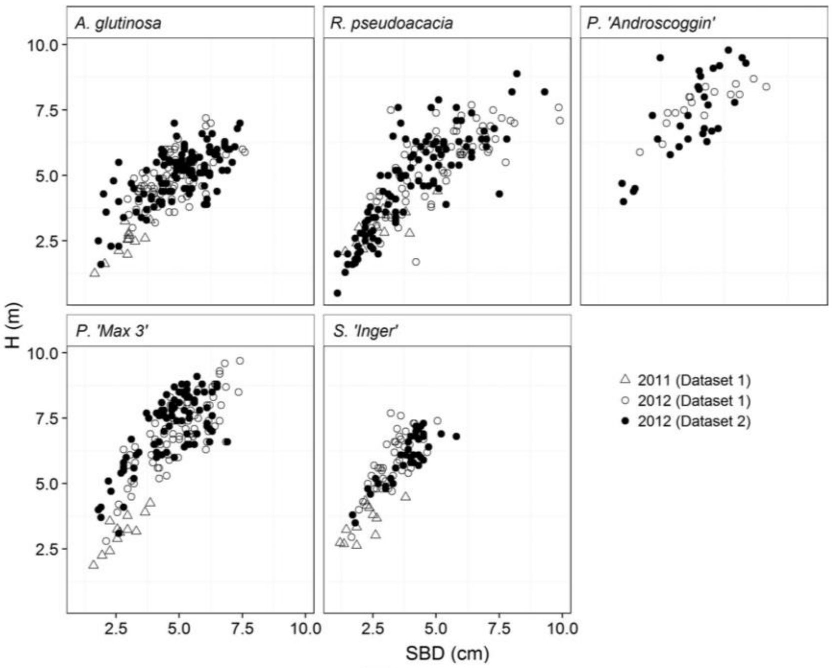

Fig. 2 Relationship between the stem base diameter (SBD) and the tree height (H) for the different tree species and clones of different years where dataset 1 refers to the data used for establishing the model, whereas dataset 2 was applied for model validation

For Eq. (5), the models with species-specific slopes (model 3) or species-specific intercepts and slopes (model 4) had a performance worse than the model with species-specific intercepts (model 2) (Table 4). For both models 2 and 3, the relative change in biomass in relation to the relative change in diameter was greatest in *R. pseudoacacia,* followed by *S. 'Inger,' P. 'Max 3,' P. 'Androscoggin,'* and *A. glutinosa.* Applying model 4 led to a change in the species order for biomass increment (in dependence on diameter increment) and favored *P. 'Max 3'* (Fig. 3).

For Eq. (6), different models with species-specific and fixed coefficients (for H, SBD, or both) were investigated. Only the two best models (model 6 and 7, Table 5) are presented in this study. SBD was the most important predictor, as it explained 95% of the single-tree dry-weights' variance, whereas tree height explained only additional 2% of the variance of M. However, the inclusion of H improved the model performance, as indicated by an overall reduction of RSE, a decrease in BIC and AIC, a higher R^2 (Tables 4, 5), and a lower MAPE (Table 7). The model with species-specific slopes (model 7) had a performance worse than model 6, and for *A. glutinosa* it resulted in a significant prediction error (Table 6). In model 6, *R. pseudoacacia* again had the highest allometric factor and the ranking between *P. 'Max 3'* and *S. 'Inger,'* as well as between *P. 'Androscoggin'* and *A. glutinosa* changed. Model 6 revealed no significant prediction error.

Model validation

For validation, the best fitting model of Eq. (5) (model 2) and 6 (model 6) was used (Table 8). Using model 2 revealed a bias ≤15% for all species, with the exception for *S. 'Inger'* (31%). For model 6, bias was ≤10%.

Except for *P. 'Androscoggin*,' biomass estimated by allometric functions was generally higher than biomass assessed by harvesting. The models are based on trees from the third and fourth growth year, but were applied on trees only from the fourth year. As H increment decreases with increasing diameter (Fig. 2), biomass was overestimated. Model 6, however, reduced this overestimation. In contrast, for *P. 'Androscoggin'* only the fourth year was used for function parametrization. Therewith, model 2 showed good results with low underestimation (4%). However, the use of the general slope for H in model 6 further reduced the estimated biomass (9%).

Overestimation of willow by model 2 was particularly high, although the previous fitting was highly precise (Table 7). This may be the result of the greater H for a given SBD of trees used for function parametrization than for validation (Fig. 2). Including H as predictor (model 6) corrected for varying biomass increments due to differences in H development. Similarly, estimations for *P. 'Max 3'* by model 6 are higher than by model 2, as H is on average higher in the validation dataset.

With the overestimation of *P. 'Max 3'* and underestimation of *P. 'Androscoggin,'* the ranking of the highest

Table 4 Summary of mixed models predicting the aboveground (leafless) biomass across the tree species in dependence of the stem base diameter (SBD)

Model	Tree species	Coefficients fixed effect[12]		Random effect	SD random effect		RSE	*df*	AIC	BIC	R^2_{marg}	R^2_{cond}
		Antilog $\beta_0 \pm$ SE	$\beta_1 \pm$ SE		b_0	b_1						
$M = (\beta_0 + b_0) * \mathrm{SBD}^{\beta_1} + \varepsilon_{ij}$												
1		0.035 ± 0.002***	2.577 ± 0.037***	1|Plot ID	0.206		0.214	4	23.35	38.72	0.91	0.95
$M = \beta_0 * \mathrm{SBD}^{(\beta_1 + b_1)} + \mathrm{Species} + \varepsilon_{ij}$												
2			2.603 ± 0.036***	SBD-1|Plot ID		0.067	0.212	8	−12.58	18.05	0.95	0.95
	A. glutinosa	0.025 ± 0.002^{a}										
	R. pseudoacacia	0.041 ± 0.006^{c}										
	P. ‘*Androscoggin*’	0.032 ± 0.003^{b}										
	P. ‘*Max3*’	0.036 ± 0.004^{bc}										
	S. ‘*Willow*’	0.037 ± 0.004^{bc}										
$M = \beta_0 * \mathrm{SBD}^{(\beta_1 + b_1)} + \mathrm{SBD} : \mathrm{Species} + \varepsilon_{ij}$												
3		0.035 ± 0.002***		SBD-1|Plot ID		0.064	0.215	8	−0.42	30.21	0.95	0.95
	A. glutinosa		2.377 ± 0.042^{a}									
	R. pseudoacacia		2.673 ± 0.034^{c}									
	P. ‘*Androscoggin*’		2.533 ± 0.054^{b}									
	P. ‘*Max3*’		2.631 ± 0.034^{bc}									
	S. ‘*Willow*’		2.638 ± 0.046^{bc}									
$M = \beta_0 * \mathrm{SBD}^{(\beta_1 + b_1)} * \mathrm{Species} + \varepsilon_{ij}$												
4				SBD-1|Plot ID		0.067	0.211	12	−1.18	44.62	0.95	0.96
	A. glutinosa	0.026 ± 0.003^{a}	2.576 ± 0.088^{a}									
	R. pseudoacacia	0.050 ± 0.017^{b}	2.532 ± 0.107^{a}									
	P. ‘*Androscoggin*’	0.037 ± 0.007^{ab}	2.521 ± 0.214^{a}									
	P. ‘*Max3*’	0.031 ± 0.007^{a}	2.752 ± 0.112^{a}									
	S. ‘*Willow*’	0.041 ± 0.010^{ab}	2.552 ± 0.130^{a}									

β_0, β_1 = coefficient estimates of fixed effects, SD = standard deviation, b_0, b_1 = random effects, SE = standard error, RSE = residual standard error, *df* = degrees of freedom, AIC = Akaike information criterion, BIC = Bayesian information criterion, R^2_{marg} = marginal and R^2_{cond} = conditional coefficient of determination

[1] Significance codes according to a p value: $^{***}p < 0.001$

[2] Values sharing the same letter are not significantly different from each other (Tukey HSD, $p < 0.05$)

Table 5 Summary of mixed models predicting the aboveground (leafless) biomass across the tree species in dependence of the stem base diameter (SBD) and the height (H), where β_0, β_1, β_2 = coefficient estimates of fixed effects, SD = standard deviation, b_0 = random effects, SE = standard error, RSE = residual standard error, df = degrees of freedom, AIC = Akaike information criterion, BIC = Bayesian information criterion, R^2_{marg} = marginal and R^2_{cond} = conditional coefficient of determination

Model	Tree species	Coefficients fixed effect[1][2]			Random effect	SD random effect	RSE	Df	AIC	BIC	R^2_{marg}	R^2_{cond}
		Antilog $\beta_0 \pm$ SE	$\beta_1 \pm$ SE	$\beta_2 \pm$ SE		b_0						
$M = (\beta_0 + b_0) * SBD^{\beta 1} * H^{\beta_2} + \varepsilon_{ij}$												
5		0.024 ± 0.002***	2.107 ± 0.051***	0.631 ± 0.055***	1|Plot ID	0.183	0.179	5	−87.02	−67.89	0.93	0.97
$M = (\beta_0 + b_0) * SBD^{\beta_1} * H^{\beta_2} + Species + \varepsilon_{ij}$												
6			2.087 ± 0.053***	0.657 ± 0.057***	1|Field/ Plot ID	0.049 0.071	0.179	9	−119.80	−81.65	0.96	0.97
	A. glutinosa	0.020 ± 0.001^{a}										
	R. pseudoacacia	0.030 ± 0.003^{c}										
	P. '*Androscoggin*'	0.019 ± 0.002^{a}										
	P. '*Max3*'	0.024 ± 0.003^{b}										
	S. '*Willow*'	0.022 ± 0.002^{ab}										
$M = (\beta_0 + b_0) * SBD^{\beta_1} * H^{\beta_2} + SBD : Species + \varepsilon_{ij}$												
7		0.024 ± 0.002***		0.652 ± 0.056***	1|Field/ Plot ID	0.049 0.071	0.181	9	−110.23	−72.08	0.96	0.97
	A. glutinosa		1.963 ± 0.050^{a}									
	R. pseudoacacia		2.218 ± 0.026^{c}									
	P. '*Androscoggin*'		1.964 ± 0.043^{a}									
	P. '*Max3*'		2.082 ± 0.029^{b}									
	S. '*Willow*'		2.000 ± 0.043^{ab}									

[1] Significance codes according to a p value: *** $p < 0.001$

[2] Values sharing the same letter are not significantly different from each other (Tukey HSD, $p < 0.05$)

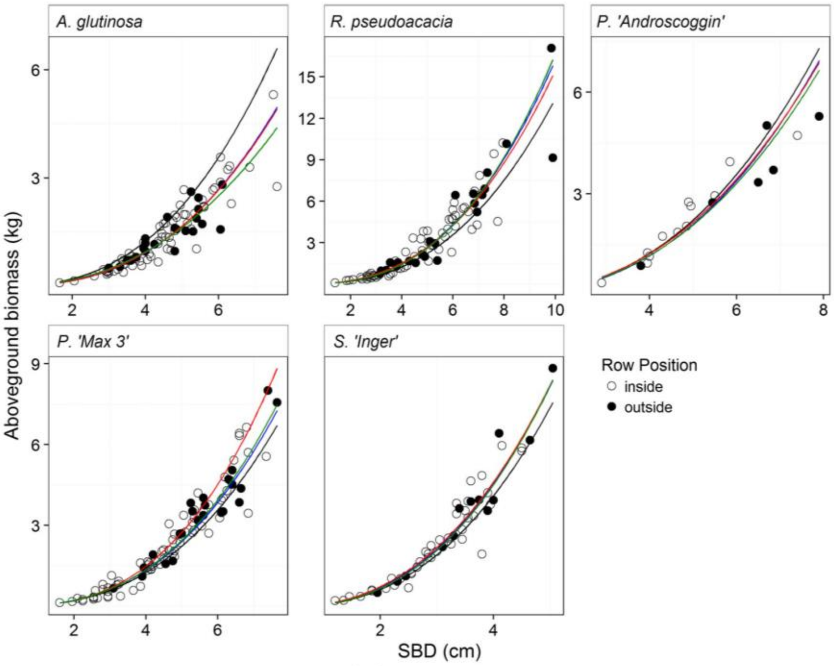

Fig. 3 Relationship between the stem base diameter (SBD) and the aboveground biomass of different species with *marked row* positions. The models were fitted across species (*black*, model 1), with species-specific intercept (*blue*, model 2), slope (*green*, model 3), and slope and intercept (*red*, model 4). (Color figure online)

Table 6 Test of significance of the intercept (*a*) and slope (*b*) of the regression of predicted against observed aboveground (leafless) tree biomass values

Model	Coefficient	Coefficient mean and 95% confidence interval				
		A. glutinosa	*R. pseudoacacia*	*P.* 'Androscoggin'	*P.* 'Max 3'	*S.* 'Inger'
1	*a*	0.17 (−0.06, 0.40)	0.17 (−0.36, 0.69)	−0.33 (−1.18, 0.53)	0.18 (−0.36, 0.72)	0.06 (−0.53, 0.66)
	b	**1.21 (1.07, 1.34)**	0.79 (0.51, 1.06)	1.21 (0.84, 1.58)	0.81 (0.53, 1.10)	0.82 (0.36, 1.27)
2	*a*	0.12 (−0.13, 0.37)	0.19 (−0.39, 0.76)	−0.32 (−1.26, 0.62)	0.19 (−0.40, 0.78)	0.07 (−0.58, 0.72)
	b	0.91 (0.76, 1.06)	0.95 (0.65, 1.25)	1.15 (0.74, 1.55)	0.88 (0.56, 1.19)	0.90 (0.41, 1.40)
3	*a*	0.22 (−0.31, 0.47)	0.11 (−0.48, 0.69)	−0.24 (−1.19, 0.71)	0.17 (−0.43, 0.77)	0.06 (−0.60, 0.72)
	b	**0.66 (0.81, 0.96)**	0.97 (0.66, 1.28)	1.10 (0.69, 1.51)	0.91 (0.59, 1.23)	0.91 (0.41, 1.41)
4	*a*	0.13 (−0.11, 0.37)	0.26 (−0.30, 0.87)	−0.23 (−1.14, 0.68)	0.09 (−0.48, 0.66)	0.08 (−0.55, 0.71)
	b	0.90 (0.75, 1.04)	0.90 (0.60, 1.19)	1.10 (0.70, 1.49)	0.96 (0.66, 1.26)	0.87 (0.40, 1.35)
5	*a*	0.14 (−0.03, 0.32)	0.26 (−0.14, 0.66)	0.00 (−0.66, 0.64)	0.20 (−0.22, 0.61)	0.09 (−0.37, 0.54)
	b	1.06 (0.96, 1.17)	**0.68 (0.46, 0.89)**	1.19 (0.91, 1.48)	0.88 (0.66, 1.10)	0.95 (0.60, 1.29)
6	*a*	0.13 (−0.07, 0.32)	0.34 (−0.11, 0.79)	0.02 (−0.72, 0.75)	0.20 (−0.27, 0.66)	0.08 (−0.43, 0.59)
	b	0.90 (0.79, 1.02)	0.86 (0.62, 1.10)	1.00 (0.68, 1.32)	0.88 (0.64, 1.13)	0.89 (0.50, 1.28)
7	*a*	0.18 (−0.02, 0.39)	0.21 (−026, 0.68)	0.14 (−0.63, 0.90)	0.21 (−0.27, 0.69)	0.10 (−0.43, 0.63)
	b	**0.84 (0.72, 0.96)**	0.91 (0.67, 1.16)	0.96 (0.63, 1.30)	0.89 (0.63, 1.14)	0.86 (0.46, 1.26)

If the 95% confidence intervals (figures in parenthesis) of *a* cover 0 and of *b* cover 1, then prediction errors are not significant. Significant errors are in bold. Coefficient mean indicates overestimation ($b > 1$) or underestimation ($b < 1$)

Table 7 Bias of the model prediction, calculated by the mean absolute percentage error (MAPE)

Tree species	MAPE (%)						
	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7
A. glutinosa	35.0	16.7	17.9	16.8	20.1	14.1	13.8
R. pseudoacacia	20.2	18.2	18.0	18.3	20.7	15.5	15.5
P. 'Androscoggin'	3.2	3.1	3.1	3.1	4.7	2.9	3.2
P. 'Max 3'	18.7	17.8	17.9	17.3	13.8	13.7	13.9
S. 'Inger'	7.9	7.5	7.4	7.5	7.7	6.6	6.8

Table 8 Comparison between estimated aboveground (leafless) biomasses (harvested and calculated by model 2 and 6) and the respective standard errors (SE) for different tree species

Tree species	Biomass (Mg ha^{-1}) ± SE		
	Harvested	Model 2	Model 6
A. glutinosa	$30.0 \pm 2.6^{b,\ A}$	$33.7 \pm 1.5^{ab,\ B}$	$32.2 \pm 1.5^{ab,\ AB}$
R. pseudoacacia	$35.4 \pm 4.0^{bc,\ A}$	$40.8 \pm 3.5^{ab,\ B}$	$37.1 \pm 3.6^{ab,\ AB}$
P. 'Androscoggin'	$41.8 \pm 5.3^{c,\ B}$	$40.1 \pm 2.2^{ab,\ AB}$	$37.9 \pm 2.2^{ab,\ A}$
P. 'Max 3'	$38.8 \pm 3.4^{bc,\ A}$	$41.2 \pm 2.2^{b,\ AB}$	$42.7 \pm 2.3^{b,\ B}$
S. 'Inger'	$20.7 \pm 4.1^{a,\ A}$	$27.1 \pm 2.0^{a,\ B}$	$21.1 \pm 2.1^{a,\ AB}$

^{a,b,c} Species sharing the same letter are not significantly different from each other (Tukey HSD, $p < 0.05$)

^{A,B} Method sharing the same letter are not significantly different from each other (Tukey HSD, $p < 0.05$)

yielding species changed and potentially led to misleading conclusions about the species yield potential.

Discussion

Influence of alley structure and farming system

In a linear simultaneous agroforestry system with alternating crop strips, trees are exposed to differing growth conditions. This situation makes it worthwhile to distinguish between biomass equations for trees of outer and inner rows. On row borders, trees may be more open-grown, and thereby, more exposed to sunlight and wind-loading regimes than inner row trees. Verwijst and Telenius (1999) detected differences in the allometry of trees from border and inner rows. In our case, the mean values of the biometric variables (SBD, H, and M) differed significantly between the inner and the border trees, but no differences in the allometric relations could be found.

The nutritional status of the forest or plantation site was also proposed to influence allometry. Heinsoo et al. (2002) showed that fertilization with N, P, and K led to an increase in shoot height but also reduced shoot dry weight compared to unfertilized shoots. Here, the tree strips were not fertilized and the nutritional status was not different between the systems, even though the previous long-term cultivation differed. No difference between the allometry of the trees in organic and conventional fields was found. Furthermore, large between- and within-field variations made it difficult to distinguish between management and site effects. Other organic farms with depleted nutrients may, however, show a different allometry.

Tree species differences

General allometric models across species show good model performances and explain a general pattern of a size-dependent shift of aboveground biomass in dependence on tree diameter and height. The good performance of these models agrees with theories of generalized interspecific allometric scaling relationships in biology and forestry (Niklas 1994; West 1997; Enquist et al. 1998; West et al. 1999; Enquist and Niklas 2001, 2002; Niklas 2004), where it is assumed that all plants share the same basic body plan and processes that govern the transport of essential materials to support cellular metabolism. To achieve more precise biomass predictions across species than provided by the theoretical models, several studies have empirically developed general biomass regression models mainly for tropical forests (Brown et al. 1989, 1995; Ketterings et al. 2001; Malhi et al. 2004; Segura 2005) or forests spanning the globe (Zianis and Mencuccini 2004; Pilli et al. 2006). Such mixed-species models satisfyingly explain the biomass of trees for a wide range of different species. Thus, they are flexible and particularly practical in forest systems with a large number of different tree species, where enormous efforts are needed to develop species-specific equations (Ketterings et al. 2001). For accurate biomass estimation, however, functions with species-specific allometric coefficients are necessary. They can account for varying tree architectures, wood densities, annual growth dynamics, and reaction to environmental factors (Telenius and Verwijst 1995; Heinsoo et al. 2002; Sevel et al. 2012).

In this study, the differences in the allometric factor and thereby in the initial aboveground biomass at a given diameter are probably accounted for by a combination of different wood densities, tree shapes, and species-specific height growth. Although the willow and poplar clones shared the greatest HD, their allometric factor was still lower than that of *R. pseudoacacia*. The latter adopts a shape well distinguished from the more tightly packed, vertical and pyramidal shoot architecture of poplar and willow. Furthermore, it has the highest wood density ($\rho = 0.60$ g cm^{-3}; Klašnja et al. 2013). *A. glutinosa* also has higher wood density ($\rho = 0.40$ g cm^{-3}; Kiaei 2013) than *Populus* ($\rho = 0.34$; Klašnja et al. 2013) and *Salix* clones ($\rho = 0.34$ g cm^{-3}; Klašnja et al. 2013). It also has a stouter crown and has the lowest allometric factor among the species, a result that may be explained by the modest height development.

A species-specific allometric factor, accounting for the initial species-specific state, was more important for predicting biomass than a quantified change in shape expressed by the specific allometric exponent. However, this is valid only for trees within the given diameter range and may change for different ontogenetic stages or ecological settings (Niklas 1995; Weiner 2004). Furthermore, tree growth is expected to be higher in the next rotation and more shoots per plant are presumed to resprout. This could lead to deviations in parameters used for estimation, such as relative lower wood density and greater height increase.

Corrective potential of the parameter height

Although fitting the data very well, our allometric functions with SBD only were restricted to specific SBD-H relations. Overall estimation accuracy was enhanced considerably by including H, although the effect on R^2 was small, which is concordant with previous studies (Joosten et al. 2004; Cienciala et al. 2005). However, for *P. 'Max 3,'* the general exponent of model 2 alters the corrective effect of model 6.

Even for young trees, ontogenetic differences between two years can lead to changes in the allometric coefficients. Although trees were just 4 years old, H increment already decreased with increasing SBD (Fig. 2). Picard et al. (2015) proved that exponents of power models with only SBD as predictor do not remain constant along the complete ontogenic development of the plant. By the inclusion of small-diameter trees into the function parameterization, the allometric factor trends to decrease, whereas the allometric exponent increases (Picard et al. 2015). With this, high-diameter trees are overestimated, while small-diameter trees are underestimated. Consequently, when functions are developed across different years but applied to only one year, like in our validation, bias in biomass estimations may appear. This makes them less transferable to other stand ages.

At our study area, an appreciable plot variance was detected, reflecting the small-scale variation in edaphic conditions and slope typical of the Tertiary hills of Germany. In model 2, those site differences influenced the allometric exponent. This indicates a higher sensitivity of tree shape, height growth, or wood density to site effects. When height was included in the model, most variation due to site differences was explained by the intercept, indicating that H already reflected site characteristics. With height growth being highly sensitive to site quality (Joosten et al. 2004; Kobal et al. 2015) and also to competition or the social status of the tree (Vanninen and Mäkelä 2000), the incorporation of H may be important when the equation is applied to varying site conditions or different environments as also suggested by Ketterings et al. (2001). However, whether the developed equations are adequate for estimating biomass of other stands or rotations and therefore serve as a practical tool for farmers remains to be tested.

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Appendix

See Tables 9, 10, 11 and 12.

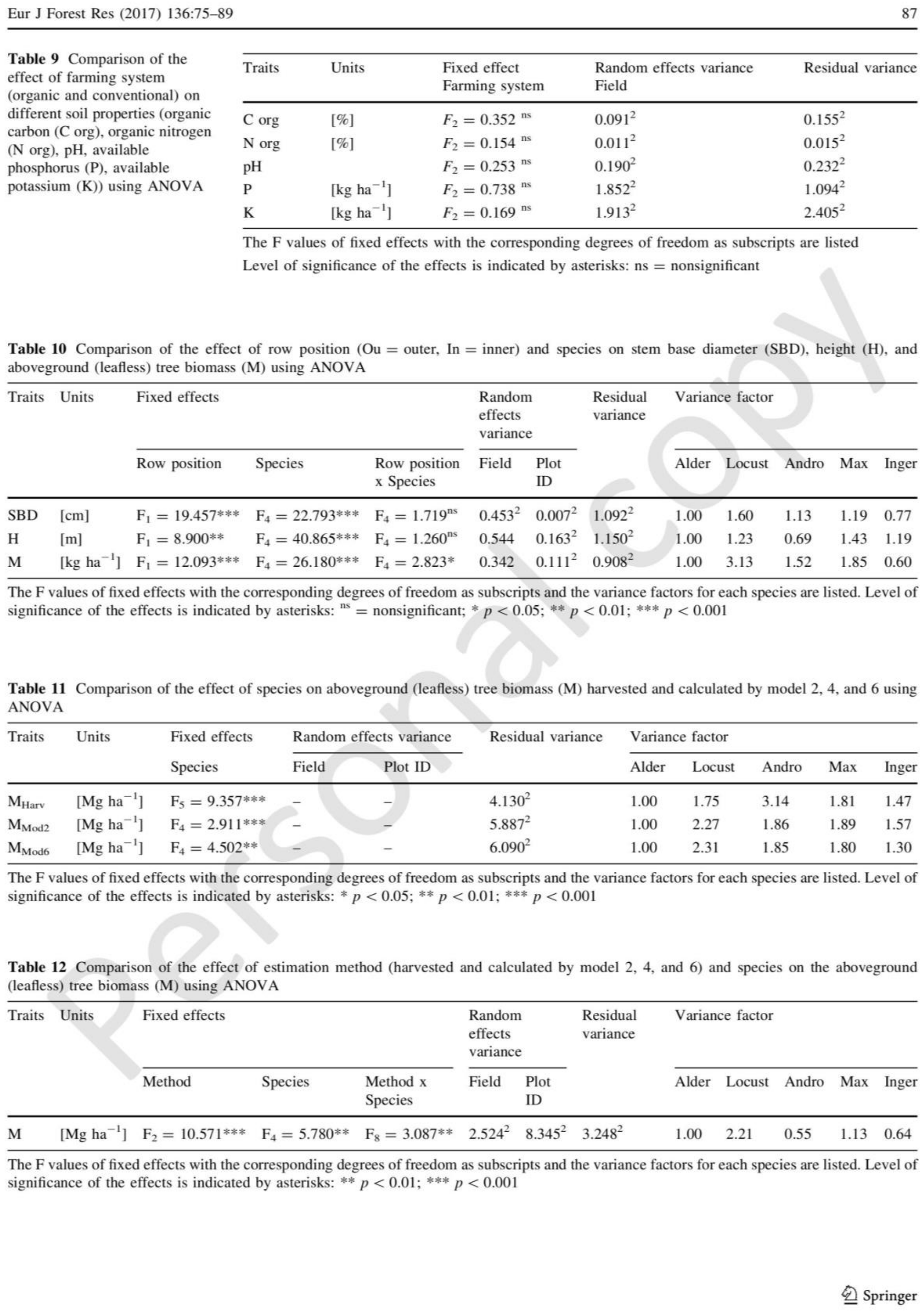

Table 9 Comparison of the effect of farming system (organic and conventional) on different soil properties (organic carbon (C org), organic nitrogen (N org), pH, available phosphorus (P), available potassium (K)) using ANOVA

Traits	Units	Fixed effect Farming system	Random effects variance Field	Residual variance
C org	[%]	$F_2 = 0.352^{ns}$	0.091^2	0.155^2
N org	[%]	$F_2 = 0.154^{ns}$	0.011^2	0.015^2
pH		$F_2 = 0.253^{ns}$	0.190^2	0.232^2
P	[kg ha^{-1}]	$F_2 = 0.738^{ns}$	1.852^2	1.094^2
K	[kg ha^{-1}]	$F_2 = 0.169^{ns}$	1.913^2	2.405^2

The F values of fixed effects with the corresponding degrees of freedom as subscripts are listed

Level of significance of the effects is indicated by asterisks: ns = nonsignificant

Table 10 Comparison of the effect of row position (Ou = outer, In = inner) and species on stem base diameter (SBD), height (H), and aboveground (leafless) tree biomass (M) using ANOVA

Traits	Units	Fixed effects			Random effects variance		Residual variance	Variance factor				
		Row position	Species	Row position x Species	Field	Plot ID		Alder	Locust	Andro	Max	Inger
SBD	[cm]	$F_1 = 19.457$***	$F_4 = 22.793$***	$F_4 = 1.719^{ns}$	0.453^2	0.007^2	1.092^2	1.00	1.60	1.13	1.19	0.77
H	[m]	$F_1 = 8.900$**	$F_4 = 40.865$***	$F_4 = 1.260^{ns}$	0.544	0.163^2	1.150^2	1.00	1.23	0.69	1.43	1.19
M	[kg ha^{-1}]	$F_1 = 12.093$***	$F_4 = 26.180$***	$F_4 = 2.823$*	0.342	0.111^2	0.908^2	1.00	3.13	1.52	1.85	0.60

The F values of fixed effects with the corresponding degrees of freedom as subscripts and the variance factors for each species are listed. Level of significance of the effects is indicated by asterisks: ^{ns} = nonsignificant; * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$

Table 11 Comparison of the effect of species on aboveground (leafless) tree biomass (M) harvested and calculated by model 2, 4, and 6 using ANOVA

Traits	Units	Fixed effects	Random effects variance		Residual variance	Variance factor				
		Species	Field	Plot ID		Alder	Locust	Andro	Max	Inger
M_{Harv}	[Mg ha^{-1}]	$F_5 = 9.357$***	–	–	4.130^2	1.00	1.75	3.14	1.81	1.47
M_{Mod2}	[Mg ha^{-1}]	$F_4 = 2.911$***	–	–	5.887^2	1.00	2.27	1.86	1.89	1.57
M_{Mod6}	[Mg ha^{-1}]	$F_4 = 4.502$**	–	–	6.090^2	1.00	2.31	1.85	1.80	1.30

The F values of fixed effects with the corresponding degrees of freedom as subscripts and the variance factors for each species are listed. Level of significance of the effects is indicated by asterisks: * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$

Table 12 Comparison of the effect of estimation method (harvested and calculated by model 2, 4, and 6) and species on the aboveground (leafless) tree biomass (M) using ANOVA

Traits	Units	Fixed effects			Random effects variance		Residual variance	Variance factor				
		Method	Species	Method x Species	Field	Plot ID		Alder	Locust	Andro	Max	Inger
M	[Mg ha^{-1}]	$F_2 = 10.571$***	$F_4 = 5.780$**	$F_8 = 3.087$**	2.524^2	8.345^2	3.248^2	1.00	2.21	0.55	1.13	0.64

The F values of fixed effects with the corresponding degrees of freedom as subscripts and the variance factors for each species are listed. Level of significance of the effects is indicated by asterisks: ** $p < 0.01$; *** $p < 0.001$

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Yield Potential of Tree Species in Organic and Conventional Short-Rotation Agroforestry Systems in Southern Germany

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Abstract The increasing demand for bioenergy and the combination of agricultural production with conservation has made short-rotation agroforestry systems (SRAFS) a sustainable land-management option. Aboveground woody biomass is a decisive factor in economic and ecological assessment of those systems. To study the yields of organic and conventional SRAFS, the tree species black alder, black locust, poplar clone Max 3, poplar clone Androscoggin, willow clone Inger, and a mixture of different native species were established in an alley-cropping configuration in 2009 and coppiced in 2012. Biomass was determined by harvesting the inner rows of the tree strips and, to investigate row differences within a strip, by an allometric model which estimates tree biomass from stem diameter. Significant variation was observed between species. For inner rows and at the conventional system, highest harvested average annual yield was observed for poplar Androscoggin (10.5 t_{odt} ha^{-1} year^{-1}), followed by black locust (9.7 t_{odt} ha^{-1} year^{-1}), poplar Max 3 (8.6 t_{odt} ha^{-1} year^{-1}), black alder (7.6 t_{odt} ha^{-1} year^{-1}), the native mix (4.9 t_{odt} ha^{-1} year^{-1}), and willow (3.9 t_{odt} ha^{-1} year^{-1}). At the organic system, highest yields were observed for poplar Max 3 (Androscoggin not planted) (10.9 t_{odt} ha^{-1} year^{-1}), followed by black locust (8.1 t_{odt} ha^{-1} year^{-1}), black alder (7.4 t_{odt} ha^{-1} year^{-1}), willow (6.4 t_{odt} ha^{-1} year^{-1}), and the native mix (4.7 t_{odt} ha^{-1} year^{-1}). Farming system differences were only significant for willow and poplar Max 3; however, the higher yields of the organic system seemed to be a result of varying small-scale site properties rather than a management effect. Border rows showed 18–111 % more yield than inner rows because of greater tree diameters or heights and higher number of stems. This edge effect was emphasized in the conventional systems, possibly indicating that trees benefit from fertilizers applied at adjacent crop fields.

Keywords Poplar · Black locust · Black alder · Willow · Allometry · Edge effect

Introduction

The cultivation of woody crops as renewable feedstock for bioenergy and bioproducts is an important way to meet the growing needs of raw material and fuel. By sequestering carbon and substituting fossil fuels, the use of woody biomass reduces CO_2 emissions into the atmosphere [1–3]. Woody biomass from short-rotation coppice (SRC) was revealed as an important greenhouse gas mitigation option for global climate policy goals (cf. UNFCCC) [4]. Furthermore, the use of such systems can provide multiple positive environmental impacts, including biodiversity enhancement and soil and water protection [2, 4, 5]. Among SRC systems, short-rotation agroforestry systems (SRAFS) have gained special attention. They combine woody biomass production with agricultural production. Such multifunctional systems are considered as an approach to sustainable intensification [6] because they balance competing demands for land and for food versus energy production while exerting positive agroecological effects and interactions such as reduced nutrient leaching and conservation of farmland

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and forest biodiversity [2, 7, 8]. Furthermore, it has been found that growing trees and crops in silvoarable systems was more productive than growing them separately [9].

To promote the use of biomass from SRC or SRAFS, sufficient yields must be sustained [10]. Some studies have investigated the ecological suitability and yield potential of various fast-growing tree species under the environmental conditions of Germany [11–17]. The reported yields are from SRC or SRAFS established on marginal [12, 14, 16] and fertile agricultural land [11, 13, 15, 17]. Only a few report the productivity of such systems in southern Germany [13, 15, 16], which is characterized by humid climate and Cambisols, thus offering high yield potential.

Short rotation woody crops are a good option to produce bioenergy feasible in low-input organic farming [18]. Nevertheless, organic short-rotation systems are less studied [15, 18], and no direct comparison between conventional and organic has been made so far. Globally, conventional farming produces overall higher agricultural crop yields than organic farming [19]. Also, increased tree yields or early culmination of biomass has been reported to be enhanced by management practices, such as fertilization [20–23], irrigation [20, 24], and weed control [21]. At the Scheyern experimental farm, an organic and conventional system has been established since 1992. Differences in structure and production features have led to significantly higher agricultural crop yields under conventional than under organic management [25, 26]. These system differences are expected to be reflected in tree yields.

In an investigation of the productivity of SRAFSs under both conventional and organic management, several tree species were planted in an alley-cropping configuration at the Scheyern (southern Germany) research farm. Two poplar and one willow clones were chosen, as hybrids of the poplar and willow genera were considered to be most promising, because of their rapid juvenile growth, high coppicing ability, adaptation to diverse conditions, and easy vegetative propagation [27–30]. However, further species have recently attracted attention as biomass crop species. For example, black locust grows rapidly when young, is well suited to sites considered too poor for alternative biomass energy species [12, 14, 20], symbiotically fixes atmospheric nitrogen, and has a high wood density, reducing transportation costs and facilitating conversion into gaseous fuels [12]. Another commonly planted species is black alder, which is adapted to a wide range of climatic conditions and site qualities [31], grows fast in the juvenile stage, and fixes nitrogen [25]. Although in general, monoculture plantings are deployed, given that a species mix improves the habitat for native wildlife and minimizes the risk of disease problems, we also planted a mixture of native species.

As most studies on SRC have been performed in plantation forestry systems and not alley-cropping systems, edge effects in tree biomass production are not well defined. Although seldom mentioned, this effect strongly influences these systems because of the alley structure of SRAFS [17].

In order to assess the productivity of different SRAFS, the main objectives of this study were as follows: (1) to estimate species-specific biomass production, (2) to compare woody biomass production between trees from border and inner rows, and (3) between farming systems.

Material and Methods

Study Area and Management Regime

In April 2009, a long-term field experiment with short-rotation agroforestry systems (SRAFS) was established in an alley-cropping configuration at the Scheyern research farm (48° 30′ N, 11° 21′ E) in Bavaria, southern Germany. In 1992, the farm had been subdivided into an organic and a conventional farming system. The organic system was established as a mixed-farming system with livestock and has been maintained as an organic farm without livestock since 2005. It is based on a seven-field crop rotation (with 29 % grass–clover–alfalfa). Mineral nitrogen and synthetic chemical plant protection products are not used. Tillage is performed with a moldboard plow. The conventional system is a high-input system with synthetic chemical plant protection, mineral nitrogen input, and a simple structured crop rotation with 50 % wheat, 25 % forage maize, and 25 % potato. Here, conservation tillage is applied. The farming systems are characterized in more detail in Küstermann et al. [26, 32].

The SRAFS were established in two fields of each farming system, covering 1.9–3.7 ha. The altitude varies between 460 and 490 m above sea level with a 2–10 % slope. Most soils have a loamy texture and are classified (WRB soil classification) as either Cambisols or Eutrochrepts with a thin layer of loess, Cambisol with sand and gravel subsoil (sandy-gravelly illuvial horizon), or small-scale clay soils [33, 34]. Meteorological data were obtained from the Altomünster-Maisbrunn weather station (48° 24′ N, 11° 19′ E) of the Deutscher Wetterdienst (DWD), 15 km from the experimental site. The climate is temperate, with an annual average temperature of 8.7 °C and an annual precipitation of 803 mm between 2009 and 2012. The long-term (1981–2010) averages are 8.3 °C and 887 mm, respectively. Precipitation during the establishment phase in 2009 (May–July) was above average (Fig. 1).

After more than 20 years, the farming system differences did not lead to a significant difference in the initial nutrient status of the soil of the SRAFS area (Table 1, published in Huber et al. [35]). Only soil organic carbon and potassium

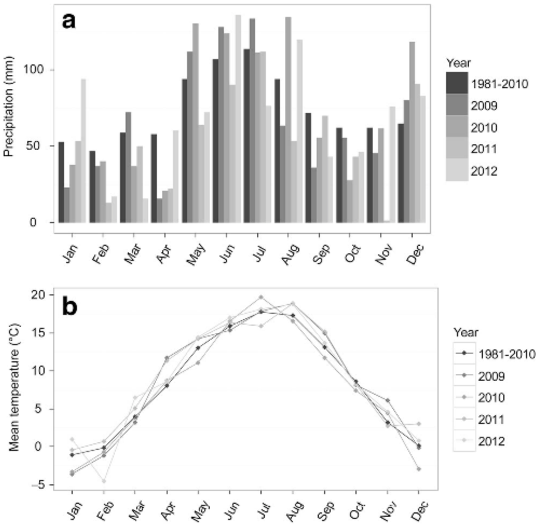

Fig. 1 Sum of monthly precipitation (mm) (**a**) and monthly mean temperature (°C) (**b**). Data from a meteorological station near the experimental site showing both the long-term average for the years 1981–2010 and the annual values during the first rotation from 2009 to 2012

were slightly higher in the organic farming system, whereas phosphorus was slightly higher in the conventional farming system.

The tree strips were not manured, but weed was controlled by herbicide application (conventional system) and mechanical weeding (organic system) during the first year of establishment. No further weed control or fertilizer was necessary.

Agroforestry Design and Plant Material

On every field, three tree strips were planted in a north–south or west–east direction (one of the four fields) with a spacing of 30 m to accommodate field crops between the strips (Fig. 2a). The orientation of the tree strips follows the predetermined geometry of the fields and machining direction. Using a randomized block design, in each strip, plots (30 m × 8.25 m) of several tree species and clones are replicated. However, it was not possible to replicate the farming systems completely randomized, as the fields were geographically assigned to each system. Therewith, the p values might be slightly inflated.

Planting arrangement was a double row design with three double rows of 75-cm distance within and 1.5 m between the double rows and a plant distance within each row of 0.5 m (Fig. 2b, c). A buffer zone of 0.75 m between crops and trees on each site was established to prevent damage during processing. Effective plot width was 6.75 m, resulting in a total density of 17,778 plants ha^{-1}.

The species studied were black alder (*Alnus glutinosa*), black locust (*Robinia pseudoacacia*), poplar clone Max 3 (*Populus maximowiczii x P. nigra*), poplar clone Androscoggin (*P. maximowiczii x P. trichocarpa*), willow clone Inger (*Salix triandra x S. viminalis*), and a mixture of five different native species (sycamore maple (*Acer pseudoplatanus*), black alder (*Alnus glutinosa*), common hornbeam (*Carpinus betulus*), common hazel (*Corylus avellana*), and goat willow (*Salix caprea*)) belonging to the functional group of pioneers with vigorous juvenile growth [10].

All plants were planted manually: poplar and willow cuttings of 20 cm in length to a depth of 15 cm, leaving one or two buds above the soil surface, and plants of the other species as bare-rooted saplings of 70–90 cm in length.

Table 1 Soil properties at 0–30-cm depth in conventional and organic farming systems from the beginning of the experiment in 2009

Component	Unit	Conventional farming Mean ± SE	Organic farming Mean ± SE
C org	% by mass	1.11 ± 0.07^{a}	1.17 ± 0.10^{a}
N org	% by mass	0.11 ± 0.01^{a}	0.11 ± 0.01^{a}
pH		5.4 ± 0.1^{a}	5.5 ± 0.2^{a}
P	kg ha^{-1}	5.2 ± 1.4^{a}	3.5 ± 1.9^{a}
K	kg ha^{-1}	8.8 ± 1.4^{a}	9.6 ± 2.0^{a}

Mean organic carbon (C org), organic nitrogen (N org), pH, available phosphorus (P), available potassium (K), and the respective standard errors (SE). Published in Huber et al. [35]

[a] Farming systems sharing the same letter are not significantly different from each other (Tukey-HSD, $p < 0.05$)

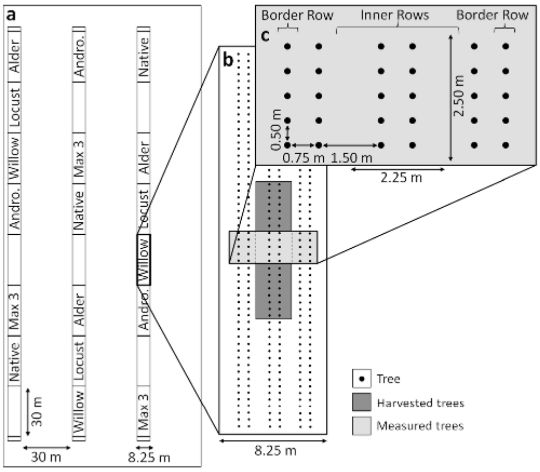

Fig. 2 Experimental design of the agroforestry systems, illustrated by the biggest field. Three tree strips of various species were planted (**a**), resulting in three plots per species and field (gaps within a tree strip are planted with a mixture of different poplar clones and are not part of the study). The inner structure of the tree strips consists of three double rows (**b** + **c**). The study area is highlighted (**b** + **c**). This design is repeated on a total of four fields (two organic, two conventional)

Measurements and Harvesting

At the end of the 4-year rotation, in the middle of each species plot, stem base diameter (SBD in centimeters, at 10 cm above soil) from all shoots of 10 trees was measured in the double row in the middle (2.25-m × 2.5-m area) and from the shoots of 10 trees in the two single rows at the border (giving 2.25-m × 2.5-m area) (Fig. 2b, c). SBD was measured in two perpendicular directions using a caliper, and the mean value was used in further calculations. Because most trees rarely developed more than two dominant shoots, sprouting performance was assessed by summing up the number of shoots of the measured trees and converting it to hectares. In total, 240 trees were measured for each species (10 trees × 2 row positions × 3 plots × 2 fields × 2 systems), with the exception of willow Inger, planted on only two of four fields ($n = 120$) and of poplar Androscoggin, planted on only one field ($n = 60$). Tree height (H in m) was measured only in the double row in the middle, using a Vertex hypsometer. Dead trees were counted and replaced with other trees for measurements. The overall tree mortality was determined as proportion of dead trees among all live trees present. Trees of the native mix were not measured.

At the end of the rotation, 40 trees of double row in the middle of each species plot (2.25-m × 10-m area; Fig. 2b) were cut manually 10 cm above soil surface. Harvested plots overlapped measurement plots. In total, 480 trees of each species were harvested, again with the exception of willow Inger and poplar Androscoggin, for which only 240 and 120 trees were harvested. The plots with the mixture of native species were also harvested. All trees from one species plot defined one sample. The fresh weight of these samples was measured on site using a load cell (±50 g) suspended from the fork of a tractor. The samples were then shredded into wood chips, and a representative aliquot was used for the determination of dry matter content by drying in a forced air oven at 105 °C until constant mass was reached. All biomass values are expressed as oven dry mass (odt).

As the border rows were not weighted on site, biomass was estimated using allometric functions, which were evaluated in a previous study on the same study site [35]. In this study, the functions incorporating tree height as covariate were the most precise ones. However, due to the lack of height measurements in border rows, the best fitting functions that estimate individual tree oven dry biomass (M in kg) from SBD (in cm) were applied. Functions with a general allometric factor across species and species-specific allometric intercepts revealed the lowest bias:

$$M_i = \beta_{0j} SBD_i^{\beta_1} \tag{1}$$

where M is the total aboveground oven dry mass for a specific stem base diameter SBD, β_0 describes the allometric factor, and β_1 describes the allometric exponent. The additional index i refers to the individual tree and index j indicates the species-specific factors listed in Table 2.

The equation was applied to all shoots. Single-shoot biomasses were summed for each species plot and yield at stand level (in $t_{odt}\,ha^{-1}$) was calculated.

Analysis

Biometric variables (SBD and H), number of shoots, and biomass were analyzed by generalized linear mixed effect modeling to account for dependencies within the hierarchical dataset and for heteroscedasticity [36]. If no random effect was significant, generalized linear models were applied. The effects of species, farming system, row position, and their interactions were treated as fixed and those of field and plot (nested within field) as random. The random effect field accounts for the correlation of the three plots within each field. The random effect plot accounts for the autocorrelation of the 20 measurements from each plot and also for the spatially nonindependent measurements of the row positions. Different variance structures were tested to account for different residual variances, such as between species and row position.

The assumptions of homoscedasticity, normality, and the absence of outliers were verified by visual evaluation of residual scatter plots (residual versus predicted values). The fixed and random effects as well as the variance structures included in the final models were selected using the likelihood ratio test applying maximum likelihood (varying fixed effects) and restricted maximum likelihood (varying random effects). Each effect in turn was omitted from the model and a likelihood-ratio statistic was calculated, contrasting the refitted model with the original model. Goodness of fit of the models was evaluated by the Akaike information criterion (AIC) [37] and the Bayesian information criterion (BIC) [38].

Table 2 Allometric coefficients to calculate aboveground biomass of different tree species, where β_0 describes the allometric factor and β_1 the allometric exponent with stem base diameter (SBD in cm) as explaining variable

Tree species	β_0	β_1
BA	0.025	2.603
BL	0.041	2.603
PA	0.032	2.603
PM	0.036	2.603
WI	0.037	2.603

BA black alder, *BL* black locust, *PA* poplar Androscoggin, *PM* poplar Max 3, *WI* willow Inger, *NM* native mix

All computations and statistical analyses were performed with R software [39]. Linear mixed effect analyses were performed with the R package "nlme" [40]. Post hoc analyses (Tukey's HSD test) in combination with the linear model were computed with the R package "multcomp" [41].

Results

Tree Species Differences

At the end of the 4-year rotation, the tree species differed significantly in all biometric traits and in their biomass production (Table 4, Appendix Table 7). However, similarities and rankings between species changed according to the specific variable, the farming system, the position within the tree strip, and the estimation method.

After 4 years, tree mortality was 10 % for black locust, followed by 8 % for black alder and 1 % for both poplar clones. No mortality was recorded for willow Inger.

Despite mortality, the number of shoots was higher than the number of trees initially planted (17,778), illustrating the development of sprouts during the rotation. Willow Inger showed the highest number of shoot among all species (Fig. 3), which was, however, only significant for the conventional farming system (Table 4). The lack of

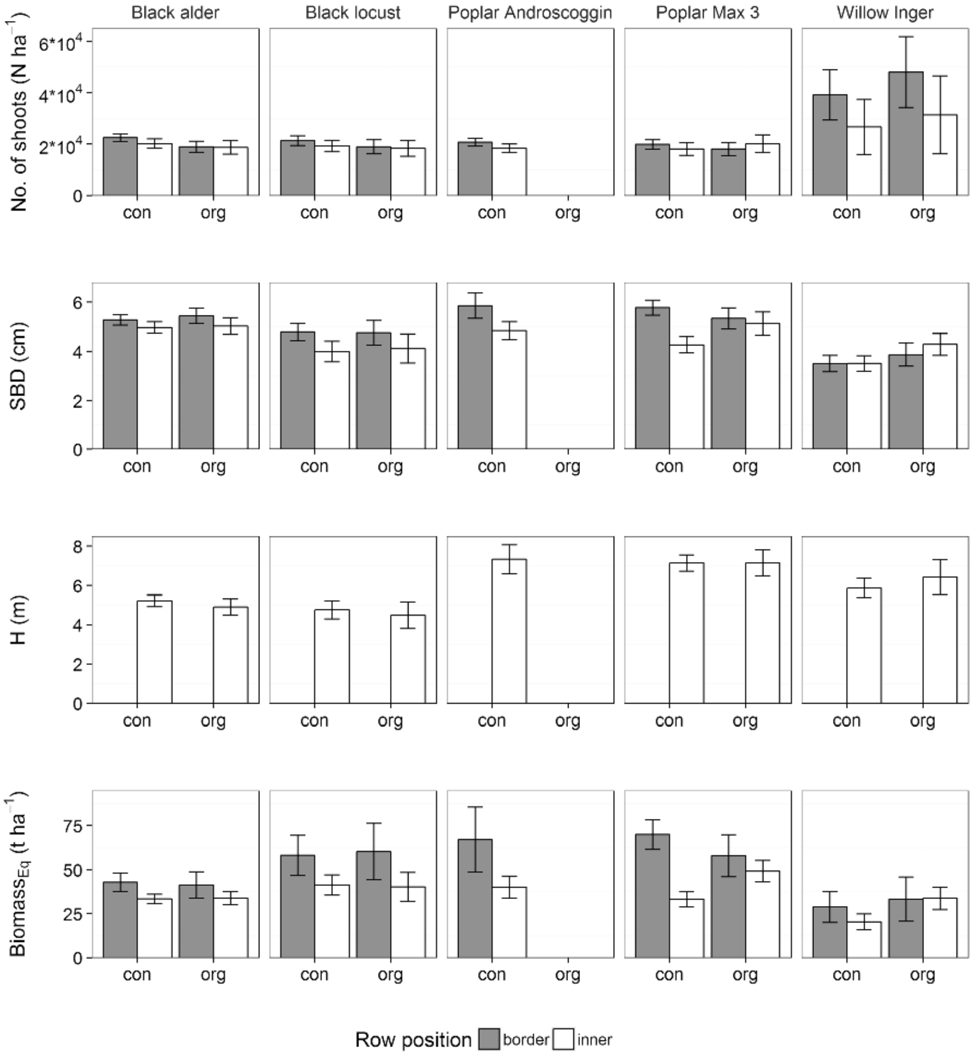

Fig. 3 Mean of different species traits for each farming system (*con* conventional, *org* organic) and row position, and the respective standard errors

significance for the organic system may be explained by the high variance in its development of shoots, visible by the higher standard error (Fig. 3, Appendix Table 10). The inclusion of species-specific variance structures was significant ($L = 51.21$, $df = 3$, $p < 0.001$). Highest variation of shoots was found for willow, which is evident from the higher variance factors (Appendix Table 8).

Willow Inger showed in all rows (3.5–4.3 cm) and black locust in the inner rows of the organic system (inner, 4.0–4.1 cm; border, 4.8 cm) significantly lower SBDs than black alder (5.0–5.5 cm) and the two poplar clones (Androscoggin, 4.8–5.9 cm; Max 3, 4.3–5.8 cm) (Fig. 3, Table 4, Appendix Table 10). Fitting different residual variance structures for each species improved the model significantly ($L = 94.48$, $df = 3$, $p < 0.001$) while showing the highest variation for black locust and the lowest for willow (Appendix Table 8).

The poplar clones had a significantly greater mean H (Androscoggin, 7.3 m; Max 3, 7.1–7.2 m) than black alder (4.9–5.2) and black locust (4.5–4.8 m), whereas that of willow Inger was intermediate at the conventional (5.9 m) and not significantly different to poplar Max 3 at the organic system (6.4 m) (Fig. 3, Table 4). The inclusion of the species-specific variance ($L = 88.71$, $df = 3$, $p < 0.001$) was significant. Black locust showed again the highest and willow Inger the lowest variation (Appendix Table 8).

The significant lowest harvested biomass was achieved by the native mix (4.9 and 4.7 t_{odt} ha^{-1} year^{-1} in the conventional and organic system, respectively) at both systems and by willow at the conventional one (3.9 t_{odt} ha^{-1} year^{-1}) (Tables 3 and 4). At the organic system, willow's biomass was intermediate (6.4 t_{odt} ha^{-1} year^{-1}), like black alder at both system (7.6 and 7.4 t_{odt} ha^{-1} year^{-1} in the conventional and organic system, respectively). The highest harvested biomass was achieved by the two poplar clones (Androscoggin, 10.5 t_{odt} ha^{-1} year^{-1}; Max 3, 8.6 and 10.9 t_{odt} ha^{-1} year^{-1} in the conventional and organic system, respectively) and by black locust (9.7 and 8.1 t_{odt} ha^{-1} year^{-1} in the conventional and organic system, respectively), although the latter species had a low mean SBD as well as a low mean H (Fig. 3), and the highest tree mortality. Biomass estimated by allometric equations deviated from the one estimated by harvesting. Due to the slight overestimation of black locust and slight underestimations of the poplar clones at the conventional system, black locust and not poplar Androscoggin showed the highest biomass (Table 3, Fig. 3, Appendix Table 10), however only significant in comparison to willow (Table 4). Although willow was overestimated by about 30 %, it still had the lowest biomass production at the conventional and an intermediate at

Table 3 Comparison between conventional and organic harvested aboveground biomasses (only inner rows) and the respective standard errors (SE) of different tree species

Tree species	Harvested biomass ± SE (t_{odt} ha^{-1})	
	Conventional farming	Organic farming
BA	30.2 ± 1.8	29.7 ± 2.5
BL	38.6 ± 3.3	32.2 ± 4.6
PA	41.8 ± 7.5	–
PM	34.2 ± 2.0	43.4 ± 4.3
WI	15.7 ± 2.4	25.7 ± 3.5
NM	19.6 ± 3.3	18.7 ± 4.7

BA black alder, *BL* black locust, *PA* poplar Androscoggin, *PM* poplar Max 3, *WI* willow Inger, *NM* native mix

Table 4 Species differences for each farming system (*con* conventional, *org* organic) and row position (*bor* border, *in* inner)

Trait		con		org	
		bor	in	bor	in
Shoots (N ha^{-1})	BA	a	abc	a	a
	BL	a	b	a	a
	PA	a	ab	–	–
	PM	a	a	a	a
	WI	b	c	a	a
SBD (cm)	BA	bc	c	b	b
	BL	b	ab	b	a
	PA	c	bc	–	–
	PM	c	b	b	b
	WI	a	a	a	a
Height (m)	BA	–	a	–	a
	BL	–	a	–	a
	PA	–	b	–	–
	PM	–	b	–	b
	WI	–	ab	–	b
Biom$_{Harv}$ (t_{odt} ha^{-1})	BA	–	b	–	bc
	BL	–	b	–	c
	PA	–	b	–	–
	PM	–	b	–	d
	WI	–	a	–	ab
	NM		a	–	a
Biom$_{Eq}$ (t_{odt} ha^{-1})	BA	ab	ab	ab	a
	BL	bc	b	b	ab
	PA	ac	ab	–	–
	PM	c	ab	b	b
	WI	a	a	a	a

Species sharing the same letter within a column are not significantly different from each other (Tukey-HSD, $p < 0.05$)

BA black alder, *BL* black locust, *PA* poplar Androscoggin, *PM* poplar Max 3, *WI* willow Inger, *NM* native mix

Table 6 Farming system differences for each species (*BA* black alder, *BL* black locust, *PA* poplar Androscoggin, *PM* poplar Max 3, *WI* willow Inger) and row position (*bor* border, *in* inner)

		BA		BL		PM		WI		NM	
		bor	in	bor	in	bor	in	bor	in	bor	in
Shoots (N ha^{-1})	con	a	a	a	a	a	a	a	a	–	–
	org	a	a	a	a	a	a	a	a	–	–
SBD (cm)	con	a	a	a	a	a	a	a	a	–	–
	org	a	a	a	a	a	b	a	a	–	–
H (m)	con	–	a	–	a	–	a	–	a	–	–
	org	–	a	–	a	–	a	–	a	–	–
$Biom_{Harv}$ (t_{odt} ha^{-1})	con	–	a	–	a	–	a	–	a	–	a
	org	–	a	–	a	–	b	–	b	–	a
$Biom_{Eq}$ (t_{odt} ha^{-1})	con	a	a	a	a	a	a	a	a	–	–
	org	a	a	a	a	a	b	a	b	–	–

Farming systems within a column sharing the same letter are not significantly different from each other (Tukey-HSD, $p < 0.05$)

development of more stems and a greater H at the conventional system. The higher biomass of poplar and willow at the organic system is likely to be a locational effect, as mentioned above. However, regarding border rows, they also developed high biomasses and poplar's conventional border rows even overtopped the biomasses of organic border rows. Likewise as stated above, trees of the border rows may benefit from the fertilizer.

The heterogeneity of the site (with respect to soil, nutritional status, altitude, and slope) within and between fields appeared to have an influence, as the inclusion of random effects resulted in a significant improvement (shoots, $L = 71.08$, $df = 8$, $p < 0.001$; SBD, $L = 103.93$, $df = 5$, $p < 0.001$, H, $L = 103.93$, $df = 5$, $p < 0.001$). The between-field variance was always lower than the within-field variance given by the random effects variance of plot (Appendix Tables 8 and 9), a finding that indicates the heterogeneity of the study site. Because of the low correlation between biomasses among plots within a field, adding field as a random effect resulted in no improvement ($Biomass_{Harv}$, $L < 0.01$, $df = 1$, $p = 0.487$; $Biomass_{Eq}$, $L < 0.01$, $df = 1$, $p = 0.953$), also confirming the variability of the site.

Discussion

Tree Species Differences

Sprouting and Mortality

Tree mortality at the end of the rotation was highest in black locust and black alder (10 and 8 %, respectively), very low for poplar clone Max 3 (1 %), and nonexistent for willow clone Inger. Mortality may be a silvicultural problem if the rate is sufficiently high to decrease stand yields [42], due to heavy interference, e.g., diseases, insects, browsing, frost, or disturbances such as wind and fire [42–45]. However, mortality is often a result of natural self-thinning because of intraspecific competition. With the exception of willow Inger, all studied species reached canopy closure at the end of the rotation. As black locust and black alder developed spreading crowns, also reported in Huber et al. [35], with no disease being recorded, mortality can be attributed to self-thinning. Although canopy closure was present for poplar, the very low mortality indicates low between-plant competition, probably because of the development of a single barely-branched orthotropic monopodial trunk and narrow crowns [35]. In general, poplar has been bred for a narrow crown architecture and small branches. The leaves on these branches fill in gaps and allow more light interception [46, 47]. But, tree mortality can also be very high in poplar, depending on the clone [48]. In contrast to other species, canopy closure of willow was not reached because the trees mostly had no more than two shoots, which were thinner than the shoots of the other species and seldom branched (see also Huber et al. [35]). With the resulting decreased mutual shading, no loss of willows was recorded. Furthermore, willow showed the highest number of shoots, although all species had a higher number of shoots than the number of trees initially planted. The high ability of willow to take advantage of the space available, and thereby, the ability to generate more shoots, was recognized by Bergkvist and Ledin [49]. In addition, Labrecque and Teodorescu [50] reported a higher stem number for willow than for poplar plants. However, growth strategies (growth of many small shoots versus fewer dominant shoots because of rapid self-thinning) also vary among poplar [43, 48] and willow clones [50, 51].

It has been shown that sprouting can be promoted by coppicing (which is intended to increase final biomass production) because trees benefit in the next rotation from the organic system. Regarding border rows, poplar Max 3 produced the highest yields at the conventional and, together with black locust, the highest yields at the organic system. Including species-specific variances improved the biomass models ($\text{Biomass}_{\text{Harv}}$, $L = 5.06$, $df = 4$, $p < 0.05$; $\text{Biomass}_{\text{Eq}}$, $L = 16.54$, $df = 4$, $p < 0.01$), and highest variation was found for black locust, the poplar clones, and the native mix (Appendix Table 8).

Differences Between Inner and Border Rows

In both farming systems and for all species, except poplar Max 3 at the organic system, trees from border rows had more shoots than inner rows (Fig. 3). However, this was not significant (Table 5, Appendix Tables 7 and 9), probably due to the high variance of the border rows combined with the lower sample size of the plot sums. There was a trend of conventional farming showing a greater difference between rows than organic farming (Appendix Table 7). High residual variance was detected for border rows (Appendix Table 8), and hence, the inclusion of row specific variances was significant ($L = 19.87$, $df = 4$, $p < 0.001$).

With the exception of willow Inger, the trees at border rows had on average a higher diameter than those at the inner rows (Fig. 3). However, this was only significant for black locust and the two poplar clones at the conventional system (Table 5, Appendix Table 7). Willow even had a significantly higher SBD for inner rows at the organic system. Including residual variance structures for each row position revealed no significant improvement ($L = 3.42$, $df = 4$, $p = 0.065$).

Because of the higher SBDs, calculated biomass was higher for the border rows, with exception for willow at the organic system. However, this was only significant for the border rows of black locust at the organic and of poplar Max 3 at the conventional system. The low significance may be caused by the lower sample size for biomass in comparison to the biometric variables. Nevertheless, with the exception of willow Inger at the organic system (2 % less biomass at border rows), 18 to 111 % higher yields were estimated. Hereby, the enhancing effect on biomass production was lowest for black alder at both systems and highest for poplar Max 3 at the conventional one. High variances were detected for border rows (Appendix Table 8).

Farming System Differences

No significant influence of farming system on the number of shoots was detected, but a trend of conventional farming having more shoots at the border than at the inner rows (Fig. 3, Table 6, and Appendix Table 7).

For SBD, farming system was only significant in interaction with row position. The inner rows of poplar Max 3 at the organic system had a significantly higher mean SBD than the inner rows of the conventional one (Fig. 3, Table 6, and Appendix Table 7). Willow showed the same effect, although not significant. This may indicate a locational influence, as one field of the conventional systems and mainly one strip within it showed this low growth performance for poplar and willow (data not shown). No system differences were found for the other species. However, only at the conventional system, for poplar's and locust's border rows had a significant higher mean SBD than inner rows. This may indicate that border trees at the conventional fields benefit from the fertilizer applied at adjacent crop fields.

For H, farming system neither had an overall influence (Appendix Table 7); however, only inner rows had been measured, and therefore, no potential fertilizer effect at the border rows was detectable.

For the inner rows, poplar Max 3 and willow achieved significantly higher yields (harvested and calculated) at the organic system than at the conventional one, due to their greater SBD (only for poplar significant), higher number of shoots (not significant), and in the case of willow, also the greater H (not significant) (Tables 3 and 6). Black alder, black locust, and the native mix had higher biomasses at the conventional system, however not significant, and for black alder and the native mix, these differences were small. The higher yields of black alder and black locust could be attributed to the

Table 5 Row position differences for each species (*BA* black alder, *BL* black locust, *PA* poplar Androscoggin, *PM* poplar Max 3, *WI* willow Inger) and farming system (*con* conventional, *org* organic)

		BA		BL		PA		PM		WI	
		con	org	con	org	con	org	con	org	con	org
Shoots (N ha^{-1})	bor	a	a	a	a	a	–	a	a	a	a
	in	a	a	a	a	a	–	a	a	a	a
SBD (cm)	bor	a	a	b	a	b	–	b	a	a	a
	in	a	a	a	a	a	–	a	a	a	b
Biom_{Eq} ($\text{t}_{\text{odt}}\ \text{ha}^{-1}$)	bor	a	a	a	b	a	–	b	a	a	a
	in	a	a	a	a	a	–	a	a	a	a

Row positions sharing the same letter within a column are not significantly different from each other (Tukey-HSD, $p < 0.05$)

the already established root system [46, 48, 51]. In particular, for willow Inger, more shoots per tree may be promoted after the first coppice at our study site, possibly leading to faster crown closure and thereby higher biomass production.

Until the time of self-thinning, competition alters growth. This is visible in the variation of SBD, H, and the biomass, detectable by the species-specific variance factors and the standard error. Variability was observed for all species, but black locust showed the highest variance and accordingly the most unevenly structured stand, whereas willow had the lowest variance (Fig. 3, Appendix Table 8).

Tree Yields

The harvested biomass of the inner rows serves as an appropriate comparison to biomass yields of other plantation systems reported in the literature.

The species-specific differences in tree and stand properties lead to significant differences in biomass production. The biomass of the poplar clones and also of black locust was superior to the other species. Clone Androscoggin exhibited highest biomass at the conventional and Max 3 at the organic system. However, Androscoggin was not tested at the organic system and might have reached higher yields than Max 3. Biomass yield of poplar was almost three times higher than that of willow. This can be explained by the highest mean H among all species paired with a high mean SBD and a low mortality. With the enormous number of clonal poplars that have been produced [29], productivity varies considerably between clones and is related to the variety of their physiological and morphological traits and their interaction with varying environmental factors even at the same site [43, 45, 52]. Thus, because of various poplar clones and sites, yields in the range of 2–25 $t_{odt}\,ha^{-1}\,year^{-1}$ have been reported [11, 22, 43, 45, 48, 50, 52–54]. Although using the same parentages as in our study, a Canadian study [50] reported poplar yields of the first 4-year rotation (17–18 $t_{odt}\,ha^{-1}\,year^{-1}$) exceeding those of ours. In a German study [11], after the first 5-year rotation, poplar yields were lower (3–8 $t_{odt}\,ha^{-1}\,year^{-1}$) because of problems in the establishment phase, but at one site, it even tripled in the second rotation. Another important factor controlling biomass production was soil fertility, mostly in terms of N availability [11, 22, 45].

Like *Populus*, *Salix* shows a great range of biomass potential, depending on species, clone, site, and treatment. Typical annual yield of different willow clones ranges between 6 and 17 $t_{odt}\,ha^{-1}\,year^{-1}$ [50, 55, 56]. In a German study, annual biomass production of a *S. viminalis* clone grown on former farmland ranged widely (2–12 $t_{odt}\,ha^{-1}\,year^{-1}$) depending on rotation and site [11]. Sevel et al. [57] found a comparable biomass production of the clone Inger of 5.2 $t_{odt}\,ha^{-1}\,year^{-1}$ on sandy soil and 8.7 $t_{odt}\,ha^{-1}\,year^{-1}$ on organic soil. Very high annual biomass yields of 13–24 $t_{odt}\,ha^{-1}\,year^{-1}$ could be obtained by fertilization and/or irrigation [51, 58]; however, very low yields of 3.5 t $ha^{-1}\,year^{-1}$ have been reported because of missing weed control in the establishment phase and sandy soil [54]. Although willow's yield in our study is of a comparable order of magnitude to those studies, it was one of the lowest among all species at our site. Probably because of its development stage, willow generally had no more than two barely branched dominant shoots. An increased final yield of willow can be reached with either extended rotation periods or an increased number of stems, and thus, earlier canopy closure induced by typical coppicing after the first growing season.

The yield of black locust was comparable to those achieved with poplar, although mean SBD was low and mean H was lowest among all species. Black locust stands covered a wide range of tree sizes. Combined with a much higher wood density of 0.60 g cm^{-3} [59] than that of the other species (ρ_{Alder} = 0.40 g cm^{-3} [60], ρ_{Poplar} = 0.34 g cm^{-3} [59], and ρ_{Willow} = 0.34 g cm^{-3} [59]), this resulted in a high stand biomass. As black locust is well adapted to unfavorable edaphic and climatic conditions [12], it is often planted on marginal land producing only 1–4 $t_{odt}\,ha^{-1}\,year^{-1}$ [12, 14]. However, it still greatly exceeded the yields of poplar and willow clones under the same conditions [12] and can achieve up to 3–10 $t_{odt}\,ha^{-1}\,year^{-1}$ under better conditions [20, 61].

Like the magnitudes of its biometric variables, biomass production of black alder was intermediate among the studied species. Black alder is still rarely studied as a biomass crop, although it has high biomass production potential. In stands in Sweden, biomass production varied between 1 and 8 $t_{odt}\,ha^{-1}\,year^{-1}$ [62].

The native mix gave the lowest biomass yield (5 $t_{odt}\,ha^{-1}\,year^{-1}$), but as it performed the functions of natural protection and risk diversification, this point was less important.

Differences Between Inner and Border Rows

Regarding absolute values of biomass calculated by allometric functions, willow's biomass was overestimated by about 30 %. Furthermore, overestimations and underestimations of calculated biomass changed the clonal ranking between black locust and poplar Androscoggin at the conventional system. Nevertheless, biomass production of all species, except of willow at the organic system, was higher at border than at inner rows, due to a greater SBD, H, and number of stems. As those border rows accounted for one third of the whole linear agroforestry system, the yield of this strip system is highly increased compared with a single-field system.

An increased diameter, dry weight of individual trees, foliage weight, and leaf area index of border rows was also recognized by Zavitkovsk [63] and explained primarily by the greater exposure to sunlight of border trees compared to inner ones. Lamerre et al. [17] also found increased yields of border rows in a studied AFS because of a higher diameter of border trees in a 6-year rotation and a higher number of shoots in a 3-year rotation as consequences of increased plant spacing and light availability. They also reported higher nutrient availability based on the proximity of the fertilized crop fields. As in our study, the unfertilized organic fields also showed this positive edge effect; hence, light and space might be the prevailing growth determinant. However, only conventional fields showed a statistical difference of stem numbers and mean SBD (not for biomass) between row positions, indicating an enhanced edge effect, probably because of the applied fertilizer at the adjacent crop fields. Willow had higher stem numbers, but no SBD increase for border rows, leading consequently to a reduced biomass increase. As willows canopy was not yet closed, the positive influence of space and light at border rows was less pronounced.

Influence of Farming System and Site Differences

Increased yields can be obtained by fertilization [20–23]. Likewise, favorable edaphic conditions can also increase the biomass yields of SRC [41, 45]. However, in our study, the tree strips were not fertilized and the nutritional status between the systems was similar, although the previous long-term cultivation differed. Furthermore, weed control minimized the influence of weed competition. Thus, in contrast to the yields of the agricultural crops, where the yields of conventionally managed (fertilized) crops exceeded those of organically managed crops (for potato by 35 % and winter wheat by 52 % during 2009–2012; data not shown), tree biomass was not enhanced in the conventional farming systems (Appendix Table 10). Indeed, willow and poplar Max 3 had a significantly higher biomass for inner rows at the organic system. This may be led back to a reduced tree growth at one field and mainly one strip at the conventional system. The between- and within-field variation due to edaphic differences made it therewith difficult to distinguish between management and site effects. However, border rows at the conventional fields produced high yields despite the low biomass of inner rows. This may indicate that border trees benefit from fertilizer of the crop fields. Black alder and black locust, however, did not show this increase in biomass, probably due to species' capacity to fix atmospheric nitrogen.

On a long-term basis, trees in the conventional system may further benefit from the fertilizer applied on the adjacent crop fields. Further research and a longer run of the experiment may be needed to detect such effects.

Conclusion

The chosen poplar clones and black locust were well adapted to the conditions of our study site (high survival, high growth). Black alder showed moderate growth among species, but still within the expected yields. Willow's yield was lower than expected because of its less-developed canopy. For this species, coppicing after 1 year of growth is recommended to promote the regrowth of multiple shoots and, hence, higher yields. The native mix showed also low biomass yield, but as it merely fulfills the aims of natural protection and risk diversification, this point was less important. Border rows showed more yield than inner rows because of greater tree diameter and height growth, as well as a higher stem number. Thus, edge effects, which are normally neglected in studies of tree plantations, strongly influence SRAFS yields. In contrast to crop yields, in Scheyern, SRAFS on organically managed fields can give the same tree biomass production as on conventionally managed fields. However, mainly for poplar and willow, trees from border rows may benefit from the fertilizer applied at the adjacent fields. Nitrogen fixing alder and locust were less affected, indicating their potential in organic farming. As the first rotation is not always representative of the growth potential, subsequent rotation yields should be studied before overall recommendations on yield development are made. Furthermore, gene–environment interactions may alter species performance at different locations. Several factors, such as species, site, plant design, rotation length, and management practices, play a considerable role for the expected outcome of tree biomass in sustainable SRC and SRAFS.

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Appendix

Table 7 Analysis of the effect of species, farming system, row position, and their interactions on different species traits (number of shoots, stem base diameter (SBD), height (H), harvested biomass ($\mathrm{Biom_{Harv}}$), and calculated biomass ($\mathrm{Biom_{Eq}}$)) using ANOVA

Traits	Units	Fixed effects						
		Species	Farming system	Row position	Species × Farming system	Species × Row position	Farming system × Row position	Species × Farming system × Row position
Shoots	(N $\mathrm{ha^{-1}}$)	$F_3 = 7.264$ ***	$F_1 = 4.672$ ^{ns}	$F_1 = 2.845$ ^{ns}	$F_3 = 0.832$ ^{ns}	$F_3 = 1.518$ ^{ns}	$F_1 = 3.568$ ‘	$F_3 = 0.306$ ^{ns}
SBD	(cm)	$F_3 = 20.100$ ***	$F_1 = 2.285$ ^{ns}	$F_1 = 16.983$ ***	$F_3 = 0.568$ ^{ns}	$F_3 = 8.452$ ***	$F_1 = 7.751$ **	$F_3 = 3.232$ *
H	(m)	$F_3 = 20.311$ ***	$F_1 = 0.234$ ^{ns}	–	$F_3 = 0.371$ ^{ns}	–	–	–
$\mathrm{Biom_{Harv}}$	($\mathrm{t_{odt}\ ha^{-1}}$)	$F_4 = 28.334$ ***	$F_1 = 7.052$ *	–	$F_4 = 5.103$ **	–	–	–
$\mathrm{Biom_{Eq}}$	($\mathrm{t_{odt}\ ha^{-1}}$)	$F_3 = 15.869$ ***	$F_1 = 5.032$ *	$F_1 = 26.887$ ***	$F_3 = 1.923$ ^{ns}	$F_3 = 3.165$ *	$F_1 = 4.202$ *	$F_3 = 1.929$ ^{ns}

The *F*-values of fixed effects with the corresponding degrees of freedom as subscripts are listed. Level of significance of the effects is indicated by asterisks

ns nonsignificant

‘$p < 0.1$; *$p < 0.05$; **$p < 0.01$; ***$p < 0.001$

Table 8 The variance-covariance structure of the respective model (*bor* border rows, *in* inner rows)

Traits	Units	Random effects variance		Residual variance	Variance factor									
		Field	Plot		BA		BL		PM		WI		NM	
					bor	in	bor	in	bor	in	bor	in	bor	in
Shoots	(N $\mathrm{ha^{-1}}$)	37.406^2	826.714^2	3612.718^2	1.00	0.76	0.80	0.01	0.66	0.84	4.62	2.10	–	–
SBD	(cm)	0.015^2	0.335^2	1.294^2	1.00		1.44		0.99		0.64		–	
H	(m)	0.042^2	0.655^2	0.891^2	1.00		2.08		1.15		0.66		–	
$\mathrm{Biom_{Harv}}$	($\mathrm{t_{odt}\ ha^{-1}}$)	–	–	4.322^2	1.00		1.56		1.38		0.68		1.59	
$\mathrm{Biom_{Eq}}$	($\mathrm{t_{odt}\ ha^{-1}}$)	–	–	6.630^2	1.69	1.00	3.19	1.89	2.10	1.24	1.61	0.95	–	–

BA black alder, *BL* black locust, *PA* poplar Androscoggin, *PM* poplar Max 3, *WI* willow Inger, *NM* native mix

Table 9 Analysis of the effect of row position (if available) on different traits (number of shoots, stem base diameter (SBD), height (H), harvested biomass ($\mathrm{Biom_{Harv}}$), and calculated biomass ($\mathrm{Biom_{Eq}}$)) of poplar Androscoggin using ANOVA

		Fixed effects	Random effects variance	Residual variance	Variance factor	
Traits	Units	Row position	Plot		bor	in
Shoots	(N $\mathrm{ha^{-1}}$)	$F_1 = 2.014$ ^{ns}	27.050^2	2703.238^2	1.00	0.38
SBD	(cm)	$F_1 = 7.727$ **	0.767^2	1.421^2	–	–
H	(m)	–	1.193^2	1.332^2	–	–
$\mathrm{Biom_{Harv}}$	($\mathrm{t_{odt}\ ha^{-1}}$)	–	–	12.960^2	–	–
$\mathrm{Biom_{Eq}}$	($\mathrm{t_{odt}\ ha^{-1}}$)	$F_1 = 2.147$ ^{ns}	–	10.977^2	2.73	1.00

The *F*-values of fixed effects with the corresponding degrees of freedom as subscripts and the variance-covariance structure of the respective model (*bor* border rows, *in* inner rows) are listed. Level of significance of the effects is indicated by asterisks

ns nonsignificant

**$p < 0.01$

Table 10 Mean of different species traits for each farming system (*con* conventional, *org* organic) and row position (*bor* border, *in* inner), and the respective standard errors (SE)

Trait	Farming system	Row position	Tree species				
			Black alder Mean ± SE	Black locust Mean ± SE	Poplar Androscoggin Mean ± SE	Poplar Max 3 Mean ± SE	Willow Inger Mean ± SE
Shoots (N ha^{-1})	con	bor	22,518.5 ± 1513.2	21,333.3 ± 1944.6	20,740.7 ± 1560.8	19,851.9 ± 1832.6	39,111.1 ± 9757.1
		in	20,148.2 ± 1853.8	19,259.3 ± 2194.3	18,370.4 ± 1670.4	18,074.1 ± 2432.0	26,666.7 ± 10740.8
	org	bor	18,963.0 ± 2140.1	18,963.0 ± 2750.1	–	18,074.1 ± 2591.7	48,000.0 ± 13798.6
		in	18,666.7 ± 2621.7	18,370.4 ± 3103.2	–	20,148.2 ± 3440.8	31,407.4 ± 15189.7
SBD (cm)	con	bor	5.3 ± 0.2	4.8 ± 0.4	5.9 ± 0.5	5.8 ± 0.3	3.5 ± 0.3
		in	5.0 ± 0.2	4.0 ± 0.4	4.8 ± 0.4	4.3 ± 0.3	3.5 ± 0.3
	org	bor	5.5 ± 0.3	4.8 ± 0.5	–	5.3 ± 0.4	3.9 ± 0.5
		in	5.0 ± 0.3	4.1 ± 0.6	–	5.1 ± 0.5	4.3 ± 0.5
H (m)	con	bor	–	–	–	–	–
		in	5.2 ± 0.3	4.8 ± 0.5	7.3 ± 0.7	7.1 ± 0.4	5.9 ± 0.5
	org	bor	–	–	–	–	–
		in	4.9 ± 0.4	4.5 ± 0.7	–	7.2 ± 0.7	6.4 ± 0.9
$Biom_{Eq}$ (t_{odt} ha^{-1})	con	bor	42.9 ± 5.3	58.2 ± 11.4	67.1 ± 18.4	69.9 ± 8.4	28.8 ± 8.9
		in	33.5 ± 2.7	41.4 ± 5.8	40.1 ± 6.3	33.2 ± 4.3	20.4 ± 4.5
	org	bor	41.4 ± 7.5	60.3 ± 16.1	–	57.9 ± 11.9	33.3 ± 12.6
		in	33.9 ± 3.8	40.2 ± 8.2	–	49.2 ± 6.1	33.8 ± 6.4

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First-rotation growth and stand structure dynamics of tree species in organic and conventional short-rotation agroforestry systems

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Abstract

Short-rotation agroforestry systems can potentially maintain agricultural production and promote conservation of soil and biodiversity, especially if grown organically. Hereby, species-specific stand growth determines woody biomass yield and influences management decisions like planting density and harvest requirements. Studies of longer-term growth dynamics in Southern Germany are scarce and none analyzed differences between conventional and organic systems. In this study, four tree species (black alder, black locust, poplar clone Max 3, and willow clone Inger) were planted in an alley-cropping configuration in Southern Germany, grown under organic and conventional systems, and monitored from 2009 to 2012. Growth was assessed with stem base diameter, height, aboveground woody biomass, sprouting, and survival. The tree species did not show a uniform ranking in biometric variables and biomass over time. Four-year mean annual biomass increment (MAI) ranged from 7 to 10 t ha^{-1} a^{-1}, with poplar and locust having the highest growth rates. Willow had the lowest MAI, as it had a low diameter growth paired with a low wood density, but it developed the highest number of shoots because of increased sprouting in the

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last year. Size inequality and skewness of the dominant stems increased for all species throughout the years suggesting asymmetric competition. Size inequality as well as mortality was greatest for black locust. Furthermore this was the only species, which developed a right skewed SBD distribution and the highest diameter size range. Size inequality was smallest for poplar and willow, with no or only minimal mortality. Alder was inbetween. For black locust and alder no difference in growth traits between organic and conventional systems appeared after four years. Organic poplar and willow stands performed better than conventional ones after the second year, leaving unclear whether this can be attributed to management or site effect.

Keywords: Agriculture, Environmental science, Plant biology

1. Introduction

Biomass from short rotation agroforestry systems (SRAFS), mostly planted as alley cropping configuration, and short rotation coppices (SRC) have garnered great interest as feedstock for renewable energy. By sequestering carbon and substituting fossil fuels, those systems help to mitigate climate change and reach the EU climate and renewable energy policy targets [1]. In addition, multiple positive environmental impacts are provided by implementing such systems, including biodiversity benefits and soil and water protection [2, 3].

To be commercially feasible as well as to enhance carbon storage and energy use efficiency, high yields have to be sustained. Hybrids of the poplar and willow genera were pronounced to be the most yielding species [4, 5, 6]. Also locust and alder were found to be well suited as short rotation crops, especially on less fertile sites, where they benefit from their ability to fix atmospheric nitrogen [7, 8, 9, 10]. Depending on species-specific growth patterns, ecophysiological mechanisms and interactions, the performance of individual species and clones varies during and between rotations according to site conditions (climate, soil properties, diseases, insects) and management (fertilization, irrigation, planting density, weed control, planting configuration). Therewith, in SRC a wide range of yield dynamics have been reported for poplar [11, 12, 13, 14, 15], willow [16, 17, 18, 19], but also within family variation for alder [20] and black locust [7]. Although some studies exist on the suitability of various tree species as short rotation crops in Germany [8, 10, 21, 22], only few were conducted in southern Germany on fertile [23, 24, 25] and marginal land [25, 26]. Furthermore, only few studies dealt with the growth performance in SRAFS with an alley configuration, where edge effects highly influence total woody biomass yields [22]. Even less studies were performed at organic SRAFS [25, 27], and to the authors' best knowledge none that compares organic and conventional systems.

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Besides total yield at the end of the rotation, the knowledge of growth dynamics is essential to determine optimal harvest cycles and to assess the influence of specific management choices or climatic conditions. Furthermore, the development of stand structures and the distribution of tree dimensions are also crucial for management decisions. For instance, for bioenergy purposes the maximum diameter is restricted by direct chip harvesting methods [28]. Also, the higher ash content in small diameter trees, which is mainly related to the amount of bark, lowers fuel quality [28, 29] and increases nutrient removal [24]. Besides, an unequal stand development may also lead to mortality of individuals, which may impact total biomass production during later rotations [30]. Competition is the main d river leading to changes in size and weight distributions within a stand and thus towards an increasing inequality between dominant and suppressed plants [31]. According to Tomé and Verwijst [30], competition between individual plants is enforced in SRFS, which mostly consist of one single species or clone where plants are genetically alike. Thus, they compete similarly for available resources. Furthermore, the spacing is dense and shoots are already under heavy competition during the first growing season. This is enhanced by the high initial growth rate of the species used in SRC and SRAFS, causing an earlier canopy closure and therewith an earlier onset of competition [30]. Although stand structure, growth dynamics, harvesting methods and wood usage are highly interdependent, studies about SRFS still often neglect stand hierarchies.

This study aims at closing the aforementioned knowledge gaps concerning growth dynamics and stand structure development of tree species under different growth-preconditions and to provide cultivation and usage recommendations. Therefore, both organic and conventional SRAFS of four tree species (black alder, black locust, poplar clone Max 3, willow clone Inger) were established in a long-term field trial at a research farm in southern Germany. The effects of species, age, and 21-year organic and conventional farming on yield and stand structure were evaluated by monitoring sprouting, stem diameter, tree height and aboveground woody biomass during the first four-year rotation of the SRAFS.

2. Materials and methods

2.1. Study area and agroforestry design

The study was performed at the Scheyern experimental farm (48°30′N, 11°21′E) in Bavaria, southern Germany. The farm consists of many independent fields in hilly terrain. Meteorological data were obtained from the nearby Altomünster-Maisbrunn weather station (48°24′ N, 11°19′ E) of the Deutscher Wetterdienst (DWD). The climate is temperate with an annual average temperature of 8.9 °C, 7.8 °C, 9.3 °C, and 9.0 °C and an annual precipitation of 804 mm, 902 mm, 664 mm, and

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841 for the years 2009−2012, respectively (Fig. 1). The long-term average (1981−2010) is 8.3 °C and 887 mm. Precipitation during the growing season (April to September) of the establishment year 2009 was above average. The season 2011 was marked by a prolonged drought (April, May, June, and August).

In 1992, the farm had been subdivided into an organic and conventional farming system, and each system was applied to different fields. The organic system is a low-input system and since 2005 maintained as an organic arable farming without livestock. It is based on a seven-field crop rotation with 29% grass-clover-alfalfa, 29% winter wheat, 14% potato, 14% sunflower, 14% winter rye. Mineral nitrogen and chemico-synthetic plant protection products are omitted. Tillage is carried out with a moldboard plow. The conventional system is a high-input system with chemico-synthetic plant protection use, mineral nitrogen input (on average 179 kg N ha^{-1} y^{-1} for 2009−2012 [32]) and a simple structured crop rotation with 50% wheat, 25% forage maize, and 25% potato. Here conservation tillage is applied

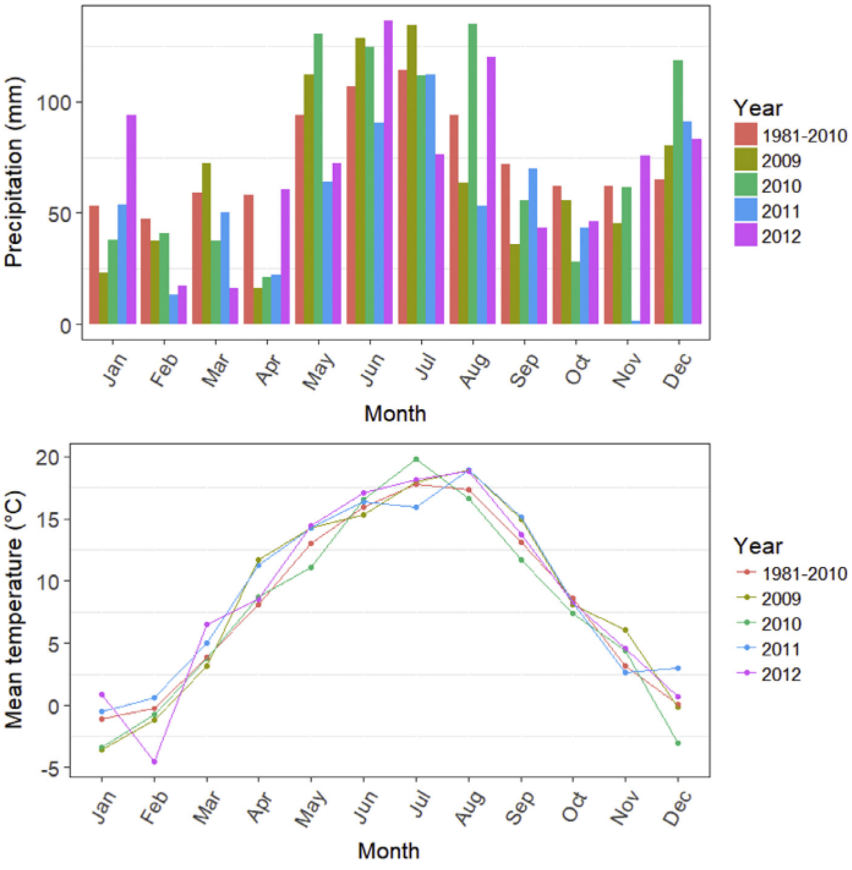

Fig. 1. Sum of monthly precipitation (mm) and monthly mean temperature (°C). Data from a meteorological station near the experimental site showing both the long-term average for the years 1981−2010 and annual values during the first rotation from 2009−2012.

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(no plowing, crop residue incorporation with a grubber, mustard catch crop). This systems has significantly higher agricultural crops yields [32, 33].

Fig. 2. Experimental design of the agroforestry systems at the Scheyern experimental farm (48°30′N, 11°21′E) in Bavaria, southern Germany. Three strips of various species were planted on four fields (two organic, two conventional). Published in Hülsbergen et al. [34].

In April 2009, short-rotation agroforestry systems (SRAFS) were established in four fields of the farm, two for each farming system (Fig. 2). The altitude varies between 450 and 550 m above sea level with a 2−10% slope. Soils have a loamy texture and are classified as either Cambisols or Eutrochrepts with thin layer of loess, Cambisol with sand and gravel subsoil (sandy-gravelly illuvial horizon) or small-scale clay soils [35].

On every field, three strips of different fast-growing tree species were planted in a north−south (three of the four fields) or west−east direction (one of the four fields), with a spacing of 30 m for the field crops in between. Tree species were allocated randomly in blocks inside each strip. Inside each strip, trees were planted in three double rows (8.25 m wide) accommodating a density of 17,778 cuttings per ha. In this study, only the middle row was used for analysis because of significant border effects (see Huber et al. [36]). The studied species were black alder (*Alnus glutinosa*), black locust (*Robinia pseudoacacia*), poplar clone Max 3 (*Populus maximowiczii* × *P. nigra*), and willow clone Inger (*Salix triandra* × *S. viminalis*). Thus the study design is a randomized block design that includes 4 fields x 3 strips x 4 species. An exception is willow, which was only planted in two fields (one conventional and one organic). Such a design was chosen because it was impossible to randomize farming systems due to the agricultural constraints, and unfeasible not to plant the species in blocks. A more detailed description of the field experimental design has been published by Huber et al. [36].

Poplar and willow cuttings, approximately 20 cm in length, were planted manually to a depth of 15 cm. The other species, 70−90 cm in length, were planted manually as bare-rooted saplings. The tree strips were not manured, but weeds were controlled by herbicide application (conventional system) and mechanical weeding (organic system) in the first year of establishment. No further weed control or fertilizer applications were provided.

After more than 20 years, the farming system differences did not lead to a significant difference in the initial nutrient status of the soil of the SRAFS area (Table 1, published in Huber et al. [37]). Only soil organic carbon and potassium were slightly higher in the organic farming system, whereas phosphorus was slightly higher in the conventional farming system.

2.2. Measurements

Measurements were made at the end of each growing season, on a selection of 10 individuals in the middle double row of each species in each strip (2.25 m × 2.5 m area), giving 120 individuals for each year and species (10 trees × 3 strips × 4 fields), respectively. Willow was planted on only two of four fields, resulting in one half of measured individuals, which is 60.

Table 1. Soil properties at 0−30 cm depth in conventional and organic farming systems at the beginning of the experiment in 2009.

Component	Unit	Conventional farming Mean ± SE	Organic farming Mean ± SE
C org	% by mass	1.11 ± 0.07^a	1.17 ± 0.10^a
N org	% by mass	0.11 ± 0.01^a	0.11 ± 0.01^a
pH		5.4 ± 0.1^a	5.5 ± 0.2^a
P	kg ha^{-1}	5.2 ± 1.4^a	3.5 ± 1.9^a
K	kg ha^{-1}	8.8 ± 1.4^a	9.6 ± 2.0^a

Mean organic carbon (C org), organic nitrogen (N org), pH, available phosphorus (P), available potassium (K), and the respective standard errors (SE).

Reprinted by permission from Springer Nature, Springer Nature, European Journal of Forest Research, Allometric tree biomass models of various species grown in short-rotation agroforestry systems, Julia A. Huber, Katharina May, Kurt-Jürgen Hülsbergen, © Springer-Verlag Berlin Heidelberg, 2016 (https://link.springer.com/journal/10342) [37].

[a] Farming systems sharing the same letter are not significantly different from each other (Tukey-HSD, $p > 0.05$).

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Stem base diameter (SBD, at 10 cm above soil) was measured for all shoots of an individual tree in two perpendicular directions using a caliper and the mean value was used in further calculations. Height (H; in m) was measured only for the dominant shoot using a Vertex hypsometer. Because most trees rarely developed more than two dominant shoots, sprouting performance was assessed by summing up the number of shoots of the measured trees and converting it to hectares. Dead trees were counted and replaced with other trees for measurements. Aboveground leafless dry biomass was estimated by allometric functions that predict individual tree dry biomass from SBD, retrieved from a previous study on the same study site [37],

$$M_i = \beta_{0j} SBD_i^{\beta_1} \tag{1}$$

where M is the total aboveground oven dry mass for a specific stem base diameter SBD, β_0 describes the allometric factor, and β_1 describes the allometric exponent. The additional index i refers to the individual tree and index j indicates the species-specific factors listed in Table 2. The equation was applied to all shoots. Single-shoot biomasses were summed for each species plot and yield at stand level (in t ha^{-1}) was calculated. Subsequently, mean annual increment (MAI) is calculated as the accumulated stand yield divided by stand age, while current annual increment (CAI) is the change in size in the current year. All biomass values are expressed as oven dry mass.

2.3. Analysis

Density curves were computed considering all or dominant shoots. For each distribution, skewness was determined to quantify size asymmetry by reflecting the proportion of large to small individuals [38]. The Gini-coefficient (G) was used to quantify size inequality [31], which is given by

$$G = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n}\left|x_i - x_j\right|}{2n^2\overline{x}} \tag{2}$$

Table 2. Allometric coefficients to calculate aboveground biomass of different tree species, where β_0 describes the allometric factor and β_1 the allometric exponent with stem base diameter (SBD in cm) as explaining variable.

Tree species	β_0	β_1
Black alder	0.025	2.603
Black locust	0.041	2.603
Poplar Max 3	0.036	2.603
Willow Inger	0.037	2.603

Adapted by permission from Springer Nature: Springer Nature, European Journal of Forest Research, Allometric tree biomass models of various species grown in short-rotation agroforestry systems, Julia A. Huber, Katharina May, Kurt-Jürgen Hülsbergen, © Springer-Verlag Berlin Heidelberg, 2016 [37].

where x_i and x_j are the sizes of individuals i and j, respectively. G reflects the variation between individuals or the dominance of the larger individuals, and when G equals zero, size equality is perfect.

While the study design includes three replicate strips inside each of the four fields, the four fields are so different to each other that the strips are not comparable between fields (except possibly the two organic fields, which are directly next to each other). Thus, a standard ANOVA was unfeasible. Instead, we chose to include a field-strip factor ($4*3 = 12$ levels) as a random effect in the analysis to account for any field-strip effects.

Mean biomass, SBD, H, and shoot density were each modelled separately using a mixed effects model. Only the dominant shoot was used to avoid underestimation. Each model included the three-way interaction between species (4 levels), farming system (2 levels, organic and conventional), and year (4 levels, 2009−2012). We explicitly chose to include year as a factor, since this study focuses on growth dynamics. Since the variation of the response variables (biomass, SBD, …) increased with year, model residuals were not homoscedastic and the residual variance increased with year. To account for this, a weighting of observations was introduced such that the error variance was allowed to vary by year, that is $Var(\varepsilon_i) = \sigma^2\phi_{year(i)}$, where ε_i is the model residual of observation i, σ is the residual variance, *year(i)* is the year of observation i, and ϕ_{year} are estimated variance ratios for the years 2010, 2011, and 2012, relative to the first year 2009 with $\phi_{2009} = 1$.

We are aware that the study design can only determine observationally any farming system effects. To test, whether we have not mistakenly interpreted farming effects as field effects, we conducted the same analysis as before but exchanged the Management factor with a field factor. Also, willow was dropped from this analysis since it was only planted on two fields. The results showed significant field-species interactions and that significant differences between fields occurred mostly between cropping systems and not within. So we left the Management factor inside the original model formulation, since for practioners it is of more value to know about management differences than field differences.

All computations and statistical analyses were performed with R software version 3.4.3. Models were estimated using the lme-function in R package nlme [39]. Pairwise differences between species and clones within each year and farming system were determined by a post hoc analysis (similar to Tukey's HSD for normal ANOVAs) using R package lsmeans [40]. P-values of the posthoc tests were adjusted for multiple testing. If not stated otherwise, p-values below 0.05 denote significance.

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3. Results

3.1. Sprouting and mortality

Initial plant density was equal for all species (17,778), but sprouting and mortality resulted in different shoot densities during the rotation (Fig. 3) The mixed models revealed for the shoot density significant three-way interactions between year, species and management for ($p = 0.049$) (Table 3). After the first year, and more distinct at the conventional system, poplar and willow developed more shoots per tree,

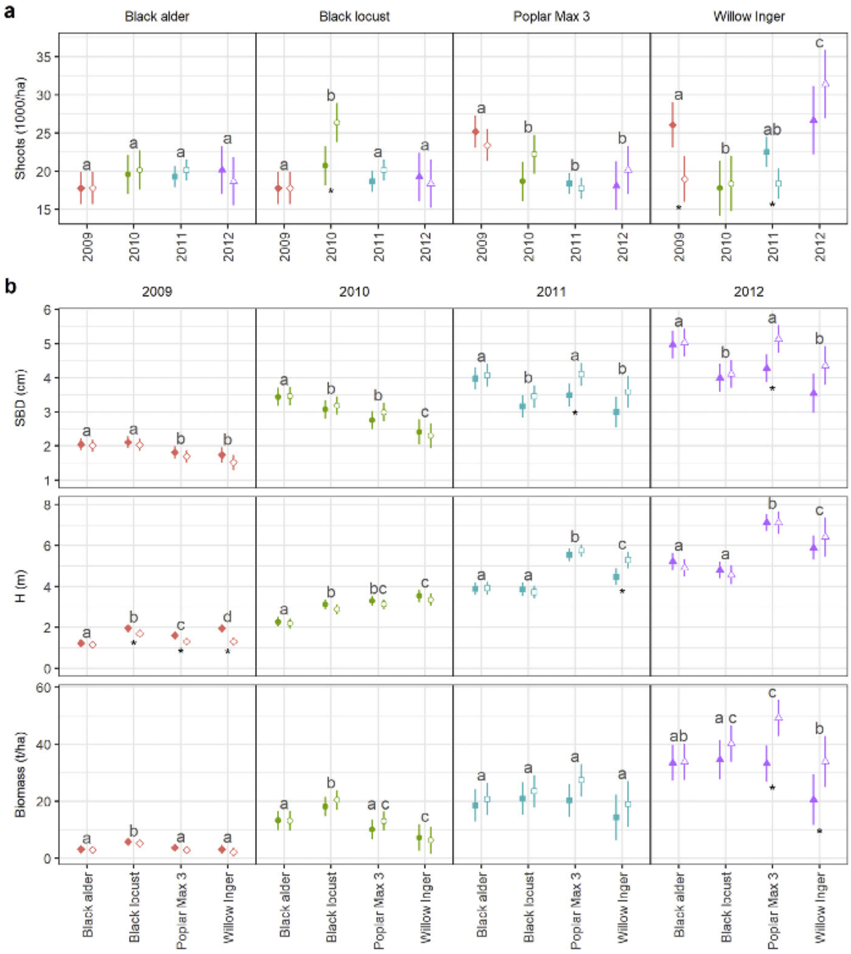

Fig. 3. Modelled mean values of a) shoot density and b) stem base diameter (SBD), tree height (H), and biomass over the first rotation of the short rotation agroforestry systems. Shown are means with 95% confidence intervals of the conventional (solid points) and organic (hollow points) farming systems. In a) years were compared within species, and years sharing the same letter are not significantly different ($p > 0.05$). In b) species were compared within years, and species sharing the same letter are not significantly different ($p > 0.05$). Asterisks indicate significant differences between farming systems ($p < 0.05$). Biomass values were modelled by allometric functions using stem base diameter as predictive variable. To avoid underestimation, only the main stem was used for analysis.

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Table 3. ANOVA results for the mixed effects models of Shoots, SBD, Height, and Biomass. Shown are F and associated p values for a sequential ANOVA. Colon (:) in the variable column denotes interactions; df is degrees of freedom. See also methods section for full details on the mixed models.

Variable	df	Shoots		SBD		Height		Biomass	
		F	p	F	p	F	p	F	p
(Intercept)	1	13347.391	<.0001	3307.615	<.0001	2687.2729	<.0001	464.4279	<.0001
Vegetation period	3	4.766	0.0035	761.920	<.0001	2163.0368	<.0001	452.3879	<.0001
Tree species	3	5.237	0.0019	40.263	<.0001	114.7499	<.0001	24.2009	<.0001
Management	1	0.105	0.7531	0.064	0.8055	6.5943	0.0280	0.1020	0.7560
Vegetation period: Tree species	9	13.702	<.0001	9.398	<.0001	54.1796	<.0001	5.3453	<.0001
Vegetation period: Management	3	5.135	0.0022	9.140	<.0001	6.2916	0.0003	7.7991	0.0001
Tree species: Management	3	6.158	0.0006	0.582	0.6272	3.7447	0.0107	0.0925	0.9641
Vegetation period: Tree species: Management	9	1.963	0.0490	1.559	0.1224	3.0888	0.0011	1.3385	0.2238

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whereas black alder and black locust mainly had one shoot. In the second year, and more intense on the organic system (significant system difference for locust), sprouting was stimulated for black alder and black locust. 3% tree mortality was detected for conventional locust, 1% for organic alder. For poplar and willow no tree mortality was recorded and shoot density decreased, mainly at the conventional system (significant system difference for poplar). After the third year, shoot density had again increased for willow at the conventional system, but decreased for poplar and black locust mainly on organic systems. Stand density stayed on the same level for alder and organic willow. No further tree mortality was recorded in this year. While the shoot density had decreased after the fourth year for organic alder (9% tree mortality in total), organic black locust (3% tree mortality), and conventional poplar (4% tree mortality), it had increased for conventional alder (5% tree mortality), conventional black locust (13% tree mortality), organic poplar (no tree mortality), and willow on both systems (no tree mortality).

3.2. Change of size distributions

After the first year, all species except organic poplar stands, showed a positively skewed SBD distribution of the main stems (Figs. 4 and 5). During growth, the SBD distribution of black alder, poplar and willow became more and more left skewed. Negative skewness resulted from the presence of some very small individuals in the stands, with most values concentrated in the higher size classes (on the right side of the mean). The SBD distribution of locust stands were always right skewed and skewness increased during growth. Distribution of organic locust stands were less skewed and became almost bimodal in 2012, as those stands had a greater portion of big trees growing. H distributions started mostly left skewed (except conventional willow and poplar stands) and skewness mainly became stronger over time. Only organic poplar stands developed bimodality in the last year, and black locust distribution stayed more or less with the same skewness value.

Black locust developed the most unequal SBD and H distributions among all species. Inequality increased during the rotation due to growth of dominant trees and growth reduction of suppressed trees. For conventional alder, poplar and willow stands, the inequality of the SBD distribution was highest in the last two (poplar, willow) or three (alder) years, since a greater portion of small trees that were still alive stayed behind. Trees of the organic stands grew more equally and inequality decreased in the last (alder) or last two (poplar, willow) years. In the case of alder the mortality of small trees may have influenced this (Fig. 3). Inequality of the H distribution was lower than that of the SBD distribution due to a more equal development of the whole stand.

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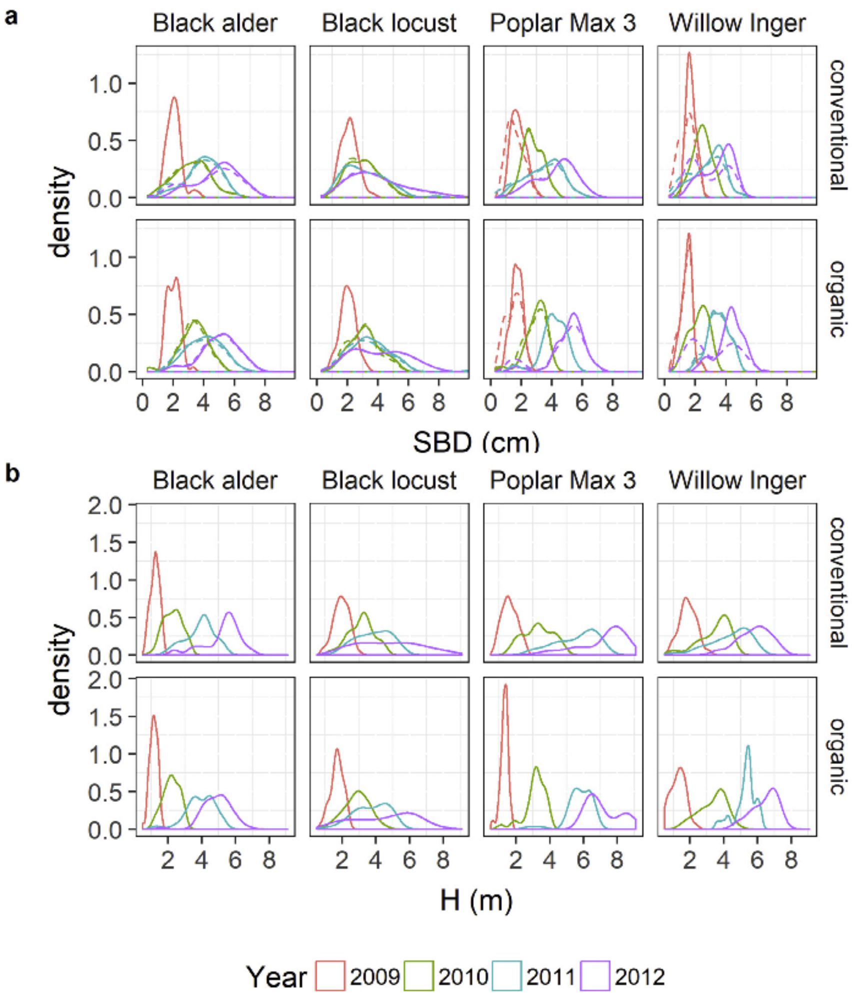

Fig. 4. Density plots per year of a) the stem base diameter (SBD) and b) tree height (H) distributions of all shoots (dashed line, only for SBD), and of only main stems (solid line) in a conventional and organic short-rotation agroforestry system for different tree species.

The inclusion of sprouts increased the amount of small trees and total size ranges and therewith inequality. In the last year, intensive sprouting at willow and organic poplar stands led to bimodality of their distribution.

3.3. Mean growth

The mixed models revealed significant three-way interactions between year, species and management for Height ($p = 0.001$), but not for SBD ($p = 0.12$) and biomass ($p = 0.22$); see also Table 3. For SBD and biomass, significant two-way interactions between year and species as well as between year and management were observed (all $p < 0.001$), while there were no significant interactions between species and management (both $p > 0.05$).

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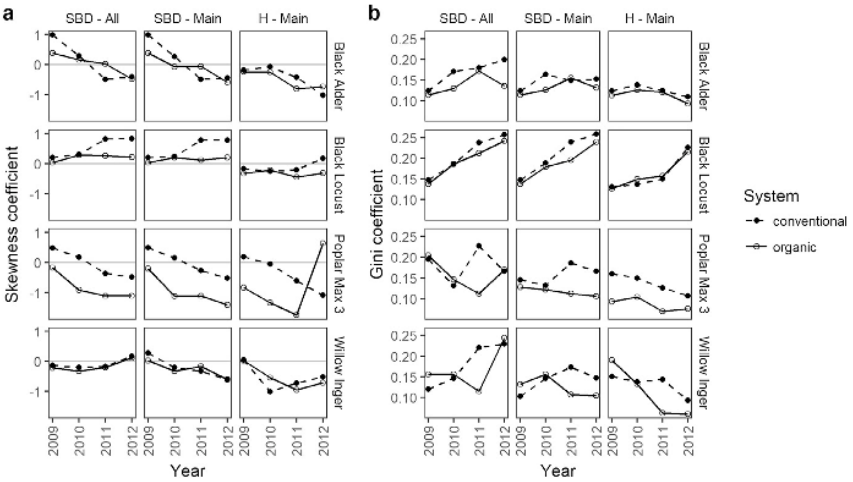

Fig. 5. a) Skewness and b) inequality (Gini coefficient) of stem base diameter (SBD) and tree height (H) distribution of different tree species and farming systems after each year of growth. All shoots (All) or main stems (Main) were considered.

After the first year, mean SBD of alder and black locust was significantly higher than of poplar and willow (Fig. 3). Since alder and black locust were planted as bare root saplings, they had a substantial advantage over the other two species, which were planted as cuttings and therewith needed time to establish rooting systems. Additionally, mean H was significantly greatest for black locust, but significantly lowest for alder, whereas poplar and willow were in between. Consequently, black locust developed the significantly highest biomass (5.5 t ha^{-1}), followed by poplar (3.4 t ha^{-1}), alder (3.1 t ha^{-1}), and willow (2.7 t ha^{-1}). The conventional system had higher values than the organic, however, only significant for H of black locust, poplar and willow.

After the second year, the high current annual increment (CAI) of SBD for alder resulted in the significantly highest SBD among species, and the low CAI for willow in the significantly lowest SBD. Regarding H, poplar and willow had a higher CAI than the other two species. Therefore, the clonal ranking for H has changed: Willow had the greatest and poplar the second greatest tree height. Black locust had the highest CAI of biomass (13.9 t ha^{-1} a^{-1}), followed by alder (10.1 t ha^{-1} a^{-1}), poplar (8.3 t ha^{-1} a^{-1}), and willow (4.1 t ha^{-1} a^{-1}). For all tree variables, the organic system showed a higher mean CAI than the conventional. Subsequently, the differences in mean H between the systems had become lower. Furthermore, mean SBD and biomass of organic tree stands was even higher than of conventional stands, except for willow. This was also due to some small trees in the conventional system, reducing the overall mean.

In the third year, mean increase in SBD had lowered for all species, especially for black locust, which almost did not grow at all. However, the H increased and for alder and poplar even more than in the previous year. The CAI of biomass was reduced to 6.5 t ha^{-1} a^{-1} for alder and to 2.9 t ha^{-1} a^{-1} for black locust, but enhanced to 12.3 t ha^{-1} a^{-1} for poplar and to 9.9 t ha^{-1} a^{-1} for willow. Species ranking in terms of SBD had changed to black locust and willow having the significantly lowest values, and in terms of H and biomass to poplar having the highest values (only for H significant). Growth of alder and black locust was probably inhibited because of the low precipitation during the vegetation period 2011 (Fig. 1). Furthermore, a late budburst was detected for locust because of frost events in spring. Again, the organic stands showed higher CAIs for all variables compared to the conventional stands, except for H of locust. The difference was significant for SBD of poplar and for H of willow. Main reasons for this may be the larger stand separation in conventional poplar and willow stands (the reduced growth of the smallest) and the uniform growth of the whole organic stands.

After the fourth year, the tree species showed an elevated growth in mean SBD and biomass, but lowered growth of H, except for black locust. At the end of the rotation, poplar developed a mean SBD comparable to alder, whereas black locust and willow achieved significantly lower mean SBD. Mean height was significantly greatest for poplar, lower for willow and significantly lowest for alder and black locust. For all species the CAI of biomass was greatest in this year and with this also MAI, except for locust due to the low growth in the third year. The highest rotation MAI of biomass was observed for poplar (10.3 t ha^{-1}), followed by black locust (9.4 t ha^{-1}), alder (8.4 t ha^{-1}) and willow (6.8 t ha^{-1}) in decreasing order. The ranking of the clones in terms of SBD was not in agreement with the observed biomass production, since wood density, branching patterns and size distribution also play an important role. By summing up the single tree biomasses, which were greatest in black locust, high stand biomass can be achieved. Although mean diameter and height were lowest for black locust, the biomass production was still comparable to that of poplar. The organic stands of alder and black locust had lower CAIs of SBD and H, and for alder also of biomass, than the conventional stands. In contrast, organic poplar and willow had much higher mean CAIs than the conventional stands, strengthened by the suppression of lower diameter classes. Finally, mean SBDs were higher in organic stands, however only for poplar significant. System differences in terms of biomass were significant for poplar and willow.

4. Discussion

4.1. Development of size hierarchies

In the initial development stage of a stand, the rate of individual tree growth is solely a function of age, species and abiotic site factors. Small trees grow without competitive interaction because the site is not fully occupied and resources are not fully

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exploited [41]. Therefore, population recruitment may continue and subordinate weeds may establish [41]. Also at this study site, additional shoots emerged in the first or second growth period because of to the availability of space. The size distribution was mostly normal, which is typical before competition initiates [41].

When stands develop further, the growth of small trees is inhibited because of shading by taller neighbors, while larger trees are less affected and continue their growth [41]. Consequently, the size variability increases and the size distribution become increasingly skewed and unequal due to intraspecific competition. In our study, all species showed a strong increase of their size range as well as an increase of inequality and asymmetry with plantation age. Except for locust, the size distribution became negatively skewed due to the steady growth of the larger trees and suppression of some small individuals under the main canopy. Locust had the most unequal stand and in contrast to the other species a positively skewed distribution with only few dominant and many suppressed individuals. In the study of Laureysens et al. [38], poplar size distributions were mainly right skewed for most clones during the 4 year rotation, and skewness decreased markedly because of the rapid elimination of the smaller shoots. However, size distributions of clones with a slow mortality of the smaller shoots still remained highly skewed at the end of the rotation.

With certain increase of tree size, suppressed trees [41, 42] as well as shoots within one tree [43] die. This natural self-thinning coincides with canopy closure [41]. The intraspecific competitive ability of trees is species- and even clone-specific and determined by specific biomass accumulation strategies, tree dimensions, leaf morphologies and canopy architectures [42, 44]. In this study, locust, alder and poplar reached canopy closure. Subsequently, those stands not only developed a size hierarchy but also underwent a loss of shoots and whole trees during the rotation. With the absence of disease or disturbances this can be attributed to self-thinning. Tree mortality was highest in black locust and alder stands, which developed the most widespread crown, and has also been reported in Huber et al. [36]. The high stand inequality, the positively skewed distribution, and the higher tree mortality indicates a stronger decline of competitiveness for black locust than for all other species. Poplar developed a orthotropic monopodial trunk with narrow crowns and small branches [36, 37, 45], probably explaining a lower between-plant competition. In contrast to the other species, canopy closure of willow had not yet been attained since the trees mostly had not more than two thin and seldomly branched shoots (see also Huber et al. [36]). Therewith, no loss of trees was recorded, and even more, new sprouts emerged already in the third growth period leading to a bimodal distribution. Willows high ability to produce more shoots when space is available was already recognized [43, 46]. In the study of Cienciala and Lindroth [46], already during the second year of a coppiced willow plantation the mortality of the smallest individuals made the initial bimodality disappear and the weight-frequency

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distributions positively skewed. With longer rotations and progressing stand development, size distributions of willow, but also of poplar and alder, may have changed to being positively skewed as well. Competition for light may not be the main driving force for shoot elimination. The suppression and removal of smaller shoots may also be caused by limited resource supply from the roots, leader shoots restoring apical dominance [38], or climatic factors and pathogens [30].

4.2. Temporal evolution of biometric variables and biomass

The biomass of black locust was comparable to poplar, although its mean diameter and height were lower. This was because black locust had some high diameter trees and the highest wood density (0.60 g cm^{-3} [47]) compared to the other species ($\rho_{Alder} = 0.40$ g cm^{-3}, $\rho_{Poplar} = 0.34$ g cm^{-3}, and $\rho_{Willow} = 0.34$ g cm^{-3}; [47, 48]). Species ranking in biomass changed in the third year because of the high growth of poplar and reduced growth of black locust, which was likely a result of the observed late budburst because of frost damage. Although physiological adaptation to cold climates was found for black locust, stem dieback and a lowered growth rate had also been reported in response to cold [49]. Black alder is reported to be relatively tolerant to late autumnal and early spring frosts [9], while frost tolerances of willow and poplar depends on clone [50].

In the third year, H growth rate remained high, whereas an overall growth decline of SBD was observed. This may be caused by the low precipitation in that year, which could have resulted in a soil water deficit. However, water limitation was shown to reduce H growth in favor of SBD growth, reducing the length of the hydraulic transport system and embolism risk [51]. In contrast, competition for light makes it advantageous to increase height growth relative to diameter growth [52]. In our study, tree height variability was lower than SBD variability, i.e. trees of different diameters had comparable heights. This underlines that subdominant trees enhanced their height growth at cost of their diameter growth to improve access to light [53]. This was particularly present for willow, poplar and alder, whereas locust showed a wider H range. Maybe a trade-off between resource allocation in H and SBD favored H growth despite the reduced water availability.

All tree species showed the highest growth rate in the fourth year. Also in the study of Heinsoo et al. [50] most willow trees performed best at the end of the first four-year rotation period, and Kauter et al. [28] recommend a minimum rotation length of 5−10 years for poplar species. For all species, the maximum biomass growth was probably not yet reached. This is mostly evident for willow that did not yet fully occupy the available space. Early coppicing of willow can promote multiple-stem regrowth, which is supposed to increase final biomass production [14, 18, 54]. Extending rotation cycles would also enhance productivity of the plantation. However, technical restrictions by tree diameter (black locust already developed SBDs up to

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9.3 cm) according to harvest or wood usage [26] may put a limit to the extension of the rotation period.

Furthermore, after cutting the trees at the end of the rotation, resprouting can differ among tree species and throughout the next rotations. Therewith, biomass production may differ in the following rotations, possibly resulting in a change in species ranking. Here, further research on the following rotations is needed.

4.3. Influence of farming system and site differences

Nitrogen fertilization has been shown to increase woody biomass yields or early culmination of biomass increment [7, 55], even for black locust, in spite of its capability to fix atmospheric nitrogen [7]. Likewise, favorable edaphic conditions can also increase the biomass yields of SRC [18]. At our research station, the yields of the conventionally managed and fertilized crops exceeded those of the organically managed ones (for potato by 35% and winter wheat by 52% during 2009−2012; [32]). In contrast, the tree strips were not fertilized in both systems. Furthermore, weed control has been applied in both systems, thus minimizing the influence of weed competition. The nutritional status was relatively similar between the systems, although the previous long-term cultivation differed. However, in the previous study of Huber et al. [36], a positive effect of fertilizer that has been applied at the adjacent fields of the conventional system was detected on tree growth of poplar and willow border rows of the AFS. In the first year, conventional systems showed higher biometric values and biomasses than organic ones. In the beginning, mineral nitrogen may have promoted tree growth and emergence of sprouts, whereas in the following years the fertilizer may have been absorbed only by the border rows and therewith inner rows reacted differently.

Generally, large between- and within-field variations due to variable soil properties and micro-climatic differences (100 m altitude difference, 2−10% slopes) made it difficult to distinguish between management and site effects, which was stated as main reason for the system differences in the previous study on the same site but only on the last year [36]. Also other authors emphasized that short rotation woody biomass yields were highly variable and site-dependent with no response to fertilizer [56], or site specific reactions [57]. Black locust and alder showed an overall growth reduction in the third year due to frost for black locust and maybe water limitation for alder. Still, black locust and alder responded much lower to farming system and showed lower plot variability than poplar and willow, which may be because of the ability to cover the use of nitrogen from their symbiotic fixation. This highlights that tree species respond differently to changing environmental conditions determining their productive potential.

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5. Conclusions

The chosen poplar clone was well adapted to the conditions of our study site displaying, high growth and low size asymmetric competition throughout the rotation. Willow also showed a high tree height growth rate, but low diameter growth and low wood density led to a low yield. Due to the lack of crown closure, sprouting was still stimulated in the fourth year. Coppicing willow after the first year might stimulate early growth of multiple stems, possibly leading to a better use of light availability and thus a higher total yield. Further research is needed here.

Black locust had a promising growth until late frost in spring caused a severe reduction in its productivity. Nevertheless, after four years its biomass production was the second highest among species. Black locust showed huge size difference and mortality within its stands. A lower planting density might reduce mortality and would save planting costs. However, this is subject of further investigation. Furthermore, the large diameters within black locust stands might be problematic when harvesting with a mowing cutter, what limits rotation lengths.

Alder showed a moderate growth among species, but was within expected yields. Alder developed like black locust an unequal stand possibly impairing the harvest and quality of the wood. High variability due to locational variation was present for willow and polar. Black locust and alder were less sensitive to their location. Furthermore, for the latter species no difference in growth traits between organic and conventional systems were found during the rotation, except greater height of conventional black locust in the first year. In contrast, poplar and willow showed significant higher values for organic farming after 4 years. However, it is unclear if this can be attributed to management or site effects. Thus, organic farming did not depress the productivity of the trees, offering high potential for short rotation biomass production under this system. Because of these gene-environment interactions, species performances may differ at other locations and management regimes, which include initial planting density in combination with rotation length, fertilizer, and irrigation. Furthermore, growth may be altered in the next rotations attributed to for example variations in shoot emissions, survival rate, and weather conditions.

Declarations

Author contribution statement

Julie Huber: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Michael Matiu: Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

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Kurt-Jürgen Hülsbergen: Conceived and designed the experiments; Wrote the paper.

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Competing interest statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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