

Article

Ecosystem Service Benefits and Trade-Offs—Selecting Tree Species in Denmark for Bioenergy Production

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Abstract: Research highlights: The study enabled us to quantitatively assess ecosystem benefits and trade-offs, to characterize species as generalists or specialists, and findings suggest that producing biomass for energy is more likely to serve multiple objectives if it is implemented in an integrated production system. Background and Objectives: Biomass is one of the main and largest sources of renewable energy. In Denmark, the production of biomass for energy is mainly based on timber harvest residues from pre-commercial thinning of forest stands. However, there is an increasing demand for bioenergy that require biomass to be grown specifically for energy purposes even though the sustainability and climate change mitigation potential of bioenergy plantations have recently been questioned in terms of food production, land use, land use change and terrestrial carbon cycles. The overall objective of the research is to better understand the opportunities and trade-offs between different woody and non-woody energy crops. Material and Methods: This study assessed the ecosystem services of seven woody species and one perennial along a management intensity continuum with a main focus on bioenergy production. Results: Results of the analysis showed that there are complex interrelations between ecosystem services and significant differences between species in providing those services. Conclusions: Species with a highest energy benefit among assessed species were poplar and grand fir, while beech and oak proved the best in providing biodiversity benefits.

Keywords: bioenergy; ecosystem services; tree species choice; production systems; multifunctionality

1. Introduction

In 2015, 55% of the European Union's (EU) greenhouse gas (GHG) emissions originated from the direct combustion of fossil fuels [1]. The demand for more sustainable solutions in providing energy and maintaining energy security has increased the use of renewable energy greatly in recent decades. From 1990 to 2015, the EU achieved an 11% reduction in GHG emission from the energy sector. By 2020, the EU has a target of 20% renewable energy in the energy mix [2], and by 2030 the target is raised to 32%. Thus, the demand for renewable energy is expected to increase further.

According to the Intergovernmental Panel on Climate Change (IPCC) [3], bioenergy is the renewable energy technology with the largest potential. Beringer, et al. [4] estimate that bioenergy could potentially cover 13–22% of the World's energy need by 2050, considering environmental and agricultural constraints. Globally, so-called modern bioenergy generation (distributed heat, electricity and biofuels) continues to increase. In 2016 biomass provided 13.1 EJ of heat to the industry and the residential sector, and 555 TWh of bio-electricity was generated in 2017 [5].

Bioenergy is expected to be a major contributor to reaching renewable energy targets in the EU [6], as well as in Denmark [7]. In 2016, bioenergy contributed 61% of renewable energy production in Denmark [8], and within bioenergy, solid biomass (straw, woody biomass, biodegradable waste and bio-oil) made up 90% [8]. The consumption of woody biomass (chips, pellets, firewood and industrial by-products) for electricity and heating increased by 57% from 2010 to 2016 [8]. This increase was partly covered by the import of wood chips and pellets, suggesting that the current supply of biomass is insufficient to meet the demand. The primary source of the current supply of woody biomass is timber harvest residues from pre-commercial thinning of forest stands [8]. Due to the increasing demand and insufficient resources of biomass, energy crops, grown specifically for their energy value, have been promoted [9]. Fast-growing agricultural and forestry crops have gained a lot of research attention during the last decade [3].

Willow (*Salix sp.*), silver grass (*Miscanthus sp.*) and poplar (*Populus sp.*) are among the most promising perennial species to provide biomass resources in southern Scandinavia [10–22]. Intensive production of energy crops is expected to ensure not only a renewable biomass resource, but also to reduce the environmental impacts of land use [18]. Long-term sustainability and climate change mitigation potential of bioenergy plantations have recently been questioned for its impact on food production, land use, land use change and terrestrial carbon cycles [4,23,24].

As bioenergy plantations, regardless of the management system, compete for land, improved instruments and regulations are needed in spatial planning [25] to balance ecological, economic and social needs [26]. Assessing and mitigating the impacts of land use decisions on ecosystems is key to sustaining human well-being [27], and therefore, there is a need to integrate such knowledge into regional planning and decision-making processes [25,28–30]. Within a certain ecosystem, e.g., forests, much research has focused on quantification of a single service being supplied and/or demanded. However, in practice, ecosystems provide multiple and interacting services. Optimization relative to a single service, e.g., biomass production could, therefore, lead to a decline of other desired services [31]. Understanding the trade-offs and relationships between these services at different spatial scales is, therefore, necessary [29,31] to determine the most applicable species and management system for biomass production for energy [32].

The overall objective of this study was to assess potential benefits and trade-offs between the environmental, economic and social aspects of biomass production for energy. The objective was met by developing a multidimensional characterization of tree species grown partly for energy under Danish/Nordic conditions. A herbaceous energy crop was included in the analysis for comparison. To address the need for understanding the supply and interaction of ecosystem services within bioenergy production at different scales, this study takes a stand-level approach with a focus on species. It is often argued, that ecosystem benefits and trade-offs are best addressed on a landscape level [33,34], and therefore, findings of this study provide input for decision support in forest management and policy making on land use planning and landscape development.

2. Materials and Methods

The analytical approach applied in this study is illustrated in Figure 1. Characterization and quantification of ecosystem services were carried out in 2018, based on scientific literature and peer-viewed datasets.

The theoretical framework applied for characterizing species as energy crops build on the concept of ecosystem services (ES). The concept has the capacity to assess the consequences of different land use decisions on multiple scales [27], allowing for comparison between different silvicultural systems, as well as woody and non-woody species. It provides a holistic picture and creates a common ground for understanding, documenting and analyzing the socio-ecological interactions within the landscape [27,29]. It is, therefore, a powerful tool to communicate the various ways of how different ecosystems contribute to human well-being [26], and how humans affect the availability and the quality of their services. It also proves to be an adequate tool for addressing the challenges of landscape

multi-functionality [35]. Balancing between economic, ecological and social goals comprise the core challenge of contemporary sustainable forestry [36].

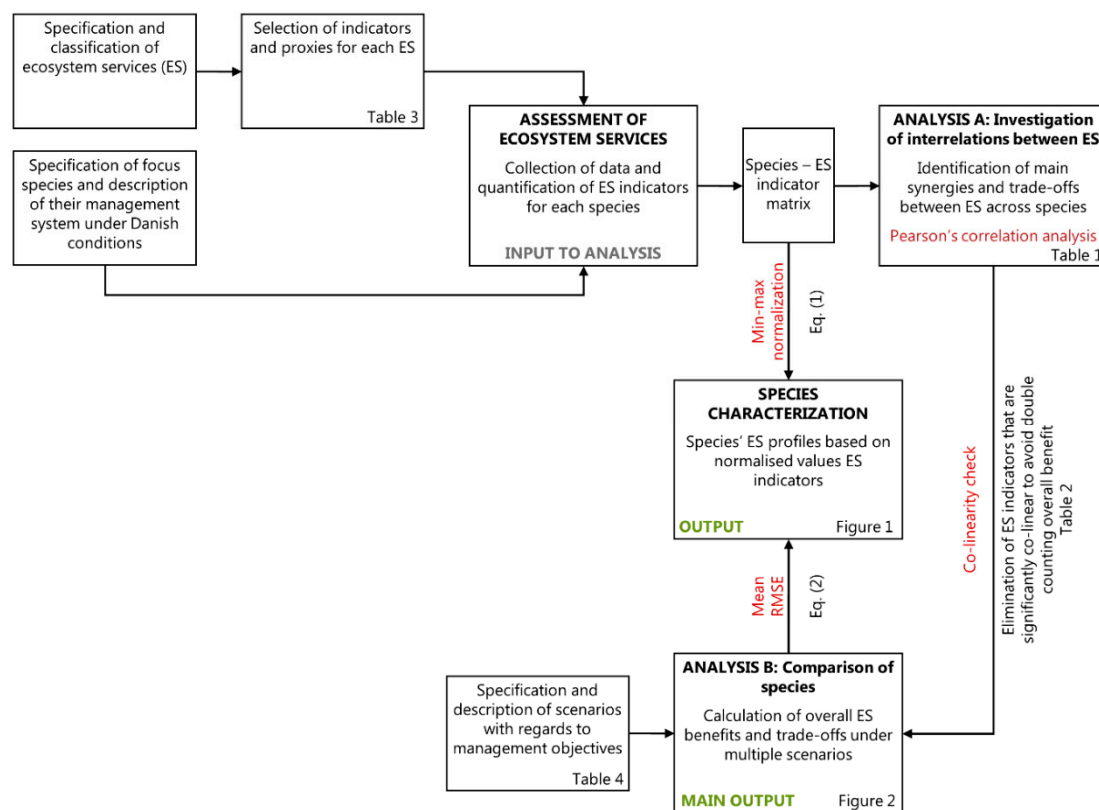


Figure 1. Methodological framework and analytical approach of the study.

Selected ecosystem services are grouped according to a universal classification scheme used within the EU (CICES) with an additional category of “supporting services” based on the Millennium Ecosystem Assessment framework in order to include biodiversity into the analysis [37]. Biomass production systems have significant potential in providing a number of different goods and services [38], however, the quantity and quality of these benefits are expected to be strongly dependent on management system and the choice of species. ES indicators from each category were selected to explore opportunities for multi-functional land use and sustainable production (Table 1), based on similar studies within forest ecosystem services [27,36]. For each indicator and proxy, a specific quantitative measure is assigned with a unit that allows cross-species comparison.

Table 1. Selection of ecosystem services included in the analysis, with their assigned indicators or proxy along with their unit of measurement.

Category	Ecosystem Service	Indicators and Proxies	Unit
provisioning	biomass based energy	productivity	$\text{t ha}^{-1} \text{ yr}^{-1}$
	biomass based energy	energy yield	$\text{GJ ha}^{-1} \text{ yr}^{-1}$
regulating	climate regulation	total carbon stock	t C ha^{-1}
	climate regulation	saved emission	$\text{t C ha}^{-1} \text{ yr}^{-1}$
	soil fertility	minimum nitrogen requirement	$\text{kg N ha}^{-1} \text{ yr}^{-1}$
supporting	soil fertility	nitrogen use efficiency	Gradient
	biodiversity	biodiversity score	1–20
	biodiversity	conservation potential	%
cultural	landscape	land use intensity	ha TJ^{-1}
	aesthetics	aesthetic score	0–20
	recreation	recreation score	0–10

The analysis is limited and biased towards the selection of ecosystem services quantified based on the focus of the study. The spectrum of provisioning services provided by selected species is limited to indicators related to bioenergy production, excluding the consideration of other provisioning services that usually are included in similar studies (e.g., hunting or drinking water yield) [27,29,36].

2.1. Selected Species by Management Type

Production systems differ greatly between non-woody and woody species, but also across woody species, depending on silvicultural practices and rotation length. Species studied here are, therefore, categorized into three management systems: Agriculture (AGR), short-rotation forestry or short-rotation coppice (SRF/SRC) and long-rotation forestry (LRF).

Silver grass (*Miscanthus sp.*), originating from eastern Asia, has proven to be a good bioenergy crop in temperate regions. It has a high yield even in a cooler climate combined with resistance to pest and diseases [39]. As a perennial crop, it has a longer growing season and requires less agricultural input (fertilization and pesticides) than conventional crops [39–41]. It has a high rate of carbon sequestration in the soil, and overall lower environmental impact, and higher potential for biodiversity compared to annual crops [39,42–45]. With C4 photosynthesis, it is about 30% more efficient in solar energy utilization than C3 plants [39]. Different species and genotypes have been tested in Denmark since the 1990s in two experimental stations at Aarhus University [18–20,46].

Short-rotation coppice and forestry differ in the method of regeneration. In coppice systems reproduction is vegetative [47]. Compared to traditional forestry, short-rotation systems have shorter harvest cycles with more frequent harvest interventions. Short-rotation systems are, therefore, suitable for fast-growing pioneer genera, such as poplars (*Populus sp.*), willows (*Salix sp.*), alders (*Alnus sp.*), and birches (*Betula sp.*). In this study, species of poplar and willow are included. Poplar species considered best suited to Scandinavian/Baltic conditions are balsam poplars or hybrids (*P. balsamifera*, *P. trichocarpa* and *P. maximowiczii*) [48]. They are in general light and nutrient demanding species, thriving on fresh, well drained soils [47]. The rotation age of poplar, grown in silvicultural systems is usually 20–30 years, with a possible thinning around 10–15 years depending on initial planting density [21]. Willow species have various morphological forms, from which shrub willows (e.g., *Salix viminalis*) are used in biomass plantations in Denmark, as they are best adapted to the northern European climate conditions [48]. The rotation age of willow is often 3–5 years, but in Denmark generally 2 or 3 years [12,14].

Long rotation or traditional forestry, refers to naturally or artificially regenerated coniferous or deciduous stands, managed primarily for timber production [48]. In this study, the most common conifer and broadleaved species in Danish forests are included: Grand fir (*Abies grandis*), Norway and sitka spruce (*Picea abies*, *P. sitchensis*), as well as European beech (*Fagus sylvatica*) and pedunculate oak (*Quercus robur*).

Norway spruce is a slow establishing, but fast-growing exotic species, with a rotation age generally around 50–60 years [49]. Sitka spruce is an introduced species, native to western North America. It grows more rapidly than Norway spruce, while its average rotation age is 50–55 years. Grand fir is also an exotic species, native to the west coast of North America. It has become important in Danish forestry, due to its high productivity, although its establishment requires care as it is prone to low temperatures and deer browsing [49,50]. Oak and beech are native broadleaved species of high economic importance in Denmark, although they establish and grow slower than conifers. Rotation age is usually between 90–120 years for beech and 120–180 for oak, depending on management objectives and soil type.

2.2. Data

2.2.1. Provisioning Services

One of the selected indicators for the provisioning of biomass-based energy is the productivity of the selected genera within each management system. Productivity was quantified by the harvestable

biomass yield of each genus. For silver grass, willow and poplar, biomass yield was calculated as the average of mean annual yields reported in a number of studies in Denmark, and a south Swedish study for poplar (Tables S1–S4). For long-rotation species, the latest findings of a robust study on biomass production [51], which is based on a common garden experiment from 13 sites across Denmark, was adopted. Productivity is reported in tones (of dry matter) per hectare per year ($t\ ha^{-1}\ yr^{-1}$). More information on the assessment of species productivity can be found in the SI, Section S2.

The other indicator for provisioning services, energy yield, was selected as a proxy for potential revenue as the settlement price for bioenergy products (bale, powder, pellet, chips, chipboard, waste or firewood) are most often given in relation to the heating value. The potential energy yield was assessed via the best mean annual biomass yield, the utilization rate for energy purposes and the lower heating value (LHV) of the different species. Energy yield is expressed in Giga joules per hectare ($GJ\ ha^{-1}$). More detail on the assessment of energy yield can be found in the SI, Section S3.

Heating values corresponding to 0% moisture content are considered in case of all species to make values comparable across species. Even though, in reality, it fluctuates according to the moisture content (insufficiently dried matter has a lower heating value), depending on the drying conditions, methods and the time of harvest [47]. Furthermore, using the lower heating value is based on the assumption that water vapor energy is not regained after biomass combustion [52]. In cases where more efficient technologies are used (e.g., combined heat and power plants and flue gas condensation), the energy yield would be higher for all species and differences between the energy yield of species.

2.2.2. Regulating Services

Ecosystems, as natural carbon sinks, have the potential to mitigate climate change by sequestering carbon from the atmosphere through photosynthesis, and storing it [53,54]. In assessing the climate change mitigation potential, the following carbon stocks were considered in accordance with IPCC guidelines: Aboveground biomass, belowground biomass, deadwood, soil organic layer, and soil. Fluctuations of the stored carbon in living aboveground biomass, due to age were omitted by assuming a so-called normal forest, where each age class is equally represented. The average production of biomass in a normal forest is, therefore, equal to the mean production per hectare over a rotation. Values reported considers a best-case scenario using the best mean yield among assessed studies. Values reflect a steady-state level as fluctuations of the stored carbon in these pools, due to harvesting or conversion are excluded, since the effect of management on these pools has a long time-span, and therefore, it is difficult to document [55]. More detail on the assessment of carbon storage can be found in the SI, Section S4.1.

Besides the natural potential of ecosystems to mitigate climate change, harvesting biomass from ecosystems potentially also contributes to climate change mitigation through product substitution; either fossil fuel substitution using biomass for energy generation, or substituting materials from non-renewable sources using biomass for long-lived wood products (e.g., furniture or construction material) [56]. Here, saved emissions consider fuel substitution from all species, and material substitution from poplar and long-rotation forestry species according to the utilization model (Figure S2). Only carbon dioxide (CO_2) emissions were considered. Following IPCC guidelines [57], emissions from biomass combustion were not accounted for. Supply chain emissions were included as a percentage of the carbon content of the fuel. GHG savings from product substitution are assumed to 2.1:1 [58] (SI, Section S4.2).

It is assumed that only stems and branches are harvested for bioenergy in all cases. Harvesting leaves, stumps and roots as an attempt to maximize harvestable biomass yield, would result in a lower heating efficiency, since leaves and roots have inferior combustion characteristics, due to higher ash and nutrient content) [59]. Higher nutrient content not only affect combustion quality, but the extraction of nutrients from the ecosystem would also have serious consequences with regards to soil fertility and nutrient cycling [60].

Furthermore, quantified provisioning and regulating services are limited to the environmental conditions and management described in studies. The best average annual yields were selected for all species illustrating best-case scenarios, which, therefore, do not include variation, due to site or management within species.

As biomass harvest removes nutrients taken up by the plants, net output of elements has to be compensated to ensure long-term soil fertility, while at the same time aiming to avoid the increased rate of leaching, due to an overload of nutrients. Here, it is assumed that the most important element for the nutrient balance is nitrogen, as it plays a significant role in both plant growth and water quality. Adopting the method of Miller [61], the effects of species on the nutrient budget and water quality were assessed by the Minimum Nitrogen Requirement (MNR) and Nitrogen Use Efficiency (NUE) of the selected species (see SI, Section S5 for details). Values reported are theoretical values, representing a best-case scenario to provide a common basis for comparison across species [61]. Results of MNR are representing a theoretical value that can only be interpreted with a proper scientific investigation of other inputs and outputs of the nutrient budget.

2.2.3. Biodiversity

Non-tangible values like biodiversity are very hard to quantify and will always depend on how they are defined and on what scale. Biodiversity, in its broadest definition, cannot be categorized as an ecosystem service, rather a result of successful balancing between ecosystem services [37,62]. Consequently, the spectrum of scientific literature on biodiversity is very wide, inconsistent and often contradictory, due to differences in definitions and interpretations of biodiversity. Here, ecosystem biodiversity is assessed on three levels; genetic (α), habitat (β), and landscape (γ) using a score. For genetic diversity, a binary score (0/1) is used, with 0 representing no genetic diversity. Habitat biodiversity is scored in accordance with Filyushkina, et al. [63]. Biodiversity on landscape level is scored from 0–3, based on the extent to which the dominance of a certain land use type in the landscape increase or fragment core areas of habitats after Lindborg, et al. [64]. Finally, the scores for all three levels were summed to get an overall score for biodiversity from 1–20, with the highest being the best (SI, Section S6.1). As potential biodiversity in an ecosystem does not indicate whether the level of biodiversity can be maintained over longer periods, a conservation potential is quantified. Scores were adopted from Filyushkina, Strange, Löf, Ezebilo and Boman [63]. The quantification of biodiversity and conservation potential is further described in the SI, Section S6.2.

While quantifying biodiversity holistically requires the use of proxies (scoring, rating and ranking) to allow cross-comparison, it increases the degree of uncertainty as relationships are often not well-understood and controversial even among scientists.

2.3. Cultural Services

In order to address the issue of land use and land scarcity, the land use intensity (LUI) was assessed. Species with smaller LUI are considered to be more beneficial in a land use planning perspective. Recreational values were assessed on a scale from 0–10. The assessment builds on expert ratings of public preferences for different management types, forest stand development phases and species adopted from Edwards, et al. [65]. The aesthetics of the studied species was assessed considering two factors: Visual impact and visual effect on different landscape types. The higher, denser and more monotone in colors a stand is, the less visually appealing it is, as it creates a “wall effect” [66]. On landscape level, scores for “scenic beauty” of different landscape types were adopted from a German study [66]. The visual effect of the different land use types was evaluated for six different landscape types: Five types adopted from Boll, von Haaren and Rode [66], and a simplified urban landscape based on preference studies on recreational aesthetics [67,68]. The assessment of cultural services is further described in the SI, Section S7.

2.4. Analysis

The analysis was carried out in two steps, first within and then between species. For both analyses, simple statistical methods were applied. Interrelations between ecosystem services were assessed by identifying pairwise mutual benefits and trade-offs between ecosystem services. These positive-negative interactions depend on whether the selected ecosystem service can be provided without excluding or significantly reducing the capacity or quality of another service [30]. As these interactions can occur on multiple spatial and temporal scales [35], it is important to note that this study only considers bioenergy production systems with several different species in a certain age/developmental phase.

Analysis of the relationship between different ecosystem services was limited to the identification of the positive/negative correlations and their degree, since the type of relationships between them were not assessed. Therefore, direct conclusions cannot be drawn from the correlation coefficient analysis as it may hide non-linear relationships, depending on the different transformations used.

The analysis identifies significant linear correlations, to avoid bias in the analysis of ecosystem services between species. Pairwise Pearson's correlation coefficients (ρ) between all ecosystem services were calculated as the quotient of the covariance and standard deviation of the two variables paired.

The correlation coefficient only investigates linear relationships, and all values of ecosystem services were transformed (log or fourth-root transformed) to minimize their variance [29]. The value of the coefficient ranges between -1 and $+1$, indicating mutual benefit in case of positive correlation ($\rho > 0$) and trade-off in case of negative values ($\rho < 0$). The relationship is considered to be strong and appropriate for a co-linearity check between ± 0.70 – 1 , moderate between ± 0.50 – 0.70 , weak between ± 0.30 – 0.50 . The co-linearity check was carried out by assessing the goodness of fit (R^2) of the linear trend line of paired indicator values.

For the analysis of ecosystem services between species, overall benefits and trade-offs were calculated for each species using the method developed by Bradford and D'Amato [69], and adopted, among others, by Dai, Wang, Zhu and Xi [31]. They define overall benefits as the “degree to which multiple objectives are achieved” and trade-offs as “the disparity in the level of achievement among objectives” [69] p. 2). The overall benefit of a species was calculated as the average of benefits from single objectives/indicators. The benefit of a specific species for a single indicator was calculated as the relative deviation from the mean of all values measured across species (eq. 1). The benefit value (B) ranges from 0 to 1 and can be interpreted as the percentage of a single species' contribution to the maximum benefit from a single indicator within each objective, relative to all species considered in the study. Note that the maximum benefit refers to the most beneficial value of a given indicator (for LUI and MNR these are the minimum values).

$$B_A = \frac{A_{\text{obs}} - A_{\text{min}}}{A_{\text{max}} - A_{\text{min}}} \quad (1)$$

where B_A is the benefit of a specific species from a single ecosystem service indicator (A). A_{obs} is the quantified value of the ES indicator for that specific species; A_{min} and A_{max} are the minimum and maximum values of the ES indicator across all the assessed species.

The overall trade-off was calculated by the simple root mean squared error (RMSE) of individual benefits (Equation (2)).

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^n (B_i - O_i)^2}{n}} \quad (2)$$

where B is the benefit of a specific species from a single ecosystem service indicator, calculated after Equation (2); O is the overall benefit of a specific species, calculated as the average of benefits from single indicators (B); and n is the number of indicators included in the study (11).

The overall benefit was calculated using a weight of 4, favouring energy production (base scenario) reflecting the focus of this study. Alternative weights were applied to assess the sensitivity of species choice against other objectives (Table 2).

Table 2. Base and alternative scenarios and the applied weights to ecosystem service indicators.

	Acronym	Primary Objective(s)	Indicator(s) Weighted	Multiplier for the Indicator(s) Benefit
Base scenario.	ENERGY	energy production	saved emission	4
Alternative scenario1	ALL	-	all are equal	-
Alternative scenario2	ECOENERGY	conservation with a focus on energy production	conservation potential and Saved emission	4 and 2, respectively
Alternative scenario3	BIODIVERSITY	conservation	conservation potential	4
Alternative scenario4	ENERGY2	energy production with a focus on conservation	saved emission and conservation potential	4 and 2, respectively

3. Results

In line with the focus of this study, 11 indicators of four types of ecosystem services were assessed. The relative benefit, based on normalized values of the assessments, of each species against the 11 indicators forms an ecosystem service benefit profile for each of the studied species (Figure 2).

From the 55 pairwise correlations of the 11 selected indicators, 27 are positive and 28 negative (Table 3). The majority (48%) of the positive correlations are strong, while the majority (61%) of negative correlations are weak, with only 14% of strong negative correlation. Most synergies were found between indicators of regulating and cultural services, as well as supporting and cultural services with 67 and 33% being characterized strong, respectively.

As a result of the co-linearity check, a significant linear relationship was found in six cases among the 13 significantly correlated indicators, with a very good fit to a linear trend line ($R^2 > 0.72$) (Table 4). Consequently, one from each co-linear indicator was ruled out, leaving six indicators from the initial 11 to be included in the final analysis between species.

Across all scenarios, beech was always, and poplar almost always among the top three species in terms of overall benefits, however, they also carried along with high trade-offs (Figure 3). In contrast, the two spruce species were among the species with the lowest trade-offs. In scenarios where energy production was favored, grand fir proved to provide the highest overall benefits with the lowest overall trade-offs. In contrast, when biodiversity values were weighted high, the highest overall benefit was achieved by beech, followed by oak and grand fir. It was, however, still grand fir that carried the lowest degree trade-off, while oak the highest.

The disparity of the overall benefits achieved in the different scenarios within species is also the highest for oak (standard deviation = 0.13), followed by silver grass (0.10), beech (0.10) and poplar (0.09), while grand fir and willow had the lowest (0.04 and 0.05 respectively).

The 1:1 reference line in Figure 3 shows the hypothetical situation where, for all values-pairs, the overall benefit equals the overall trade-off. Species above the line; conifers, poplar and beech, are considered to be more efficient in terms of providing benefits from multiple objectives, as they come with fewer trade-offs. From species above the reference line, depending on the significance in the difference between the overall benefits, the ones with the lowest trade-offs are the most efficient for multiple objective management, realizing land use multi-functionality.

Compared to the 1:1 reference line, silver grass stayed below the line in all scenarios, meaning that the trade-offs outweigh the synergies no matter how ecosystem services are weighted. Silver grass proved to be unsuitable to serve multiple objectives efficiently, due to its specialist profile. In contrast, the benefits of conifers, poplar and beech outweigh the trade-offs in all scenarios, while willow and oak shifted around the line, depending on which ecosystem service was favored.

Table 3. Results of the pairwise correlation analysis between ecosystem services.

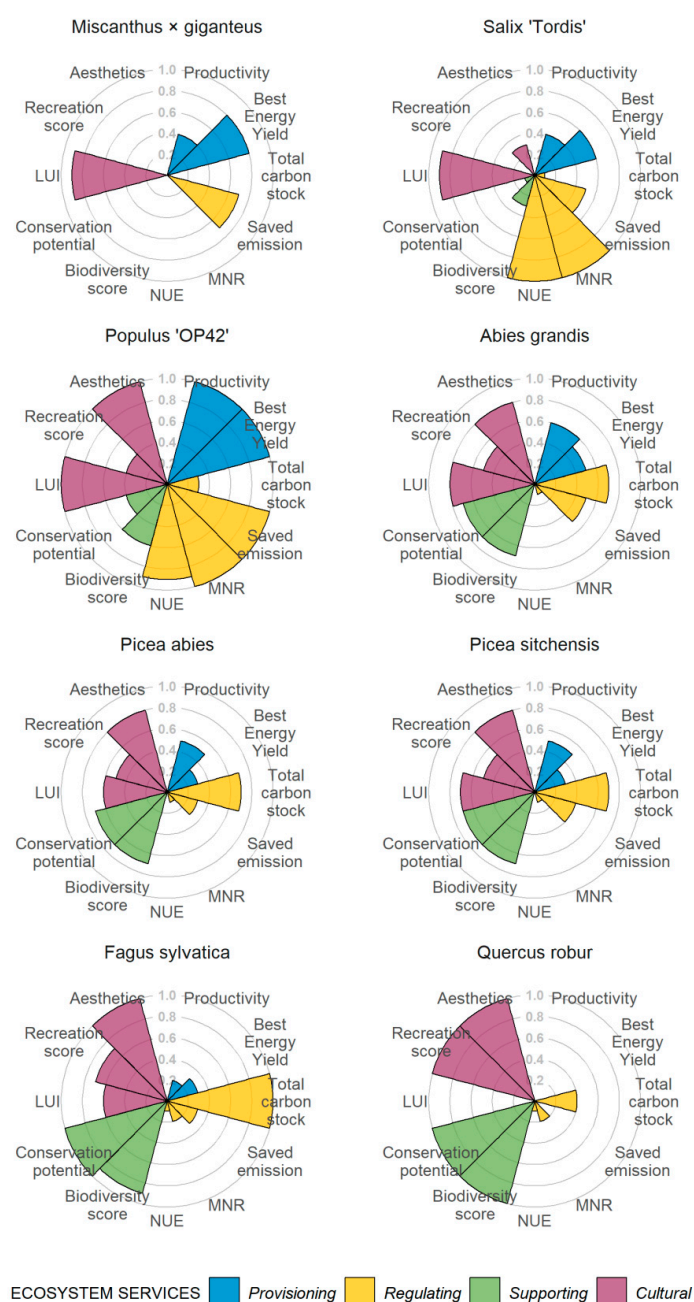
Transformation	Log Productivity	Log Best Energy Yield	Log Total Carbon Stock	Log Saved Emissions	Log MNR	Log NUE	$\sqrt[4]{}$ Biodiversity	Log Conservation Potential	Log LUI	$\sqrt[4]{}$ Recreation	$\sqrt[4]{}$ Aesthetics
productivity											
best Energy											
Yield											
total carbon											
stock											
saved emission											
mnr											
nue											
biodiversity											
score											
conservation											
potential											
lui											
recreation											
score											
legend	+	strong	modest	weak	none	-	strong	modest	weak	none	

Colour scheme: (+) Green = synergy; (–) red = trade-off. Scale: Strong between ± 0.7 and ± 1 ; modest between ± 0.5 and 0.7 ; weak between ± 0.3 and 0.5 ; none between 0 and ± 0.3 . Transformation types are indicated in the top row. Indicators in bold were included in the analysis between species, while others were excluded, due to co-linearity with one of the indicators already included.

Table 4. Significant co-linearities with the goodness-of-fit for the linear trend line and the indicators that have been ruled out from the analysis between species.

Significant Co-Linearity ($>\pm 0.7$)	R ²	Ruled Out
Productivity - Saved emission	0.7214	Productivity
Best Energy Yield - Saved emission	0.9703	Best Energy Yield
Best Energy Yield- LUI	0.8200	Best Energy Yield
Saved emission- LUI	0.8016	LUI
MNR- NUE	0.9937	MNR
Biodiversity score - Aesthetics	0.8710	Biodiversity score

LUI = Land Use Intensity, MNR = Minimum Nitrogen Requirement, NUE = Nitrogen Use Efficiency.

**Figure 2.** Species' ecosystem service benefit profiles with all the quantified indicators. Color code: Blue = provisioning service; yellow = regulating services; green = supporting services; purple = cultural services.

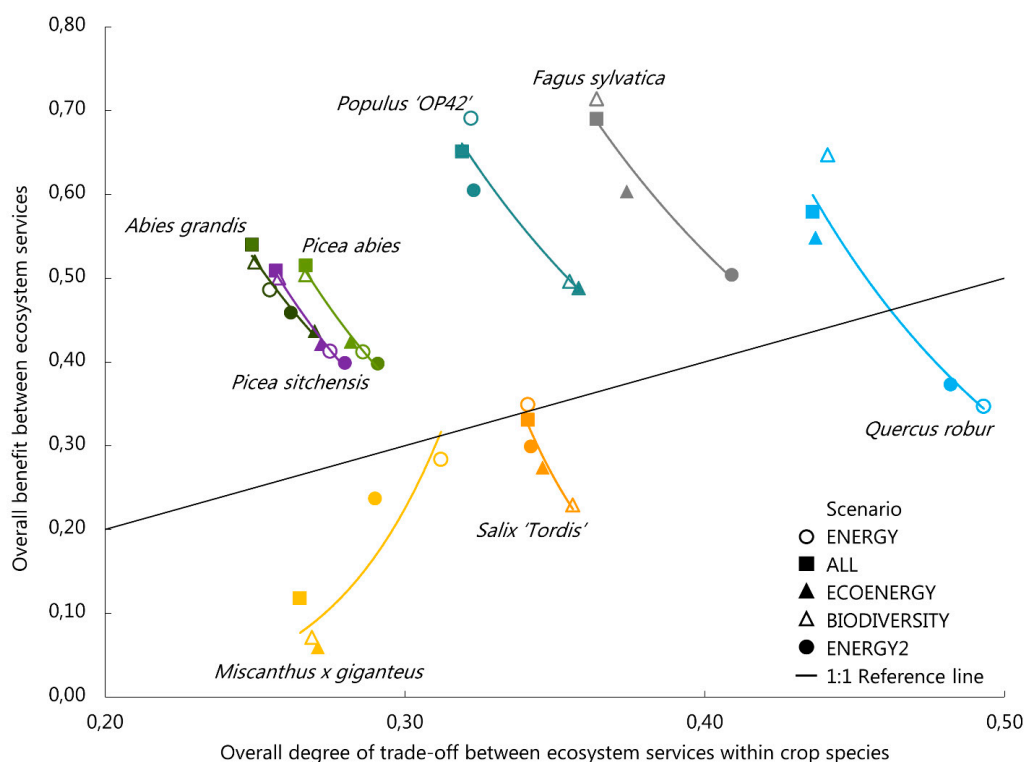


Figure 3. Comparison between species, based on overall benefits and trade-offs.

4. Discussion

Understanding the interrelations between the different ecosystem services within a species profile is vital to explain the levels and changes of overall benefits and trade-offs that enables the comparison between species [69]. Despite the many positive and negative relations found between different services, representing the complexity, the results clearly demonstrate well-known trade-offs between management and nature [29,31,36,69]. As the intensity of management increases, services connected to natural ecosystem processes and functions are suppressed. Interrelations between the different types of ecosystem services can be explained as an antagonistic relationship between intensive management and nature.

Changes in the overall benefit and trade-off rates lie behind the individual ecosystem service profiles of species. Species with a widespread profile across the different types of ecosystem services (e.g., fir, spruces or willow) are likely to achieve the lowest degree of trade-off. Since they already carry a certain trade-off within their profile (inherited trade-offs), putting a weight on one objective will not result in a significant shift along the trade-off axis.

This degree of shifting is represented by the disparity, showing that some species are quite generalists, while others are specialized to serve a specific objective. From the species above the reference line, those with the lowest trade-off are considered the most efficient for land management towards multiple objectives.

As a general pattern across species, it is shown that the more intense the production in a management system, the more it limits the provision of other services. If inefficient in providing multiple services, a production-oriented system promotes functional segregation. Even though high trade-offs are also associated with biodiversity objectives, that would also mean certain functional segregation in order to maximize the benefit (e.g., untouched forests or forest reserves) it is not exclusive with other services to the same extent.

Biomass as an alternative to fossil fuels is much discussed in relation to the green energy transition in Denmark. Carbon neutrality and sustainability is questioned, while concerns also surround the large consumption, dependence on imported products (mainly wood pellets) and also the distortions of the

Danish energy taxation system, related to state economic issues and inequality towards other types of alternative energy resources (wind, solar and heat pumps) [70]. Regardless of the heated debate and opposing opinions, it is generally accepted among politician, economist and scientist that biomass is an alternative to fossil fuel (even if it is not the best) and that biomass was, is, and will be crucial for displacing fossil fuels in Denmark at least until 2030, being the largest renewable energy resource [71].

On the other hand, other ambitious political targets are addressing the enhancement of biodiversity in state forests. According to the new suggestions to the National Forest Plan of Denmark, it can be realized by setting aside 20% of the total forested areas as untouched before 2030.

Producing biomass for energy is more likely to serve multiple objectives if it is implemented in a polycultural and multi-objective production system (mixed stands of ex. poplar and LRF species). It can also be true in the case of willow to some extent. The most efficient species in providing high energy benefits, while serving multiple objectives at the same time are poplar and the conifers (grand fir, Norway spruce and Sitka spruce), with poplar providing lower biodiversity, but higher energy benefits. Willow, on the other hand, might be more flexible to changes in management and climate, considering the significantly shorter rotation age. This is also true for poplar compared to long-rotation forestry species.

Focusing on biomass production, and therefore, intensifying production of, e.g., beech and oak are not recommended as it would significantly suppress their potential to provide services related to biodiversity and recreation, while their productivity cannot be enhanced enough to be a competitive alternative to poplar or conifers [15,36,60]. Biomass production for energy with silver grass is only recommended if willow (or any other species) is not available as an alternative. Since it has very low overall benefits and even its productivity is not remarkable high compared to the alternative species.

The choice of species always depends on the management objective, defined by the owner/manager, but also on profitability [72]. As an economic analysis was not included in this study, it cannot be concluded that species with the highest energy benefit are the most profitable. Firstly, because revenue from energy yield is not necessarily the only income and secondly because of the differences in costs arising according to management [49]. The questions of how to optimize the management to enhance the production potentials, while maintaining the provisioning of other services along with the corresponding economic consideration for a given management alternative still remain.

Overall benefits and trade-offs presented in this paper is limited to the chosen spatial scope (stand-level). It is often argued that the spatial distribution of ecosystem services and effective balancing between conflicting management options goes beyond stand/property borders and best addressed within a forest or landscape [33,34,73]. While findings of this paper provide valuable knowledge and input to decision making processes, it is noted, that stand-level approaches to optimize overall benefits from ecosystem services may not be the most effective way.

5. Conclusions

This study has assessed the ecosystem services of seven woody species and one perennial along a management intensity continuum with a main focus on bioenergy production in Denmark. Results of the analysis between ecosystem service indicators showed that there are complex interrelations among them originating partly from the antagonistic relationship between intensive, production-oriented forest management and provision of diverse services connected to natural ecosystem processes and functions. The ecosystem service profile species, based on individual benefits from all 11 indicators for all four types of ecosystem services, clearly shows that there are significant differences between species of different management systems in providing goods and services in Nordic conditions. Comparison between species in this study is limited to the specific species selected, based on the focus area (woody biomass production for energy) and do not show the whole spectrum of solid bioenergy production. Within this scope and area of the study, some species have proved to be very specialist (either for production or nature conservation), while others are more generalist, providing moderately high services of all types. Stand-level analysis between species showed that producing biomass for energy

is more likely to serve multiple objectives, at the same time, if it is implemented in an integrated production system. Species with the highest energy benefit among assessed species were poplar and grand fir, while beech and oak were the best in providing biodiversity benefits in given conditions.

Findings presented here, indicate that the effect on ecosystem services of a specific choice of species/management system should be assessed in the frame of overall benefits and trade-offs from multiple objectives. Meanwhile realizing that there is no best single solution for “having it all”, research on individual responses of ecosystem services to a specific management type should be continued.

Supplementary Materials: The following are available online at <http://www.mdpi.com/1999-4907/11/3/277/s1>. Further information and data on species productivity (Table S1: Reported Silver grass yields, Table S2: Reported willow yields, Table S3: Reported poplar yields and Table S4: Results of literature research and projection of productivity and Figure S1: Productivity of long rotation tree species across sites), energy yield (Figure S2: Applied utilization model for poplar and long-rotation forestry species and Figure S3: Range of reported Lower Heating Values (LHV) from different sources. Data sources and Table S5: Energy yields of studied species), carbon storage (Table S6: References used to quantify carbon in deadwood and soil, Table S7: Amount of carbon stored in different pools and the total carbon stock of species, reported in t C ha⁻¹. and Figure S4: Total carbon stocks in relation to totally saved emission), fossil carbon displacement (Table S8: Life cycle inventory and assumptions on substitution, Table S9: Assumed production chain emission rates and values for fuels and Figure S4), nutrient balance (Figure S5: Minimum Nitrogen Requirement of species for different energy yields indicating the Nitrogen Use Efficiency by slope of the fitted line), biodiversity (Table S10: Factors considered in the assessment of habitat biodiversity, Table S11: Habitat biodiversity scores of the selected species and Table S12: Total biodiversity scores on all three levels and conservation potential), land use intensity (Figure S6: Land Use Intensity (LUI) of species in ha TJ⁻¹), recreation (Table S13: Recreation scores for species at different phases of development), and aesthetics (Table S14: Visual impact scoring based on selected factors at eye-horizon level Table S15: Definition of the assessed landscape types by their composition Table S16: Visual effect on landscape Table S17: Summary and result of aesthetics score).

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