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Sustainable biomass sourcing through agroforestry systems based on poplar and eucalyptus as fast-growing trees

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Abstract

Global biomass demand is expected to increase during the next decades, which bears risks of accelerating food insecurity and biodiversity loss. Therefore, guidelines and standards have been developed to ensure sustainable biomass sourcing as feedstock for material or energetic purposes. This review addresses the question of how fast-growing trees in agroforestry systems increase biomass production and serve as sustainably sourced biomass feedstock. The Land Equivalency Ratio (LER), a measure of productivity gains by agroforestry, was positively correlated with the number of trees per hectare ($R = 0.561$) and with the spacing between tree rows ($R = 0.26$). The former corresponds to a high wood yield of the given agroforestry systems, while the latter corresponds to high crop yields within the agroforestry systems. The LER of tree windbreak systems (spacing between tree rows >100 m) was 1.1-2.1. Tree windbreak systems adhered to principles of sustainable biomass sourcing, while other agroforestry systems often provided lower food crop yields compared to the corresponding crop monoculture. Still, such agroforestry systems help to diversify incomes, have the potential to protect croplands against erosion, and improve the microclimate. Depending on local conditions, biomass from those agroforestry systems can be considered sustainable, too.

Keywords: Alley cropping, Bioeconomy, Biomass demand, Land equivalency ratio, Material use, Tree windbreak systems, Woody biomass.

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Contents

Contribution of this paper to the literature:
This study, for the first time, pools together data on wood and crop yields of agroforestry systems with fast-growing trees. These data are discussed to assess agroforestry systems as biomass feedstock in light of the emerging issue of sustainable biomass sourcing for the bio-economy.

1. Introduction

Global biomass demand is expected to increase during the next decades, as shown by, for instance, [1], who assumed that the global biomass demand will increase from 12.14 Gt in 2011 to between 17.13 Gt and 20.36 Gt by 2050, in order to satisfy the needs for increased food production as well as for the material and energetic use of biomass. Biomass is primarily used to feed livestock (58% of global biomass use), bioenergy (amounting to 16%), food (14%), material use (10%), and biofuels (biodiesel and bioethanol for transport account for 1%) [1].

In the course of reducing the use of fossil carbon sources for material uses, it is claimed that the overall consumption of materials needs to be reduced, recycling needs to be increased, and bio-based products need to be used for the amount of production of virgin materials (such as chemicals, but also construction materials) that cannot be covered by the reduction of consumption and recycling [2]. This is underlined by UNEP [3], which states that a sustainable and circular bioeconomy must be based on prioritizing the use of biomass to maximize well-being, while the conversion of biodiversity- and carbon-rich natural systems must be avoided.

Yet, the production and sourcing of an increasing amount of biomass for human demands bear high risks of accelerating food insecurity, biodiversity loss, and climate change. Therefore, guidelines, safeguards, and standards have been developed to ensure sustainable biomass sourcing as feedstock for material or energetic purposes across different feedstocks [4, 5], as well as for specific feedstocks, such as sugar cane [6], soy [7], or palm oil [8]. To address the concerns regarding food insecurity, biodiversity loss, and climate change, the BFA [4], for instance, stipulated the following principles that sustainably sourced biomass must fulfill: i) it is derived from renewable biomass whose production is sustainably managed, ii) it does not adversely impact food security and affordability and maintains or improves social and economic conditions along with ecosystem services in producing communities, iii) it does not directly or indirectly result in the destruction of critical ecosystems or loss of high conservation value habitats, and iv) it contributes to landscape resilience and is resilient to the impacts of climate change. Other standards, such as RSB [5], adhere to very similar principles.

Agroforestry (AF) systems, which according to FAO [9] deliberately integrate woody perennials (trees, shrubs, palms, bamboos, etc.) with agricultural crops and/or animals, are acknowledged to increase overall biomass productivity compared to respective monocultures of trees and crops, while providing a number of benefits to improve food insecurity, contribute to halting biodiversity loss, and help mitigate and adapt to climate change. Furthermore, AF has the potential to improve soil fertility, reduce erosion, improve water quality, sequester carbon, increase aesthetics [10], and enhance the microclimate for crops [11].

In particular, fast-growing trees can contribute substantially to increasing the productivity of AF systems. Hence, in the first step, this paper assesses the productivity gains of AF systems from fast-growing trees, followed by a discussion of how far the criteria for sustainable biomass sourcing are met. Thereby, this paper focuses on AF systems with the two fast-growing tree species, poplar and eucalyptus, which are listed among the most widely used fast-growing tree species in AF globally [12]. In this paper, the jurisdictional and societal principles are not studied, such as sustainably sourced biomass must adhere to labor laws and must economically benefit local and rural communities.

The Land Equivalency Ratio (LER) after [13] is a widely used metric to express productivity gains of agroforestry (AF) systems versus corresponding monocultures of crops and trees. The LER is calculated as follows.

$$LER = \frac{Yield\ tree\ agroforestry}{Yield\ tree\ reference} + \frac{Yield\ crop\ in\ agroforestry}{Yield\ crop\ reference}$$

Yield tree reference is a plantation of the given tree, while yield crop reference refers to a field plot of the given crop with no kind of intercropping. Thus, LER only considers biomass yield changes (wood yields from the trees and crop yields), regardless of their economic value or further benefits beyond sheer biomass. Crop-related LER (LERc) after [14] focuses on crop yield changes by AF systems and therefore highlights the benefits associated with crops rather than trees. Hence, LERc captures the impact of AF systems on food supply.

$$LERc = \frac{Yield\ crop\ in\ agroforestry - Yield\ crop\ reference}{Yield\ crop\ reference}$$

2. Methods

The productivity gains by agroforestry (AF) of fast-growing trees were assessed through a literature review using the search terms "land equivalency ratio" AND "poplar" and "poplar agroforestry" as well as "land equivalency ratio" AND "eucalyptus" and "eucalyptus agroforestry," which were used in Google Scholar and Web of Science. Papers were screened for absolute crop yield data for crops within AF in comparison to the same crop grown as a monoculture to be able to calculate LERc. Those papers that, in addition to crop yield data, contained tree yield data for the AF trees and trees from plantations were used to calculate LER values.

Crop yields and tree yields were converted into t ha^{-1} yr^{-1}. Thereby, tree yields referred to above ground woody biomass, mostly stem wood biomass, which was divided by the given tree age. Part of the studies on poplar-based AF systems reported tree or stem volumes, which were converted into biomass with a wood density of 0.35 t m^{-3} after [15].

Next to the crop and tree yield data, the following data were extracted from the selected papers, as far as they were available.

- Site data: Geographical location (by name), climate classification (Köppen-Geiger), mean air temperature, and annual precipitation.
- AF system data: Type of AF system, tree species (clone, if available), spacing between tree rows and within rows, number of trees per hectare, tree height, and crop.

LER and LERc values were grouped by tree (poplar and eucalyptus), AF system, and crop in order to calculate the respective averages and standard deviations. The differences between averages were tested for significance at $\alpha < 0.05$ through a t-test (the averages by tree) and by an analysis of variance, respectively.

The studies of the AF experiments reviewed did not contain tree windbreaks or field boundaries of wide spacing (100 m and more), so this gap was closed with crop yield data from [16] and our own tree yield data. Those own tree yield data stem from a dataset of poplar-based (P. nigra, local clone Mirza Terek) tree windbreaks in Kyrgyzstan, Jalalabad Region, (spacing of 200 m) and plantations from the same poplar clone in that region. The selected tree windbreaks and plantations consisted of 10-year-old trees.

3. Results

A total of 23 field experiments were screened for this study, which yielded a total of 100 LER datapoints, of which 58 and 42 datapoints were from poplar and eucalyptus AF systems, respectively. The vast majority (87%) of those datapoints stemmed from experiments that were laid out as alley cropping systems or contiguous plantations with the given crop as understory vegetation, while only 13% were oriented around tree rows as field boundaries. The tree spacing within the contiguous plantations was 3m x 3m, while most of the alley cropping had spacings between tree rows of less than 8 m. The majority of all datapoints (70%) stemmed from AF systems with trees aged 5 years and younger. Nine additional datapoints allowed for the calculation of LERc only, because no tree data were reported. These nine additional datapoints stem from experiments laid out as alley cropping, with eight datapoints from poplar AF systems and one from a eucalyptus AF system.

The LER and LERc averaged across all data points were 1.51 and -0.29, respectively. The LERs divided by AF tree species were 1.57 for poplar and 1.42 for eucalyptus AF systems, whereby the two did not show significant differences (Table 1). The LERs divided by AF system did not differ significantly either (Table 2). Additionally, LER by major crops did not show significant differences (Table 3). Out of the 100 data points, only six show an LER < 1; these six data points all stem from eucalyptus AF systems, while the minimum LER among the poplar AF systems was 1.14 (Table 1).

Table 1. Land equivalency ratio (LER) of AF systems by poplar and eucalyptus.

Tree	LER average ± standard deviation	LER maximum	LER minimum	Number of data points
Poplar	1.57 ± 0.37	2.78	1.14	58
Eucalyptus	1.42 ± 0.4	2.19	0.68	42
All data points	1.51 ± 0.39	2.78	0.68	100

Table 2. Land equivalency ratio (LER) of the different AF systems: alley cropping, contiguous plantations with the given crop as understory vegetation, and tree rows as field boundary.

Tree	LER average ± standard deviation	LER maximum	LER minimum	Number of data points
Alley cropping	1.48 ± 0.36	0.68	2.78	81
Contiguous plantations	1.56 ± 0.19	1.27	1.83	6
Field boundary	1.62 ± 0.57	0.85	2.23	13

Table 3. Land equivalency ratio (LER) of AF systems by crops, poplar and eucalyptus pooled together under each crop.

Crop	LER average ± standard deviation	LER maximum	LER minimum	Number of data points
Wheat	1.51 ± 0.47	2.78	0.85	35
Switchgrass (Panicum virgatum L.)	1.46 ± 0.18	1.71	1.26	6
Sorghum	1.55 ± 0.24	2.01	1.18	24
Fodder grass	1.76 ± 0.19	1.94	1.45	5
Cowpea	1.5 ± 0.16	1.64	1.23	5
Barley	1.58 ± 0.66	2.77	1.22	5

The LERc values of poplar and eucalyptus agroforestry (AF) systems did not differ significantly (Table 4). Divided by AF system, the LERc of field boundary AF systems was significantly higher than the LERc values of alley cropping and plantation with crops as understory vegetation (Table 5).

Table 4. Crop related land equivalency ratio (LERc) of AF systems by poplar and eucalyptus.

Tree	LERc average ± standard deviation	LERc maximum	LERc minimum	Number of data points
Poplar	-0.23 ± 0.23	0.35	-0.74	66
Eucalyptus	-0.37 ± 0.24	0	-0.82	43
All data points	-0.29 ± 0.24	0.35	-0.82	109

Table 5. Crop related land equivalency ratio (LERc) of the different AF systems: Alley cropping, contiguous plantations with the given crop as understory vegetation, and tree rows as field boundary.

Tree	LERc average ± standard deviation	LERc maximum	LERc minimum	Number of data points
Alley cropping	-0.3 ± 0.24a	0.35	-0.82	89
Contiguous plantations	-0.48 ± 0.21a	-0.17	-0.73	7
Field boundary	-0.08 ± 0.13b	0.14	-0.25	13

Note: The letters a and b indicate significant differences of the averages of LERc ($\alpha = 0.05$).

The large majority of the LER datapoints (94%) and all nine additional LERc datapoints showed lower crop yields inside the AF system compared to the corresponding monoculture crop yields. This crop yield reduction increased with tree age and thus tree height (see data points by Kimura et al. [17]). Among the experiments listed here, crop yields decreased more pronouncedly the narrower the tree spacing had been laid out (see data points by Sirohi et al. [18]). The datapoints with crop yields higher inside AF than the corresponding monoculture refer to AF systems with spacing between tree rows of 25 m, 40 m, and 48 m, respectively, which is wide spacing compared with the majority of the datapoints included in this study.

LER was significantly positively correlated with the number of trees per hectare ($R = 0.561$) and with the spacing between tree rows ($R = 0.26$). The former corresponds to a high wood yield of the given agroforestry (AF) systems due to a high tree density, while the latter corresponds to high crop yields within the AF systems. LERc was not significantly correlated with the number of trees per hectare, but it was positively and significantly correlated with the spacing between tree rows ($R = 0.5$), which underlines that a wider spacing between tree rows impacts crop yields to a lesser extent. LERc was significantly and negatively correlated with the tree yield in the given AF systems ($R = -0.24$), which indicates a trade-off between crop yields and tree biomass yield for AF systems with a narrow spacing between tree rows.

In contrast to the experiments listed here, crop yields on average increased in tree windbreak systems, i.e., agroforestry (AF) systems with distances between tree rows of 100 m or several hundred meters, which is reflected in positive LERc values across crops (Table 7) [16]. Tree yield data of poplars in tree windbreaks versus plantations were drawn from our own data in Kyrgyzstan (Table 6). The LER of those systems also indicated an overall increase in biomass yields inside AF systems compared to separated monocultures (Table 7).

Table 6. Tree age, DBH, height, volume, biomass, and tree yield of tree windbreaks with 200 m spacing (single row) and corresponding plantations in the Jalalabad Region, Kyrgyzstan. Tree windbreaks and plantations consisted of P. nigra, local clone Mirza Terek.

Tree parameter (Average)	Tree wind break	Plantation
Tree age [yr]	10	10
DBH [cm]	21	17.8
Height [m]	22.3	19.5
Tree volume [m^3]	0.32	0.2
Tree biomass [kg]	127	79
Trees per ha	100	2500
Biomass [$t\ ha^{-1}$]	12.7	198.4
Yield [$t\ ha^{-1}\ yr^{-1}$]	1.3	19.8

Table 7. Crop yield increases, LER, and LERc of tree windbreak systems.

Crop	Crop yield increase [%] of crop within tree wind break system, after [16]	LER	LERc
Spring wheat	8	1.1	0.08
Winter wheat	23	1.3	0.23
Barley	25	1.3	0.25
Oats	6	1.1	0.06
Rye	19	1.3	0.19
Millet	44	1.5	0.44
Corn	12	1.2	0.12
Alfalfa	99	2.1	0.99

4. Discussion

4.1. LER and LERc Values

Experimental studies of agroforestry (AF) systems with tree species other than poplar or eucalyptus revealed LER values larger than one; for example, [19] reported an LER of 1.36 for the AF system of alder and wheat.

Further studies also underlined that crop yields shrank under agroforestry (AF) systems with a high tree density [20], which is due to the shading of the crops. Pardon et al. [21] and Zhao et al. [22] found that crop yields, compared to corresponding monocultures, shrank the closer the crop grew to AF trees and the taller those trees were. This is compounded by findings from [23] that the photosynthetically active radiation significantly drops close to AF trees. Despite the lower crop yields in narrowly spaced AF systems, those systems, in most cases, show an increased Land Equivalent Ratio (LER). This can be explained by the high wood yield associated with the high tree density, which overcompensates for the loss of crop yields. In other words, the wood biomass yielded from such AF systems implies a trade-off in terms of crop yield, which in most cases are food or fodder crops. This trade-off is underlined by the mostly negative values of LERc across AF systems and crops, which indicate lower crop yields inside AF systems compared to the respective monocultures.

In the context of tree windbreaks, crop yields were found to be reduced in the neighborhood of windbreaks to a distance of 1 x tree height [24], 2 x tree height [25], and 3 x tree height [26], respectively, also due to the shade that impacted the given crops. In the case of tree windbreaks with tree row spacing of 100 m and more, crop yields do increase on average, while the annual growth of the single agroforestry (AF) trees is also larger than that of trees in corresponding plantations. Therefore, tree windbreak systems offer land equivalent ratio (LER) values of larger than one, albeit lower than the reviewed alley cropping systems, but without facing the trade-off of sacrificing food or fodder crop yields, which is underlined by positive LERc values across all crops (Table 7).

4.2. Discussion of Agroforestry and Sustainable Biomass Sourcing

This second part of the discussion examines the changes in crop and tree yields of agroforestry (AF) systems compared to the respective monocultures in light of the principles for sustainable biomass sourcing [4] that are listed in the introduction.

Wood biomass sourced from AF systems is a renewable biomass because trees can be regrown after the preceding harvest of AF trees. If the AF systems are managed according to so-called good agricultural practices, which do not degrade soils and water resources, then the production of the wood biomass can be considered sustainably managed [5] to adhere to the first principle of BFA [4] for sustainable biomass sourcing.

According to the results of the agroforestry (AF) experiments listed in this study, food or fodder production is compromised when a given crop monoculture is converted into an AF system with narrow spacing between trees, high tree density, and hence high yields of woody biomass. This is also reflected in the negative Land Equivalent Ratio (LERc) values of those AF systems, as listed in the results section. On the other hand, wood biomass offers an additional income to farmers, which may improve food affordability and the social and economic situation of local and rural communities, and therefore helps diversify farmers' income [12]. If the overall social and economic situation of the local population is improved, then this second principle would be adhered to. The tree windbreak systems (Table 7), however, do adhere to the second principle of BFA [4] for sustainable biomass sourcing, because food and fodder production is not compromised, but often even increased compared to a respective monoculture, while obtaining an additional benefit from the tree biomass. If plantations of fast-growing trees are planned in areas that have not been producing food or fodder, then those plantations can be enriched with an understory crop to form AF systems that also adhere to the second principle, because additional food or fodder production is added to a given area and its population.

AF systems must not be established within the area of critical ecosystems in order to avoid directly causing the loss of critical ecosystems or habitats of high conservation value. AF systems with negative LERc values, which compromise food and fodder production, may lead to land conversion to compensate for the loss of food or fodder production, which may indirectly result in the destruction of critical ecosystems or losses of high conservation value habitats. Therefore, AF systems with negative LERc values are prone to violate the third principle by BFA [4].

AF systems offer a number of benefits to landscape resilience and are resilient to the impacts of climate change themselves. The potential of AF systems to improve soil fertility, reduce erosion, improve water quality, and enhance the microclimate for crops [10, 11] strengthens landscape resilience and is delivered by AF systems with both high and low LER or LERc values alike. AF systems with a high tree density, which tend to deliver reduced crop yields compared to respective monocultures, offer a high potential to protect soils from erosion. Gupta et al. [27] showed that water erosion of soils was significantly reduced under a poplar AF system with tree spacing of 6.5 m x 4.3 m in Punjab, India. Additionally, in New Zealand, poplars and willows have been planted on pastures to form an AF system to control water erosion on slopes for the past 60 years [28, 29]. Young eucalyptus plantations (tree age between 3 and 7 years) in Brazil reduced soil erosion by more than 50% compared with bare soils on slopes of 20° steepness [30]. As a result, the older and larger the eucalyptus tree grew, the lower the soil losses became. Furthermore, such systems can improve soil properties, such as infiltration for water, thereby contributing to mediating the water cycle and improving water quality [10].

AF systems with high tree density and reduced crop yields compared to the corresponding crop monocultures tend to protect the soil better against erosion. If, in a given region, erosion control on cropland is an overarching goal, then introducing AF and careful harvesting of its wood biomass would seem justifiable, as long as the affordability of food for the local population is not compromised. Programs to control soil erosion, such as China's so-called Green for Grain Program, incentivized tree planting on mainly marginal cropland prone to erosion (see [31]). On the other hand, poplars and eucalyptus trees are substantial water consumers, so newly established AF systems with high tree density may over-exploit local water resources and cause water stress in a given landscape, as was shown, for instance, for afforestation programs with poplars in northern China [32, 33].

AF systems change the microclimate under which the accompanying crops grow through shade (reduced radiation), lower temperatures, increased air humidity, and reduced wind speed compared with respective monocultures. In particular, tree windbreaks are designed to reduce wind speed and thereby decrease crop water consumption, mechanical damage to crops, and wind erosion of cropland soils (Alemu [34]). Thevs et al. [35] showed that tree windbreaks of poplars at a spacing of 100 m or more reduced the water consumption of the whole AF system compared to the corresponding crop grown as a monoculture. These effects on the microclimate make the AF systems themselves more resilient to climate change, specifically increased temperatures, enhanced water stress, and extreme weather events, than corresponding crop monocultures, as detailed by Quandt et al. [36]. Thus, shading lowers air temperatures and crop water consumption, minimizes soil erosion and soil loss during heavy rainfall and/or flood events, and protects crops from strong winds. Reduced wind speeds also correspond with lowered crop water consumption and a lower risk of crops suffering from water stress (Weninger et al. [37]).

The compliance with the principles for sustainable biomass sourcing by BFA [4] AF systems is summarized in Table 8.

Table 8. Compliance of AF systems with negative and positive LERc with the principles for sustainable biomass sourcing by BFA [4]. AF system refers to AF system.

Principle	AF system with high tree density and negative LERc	AF system with low tree density (tree stand breaks, field boundaries) and positive LERc.
Biomass is derived from renewable sources, and its production is sustainably managed.	Adheres to principle.	Adheres to principle.
Biomass sourcing does not adversely impact food security and affordability, and it maintains or improves social and economic conditions along with ecosystem services in producing communities.	Compromises food/fodder production but may provide additional income and, hence, improve social and economic conditions. Ecosystem services are often improved (see explanation in the text to principle 4).	Adheres to principle
Biomass sourcing does not directly or indirectly result in the destruction of critical ecosystems or the loss of high conservation value habitats.	Adheres to the principle, as long as the AF system is not established inside the area of critical ecosystems. It may result in indirect destruction of critical ecosystems or loss of high conservation value habitats.	Adheres to the principle, as long as the AF system is not established inside the area of critical ecosystems.
Biomass sourcing contributes to landscape resilience and is resilient to the impacts of climate change.	Largely adheres to principles. May cause water stress in drylands.	Adheres to principle.

5. Conclusion

Literature data on poplar and eucalyptus-based agroforestry (AF) systems were reviewed to calculate Land Equivalent Ratio (LER) and corrected Land Equivalent Ratio (LERc) values across a range of regions, climates, crops, and AF systems, which included alley cropping, plantations with a crop as understory vegetation, field boundaries, and tree windbreaks.

AF systems with narrow spacing and high tree density, i.e., alley cropping, plantations with a crop as understory vegetation, and field boundaries, as reviewed in this study, provide high wood biomass yields but often lower crop yields than the corresponding crops and trees grown as monocultures. In total, those AF systems deliver more biomass than the corresponding crops and trees would deliver when grown as separate monocultures, which results in high LER values, as listed above in this study. Yet, the LERc values of most of those AF systems are negative, which is a result of the reduced crop yields within those AF systems compared to the corresponding crop monocultures. In contrast, tree windbreak systems, in which the spacing between tree lines is much wider than the AF systems above, often 100 m and more, show LER > 1 and LERc > 0. This indicates that the tree windbreak systems produce more total biomass than the corresponding crops and trees would deliver when grown as monocultures and that crop yields do not decrease within those AF systems.

Given that tree windbreak systems also contribute to soil protection and often improve the microclimate, biomass sourced from those agroforestry (AF) systems has a high potential to fulfill the criteria of sustainably sourced biomass. Additionally, the AF systems with negative LERc values have the potential to fulfill the criteria of sustainably sourced biomass if the overall income and socio-economic situation of the local population is improved by, for example, additional income from the woody biomass. If AF systems with high tree density contribute substantially to landscape resilience, such as soil protection or regulating the water cycle, they also have the potential to fulfill the criteria of sustainably sourced biomass. If landscape resilience is an overarching goal in a given region, then AF systems with high tree density should be considered to fulfill the criteria of sustainably sourced biomass.

References

[1] S. Piotrowski, M. Carus, and R. Essel, "Global bioeconomy in the conflict between biomass supply and demand," *Industrial Biotechnology*, vol. 11, no. 6, pp. 308-315, 2015. https://doi.org/10.1089/ind.2015.29021.stp

[2] O. Arodudu, B. Holmatov, and A. Voinov, "Ecological impacts and limits of biomass use: A critical review," *Clean Technologies and Environmental Policy*, vol. 22, no. 8, pp. 1591-1611, 2020. https://doi.org/10.1007/s10098-020-01911-1

[3] UNEP, "Global resources outlook 2024: Bend the trend – pathways to a liveable planet as resource use spikes, International Resource Panel: Nairobi," 2024. Retrieved: https://www.resourcepanel.org/reports/global-resources-outlook-2024. 2024.

[4] BFA, "Methodology for the assessment of bioplastic feedstocks. WWF," 2022. Retrieved: https://www.worldwildlife.org/publications/report-methodology-for-the-assessment-of-bioplastic-feedstocks. 2022.

[5] RSB, "RSB principles & criteria RSB-STD-01-001. The Roundtable on Sustainable Biomaterials," 2023. Retrieved: https://rsb.org/. 2023.

[6] Bonsucro, "Bonsucro production standard version," 2023. Retrieved: https://bonsucro.com/wp-content/uploads/SCH_Bonsucro-Production-Standard-V5.2-July-2023-ENG.pdf. 2023.

[7] RTRS, "RTRS standard for responsible soy production. Roundtable on Responsible Soy," 2021. Retrieved: https://responsiblesoy.org/wp-content/uploads/2023/03/RTRS-Standard-for-Responsible-Soy-Production-V4.0.pdf. 2021.

[8] RSPO, "A global certification system for certified sustainable palm oil," 2024. Retrieved: https://rspo.org/as-an-organisation/certification/. 2024.

[9] FAO, "Agroforestry," 2024. Retrieved: https://www.fao.org/agroforestry/. 2024.

[10] S. Jose, "Agroforestry for ecosystem services and environmental benefits: An overview," *Agroforestry Systems*, vol. 76, pp. 1-10, 2009.

[11] A. Pantera, M. Mosquera-Losada, F. Herzog, and M. Den Herder, "Agroforestry and the environment," *Agroforestry Systems*, vol. 95, no. 5, pp. 767-774, 2021. https://doi.org/10.1007/s10457-021-00640-8

[12] FAO, "How can fast-growing trees optimize agroforestry benefits," 2024. Retrieved: https://openknowledge.fao.org/server/api/core/bitstreams/0cdaeaa6-e4a9-4d59-ae9c-46e50d2e08e9/content. 2024.

[13] R. Mead and R. Willey, "The concept of a 'land equivalent ratio'and advantages in yields from intercropping," *Experimental agriculture*, vol. 16, no. 3, pp. 217-228, 1980. https://doi.org/10.1017/s0014479700010978

[14] C. K. Ong and R. M. Kho, *A framework for quantifying the various effects of tree-crop interactions, in C.K. Ong and P. Huxley, Eds., Tree-crop interactions: a physiological approach*. CABI International. https://www.cabidigitallibrary.org/doi/pdf/10.1079/9781780645117.0001, 1996.

[15] FAO (Food and Agriculture Organization of the United Nations), "Global forest resources assessment 2005: Progress towards sustainable forest management," FAO Forestry Paper No. 147. Food and Agriculture Organization of the United Nations, 2005, 2005. https://www.fao.org/4/a0400e/a0400e00.htm

[16] J. Kort, "9. Benefits of windbreaks to field and forage crops," *Agriculture, Ecosystems & Environment*, vol. 22, pp. 165-190, 1988. https://doi.org/10.1016/0167-8809(88)90017-5

[17] E. Kimura *et al.*, "Effect of intercropping hybrid poplar and switchgrass on biomass yield, forage quality, and land use efficiency for bioenergy production," *Biomass and Bioenergy*, vol. 111, pp. 31-38, 2018. https://doi.org/10.1016/j.biombioe.2018.01.003

[18] C. Sirohi, K. Bangarwa, R. Dhillon, and K. Bhardwaj, "Performance of different wheat varieties under poplar (Populus deltoides) based agroforestry system," *Indian Journal of Ecology*, vol. 43, no. 2, pp. 752-755, 2016.

[19] L. M. Lehmann *et al.*, "Productivity and economic evaluation of agroforestry systems for sustainable production of food and non-food products," *Sustainability*, vol. 12, no. 13, p. 5429, 2020. https://doi.org/10.3390/su12135429

[20] S. Fang, H. Li, Q. Sun, and L. Chen, "Biomass production and carbon stocks in poplar-crop intercropping systems: A case study in Northwestern Jiangsu, China," *Agroforestry systems*, vol. 79, pp. 213-222, 2010. https://doi.org/10.1007/s10457-010-9307-x

[21] P. Pardon *et al.*, "Effects of temperate agroforestry on yield and quality of different arable intercrops," *Agricultural Systems*, vol. 166, pp. 135-151, 2018. https://doi.org/10.1016/j.agsy.2018.08.008

[22] Y. Zhao *et al.*, "The optimal size of a Paulownia-crop agroforestry system for maximal economic return in North China Plain," *Agricultural and Forest Meteorology*, vol. 269, pp. 1-9, 2019. https://doi.org/10.1016/j.agrformet.2019.01.043

[23] S. Newman, K. Bennett, and Y. Wu, "Performance of maize, beans and ginger as intercrops in Paulownia plantations in China," *Agroforestry Systems*, vol. 39, pp. 23-30, 1997. https://doi.org/10.1023/A:1005938310106

[24] R. A. Read, *Tree windbreaks for the central great plains. Agricultural Handbook*. Washington, DC: U.S.D.A. Forest Service, 1964.

[25] L. Lyles, J. Tatarko, and J. Dickerson, "Windbreak effects on soil water and wheat yield," *Transactions of the ASAE*, vol. 27, no. 1, pp. 69-0072, 1984. https://doi.org/10.13031/2013.32737

[26] B. W. Greb and A. L. Black, "Vegetative barriers and artificial fences for managing snow in the central and northern plains," presented at the Snow and Ice in Relation to Wildlife and Recreation, in A.O. Haugen, Ed., Proc. Symp., Iowa State University, Ames, IA, pp. 96-111, 1971.

[27] N. Gupta, S. Kukal, and P. Singh, "Soil erodibility in relation to poplar based agroforestry system in North Western India," *International Journal of Agriculture and Biology*, vol. 8, pp. 859-861, 2006. https://doi.org/10.1007/s10457-009-9219-9

[28] I. McIvor, G. Douglas, J. Dymond, G. Eyles, and M. Marden, *Pastoral hill slope erosion in New Zealand and the role of poplar and willow trees in its reduction. In D. Godone & S. Stanchi (Eds.), Soil Erosion Issues in Agriculture*. Rijeka, Croatia: InTech, 2011.

[29] A. Wilkinson, "Poplars and willows for soil erosion control in New Zealand," *Biomass and Bioenergy*, vol. 16, no. 4, pp. 263-274, 1999. https://doi.org/10.1016/s0961-9534(99)00007-0

[30] A. H. Oliveira, M. L. N. Silva, N. Curi, J. C. Avanzi, G. Klinke Neto, and E. F. Araújo, "Water erosion in soils under eucalyptus forest as affected by development stages and management systems," *Ciência e Agrotecnologia*, vol. 37, pp. 159-169, 2013. https://doi.org/10.1590/s1413-70542013000200007

[31] C. Lyu and Z. Xu, "Crop production changes and the impact of Grain for Green program in the Loess Plateau of China," *Journal of Arid Land*, vol. 12, pp. 18-28, 2020. https://doi.org/10.1007/s40333-020-0091-9

[32] S. Cao, L. Chen, and X. Yu, "Impact of China's Grain for Green Project on the landscape of vulnerable arid and semi‐arid agricultural regions: A case study in Northern Shaanxi Province," *Journal of Applied Ecology*, vol. 46, no. 3, pp. 536-543, 2009. https://doi.org/10.1111/j.1365-2664.2008.01605.x

[33] Z. Wang, D. Peng, D. Xu, X. Zhang, and Y. Zhang, "Assessing the water footprint of afforestation in Inner Mongolia, China," *Journal of Arid Environments*, vol. 182, p. 104257, 2020. https://doi.org/10.1016/j.jaridenv.2020.104257

[34] M. M. Alemu, "Ecological benefits of trees as windbreaks and shelterbelts," *International Journal of Ecosystems*, vol. 6, pp. 10-13, 2016.

[35] N. Thevs, A. J. Gombert, E. Strenge, R. Lleshi, K. Aliev, and B. Emileva, "Tree wind breaks in Central Asia and their effects on agricultural water consumption," *Land*, vol. 8, no. 11, p. 167, 2019. https://doi.org/10.3390/land8110167

[36] A. Quandt, H. Neufeldt, and K. Gorman, "Climate change adaptation through agroforestry: Opportunities and gaps," *Current Opinion in Environmental Sustainability*, vol. 60, p. 101244, 2023. https://doi.org/10.1016/j.cosust.2022.101244

[37] T. Weninger *et al.*, "Ecosystem services of tree windbreaks in rural landscapes—a systematic review," *Environmental Research Letters*, vol. 16, no. 10, p. 103002, 2021. https://dx.doi.org/10.1088/1748-9326/ac1d0d