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Multifunctional perennial production systems for bioenergy: performance and progress

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Abstract

As the global population increases and becomes more affluent, biomass demands for food and biomaterials will increase. Demand growth is further accelerated by the implementation of climate policies and strategies to replace fossil resources with biomass. There are, however, concerns about the size of the prospective biomass demand and the environmental and social consequences of the corresponding resource mobilization, especially concerning impacts from the associated land-use change. Strategically integrating perennials into landscapes dominated by intensive agriculture can, for example, improve biodiversity, reduce soil erosion and nutrient emissions to water, increase soil carbon, enhance pollination, and avoid or mitigate flooding

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events. Such "multifunctional perennial production systems" can thus contribute to improving overall land-use sustainability, while maintaining or increasing overall biomass productivity in the landscape. Seven different cases in different world regions are here reviewed to exemplify and evaluate (a) multifunctional production systems that have been established to meet emerging bioenergy demands, and (b) efforts to identify locations where the establishment of perennial crops will be particularly beneficial. An important barrier towards wider implementation of multifunctional systems is the lack of markets, or policies, compensating producers for enhanced ecosystem services and other environmental benefits. This deficiency is particularly important since prices for fossil-based fuels are low relative to bioenergy production costs. Without such compensation, multifunctional perennial production systems will be unlikely to contribute to the development of a sustainable bioeconomy.

This article is categorized under:
Bioenergy > Systems and Infrastructure
Bioenergy > Climate and Environment
Energy Policy and Planning > Climate and Environment

KEYWORDS

bioenergy, biomass, land use, multifunctional production systems, perennial crops

1 | INTRODUCTION

As the global population increases and becomes more affluent, biomass demands for food and biomaterials will increase. Biomass demand growth is further accelerated by the implementation of climate policies and strategies to replace fossil fuels and other resources with biomass. For example, in most IPCC scenarios designed to meet global climate targets of 1.5 or 2°C (Clarke et al., 2014; IPCC, 2018), bioenergy plays an important role. The size of the

BOX 1 LAND-USE CHANGE (LUC)

Biomass production for bioenergy can cause direct or indirect LUC. The below definitions are used in this article. Note, however, that these terms can be used differently in different contexts.

Land use change refers to any change in land use or land management. This often relates to conversion of natural ecosystems into biomass production but could also include, for example, management changes, such as shifts between crops or rotations, harvesting techniques, and agricultural land uses (e.g., pasture to cropland).

Direct LUC (dLUC) refers to LUC at the site where, for example, new biomass production is established, or existing land management is altered.

Indirect LUC (iLUC) refers to LUC that is caused by LUC elsewhere. For example, expansion of bioenergy crop plantations in one area could displace food producers, who as a result move their production to other locations by clearing new land. In this case, the expansion of bioenergy plantations could be considered *indirectly* responsible for this LUC, and corresponding impacts. Although iLUC often refers to land conversion, it can also include, for example, changes in crop rotations and/or management intensity in production systems for food or feed.

Beneficial LUC (bLUC), refers to LUC that results in environmental benefits (Englund et al., 2019), either locally (*direct* bLUC) or elsewhere (*indirect* bLUC). One example of direct bLUC is the establishment of multifunctional production systems, as discussed in this article.

prospective biomass demand and consequences of the corresponding resource mobilization are, however, contentious issues (Berndes, 2002; Berndes, Hoogwijk, & van den Broek, 2003; Creutzig et al., 2014; Haberl et al., 2011; Slade, Bauen, & Gross, 2014; Smeets, Faaij, Lewandowski, & Turkenburg, 2006; Smith et al., 2013). A divisive issue concerns potential effects of increased biomass production on land-use change (LUC, Box 1) (Berndes, Ahlgren, Börjesson, & Cowie, 2013; Kline & Dale, 2008; Searchinger et al., 2008).

Organic wastes and harvest residues, which are biomass sources with minimal LUC effects, are considered insufficient for meeting the projected biomass demands (Clarke et al., 2014; Daioglou, Doelman, Wicke, Faaji, & van Vuuren, 2019; IPCC, 2018). It is therefore necessary to produce additional biomass volumes from dedicated biomass production systems. Future projections about land needed for production of biomass with "dedicated energy plantations" vary widely, ranging from 20 to 720 million hectares (Mha) in the four pathways illustrated by IPCC (2018). Nevertheless, realizing a substantial expansion is complicated by the limitation of productive land on Earth. Almost half of the global productive area is already under anthropogenic use, which has caused severe land degradation and impacts on biodiversity (Rockström et al., 2009). Uncontrolled expansion of dedicated bioenergy crops can cause extensive additional LUC and associated environmental impacts, potentially resulting in limited climate benefits and trade-offs with multiple other sustainable development goals (SDGs) (IPCC, 2018).

To minimize LUC effects, efforts to intensify biomass production are important. A complicating factor, however, is that intensive agricultural production, most notably of annual crops, has caused a number of negative environmental impacts, and mitigation of such impacts is another important societal objective (Englund et al., 2019). Further intensification of agriculture is therefore problematic. Furthermore, measures to mitigate impacts from intensive agriculture can create negative effects on biomass productivity at the regional scale, which can counteract expansion and intensification of biomass production elsewhere. To resolve this dilemma, biomass mobilization and impact mitigation can be considered as interconnected, not parallel, challenges. This requires solutions that can uphold or increase biomass productivity while avoiding, or even mitigating, negative environmental impacts from agriculture.

This article reviews options for integrating perennials into agricultural landscapes, in order to provide biomass for the bioeconomy and additional environmental benefits. Seven different cases in different world regions are here reviewed to exemplify and evaluate (a) multifunctional production systems that have been established to meet emerging bioenergy demands and (2) efforts to identify locations where the establishment of perennial crops will be particularly beneficial. Furthermore, opportunities and barriers for wider implementation are discussed, and associated needs for future research.

2 | MULTIFUNCTIONAL PERENNIAL PRODUCTION SYSTEMS

Multifunctional production systems can have very different character, both in terms of crop and management system, but also regarding their associated environmental benefits. In this chapter, we summarize four cases where different kinds of lignocellulosic crops, in different world regions, have been established with the purpose of meeting emerging bioenergy demands. Common for all cases is the aim to enhance conditions for ecosystem services and thus provide environmental benefits in addition to biomass. These cases exemplify the variety of possible options for cultivating lignocellulosic plants to produce biomass and provide additional environmental benefits.

2.1 | Case 1: short rotation coppice willow production for bioenergy in Ireland

In 2010, Ireland decided to implement co-firing of biomass in three state-owned peat power plants, to support bioenergy deployment and comply with EU renewable energy targets. The goal was to generate 50% of the maximum rated capacity by 2020 using biomass (DCCAE, 2010). To date, only one of these plants (Edenderry) is co-firing biomass, using 300,000 t of biomass annually to generate 30% of the total maximum rated capacity alone. In 2007, a national bioenergy scheme was introduced to stimulate biomass production, offering financial support for short rotation coppice (SRC) willow production. A parallel support scheme was introduced by the operator of the Edenderry power plant, targeting farmers that could supply the power plant with willow. This resulted in an increase in total willow area from around 100 ha in 2008 to more than 900 ha in 2015, nationally (Dáil Éireann, 2015). Although there have been few applications for establishment support since 2015, the demand for willow as an indigenous source of bioenergy is likely to increase. The two remaining peat-fired plants are due to start co-firing with biomass in 2020 (Dáil Éireann, 2019a), and the new Renewable Heat Support Scheme is due to come online in 2019, providing operational support for commercial, industrial, and district heating biomass boilers (Dáil Éireann, 2019b). In the Irish context, willow is a promising crop for co-firing with peat. Largely due to suitable agroclimatic conditions, but also due to a high willingness among farmers to produce energy crops (Augustenborg et al., 2012). Production of willow for such a purpose will, however, need to achieve meaningful greenhouse gas reductions and also provide additional environmental benefits. For that purpose, detailed life cycle inventory assessments have been conducted for willow production under different management regimes (application of synthetic vs. biological fertilizers, harvesting of chip vs. rods, and varying distances for transportation). Furthermore, energy- and greenhouse gas balances have been compared with systems based on imported biomass sources and fossil fuels, respectively (Murphy, Devlin, & McDonnell, 2014).

The results indicate that fertilization, harvesting, and transportation significantly influence the environmental performance (Figure 1). Using synthetic fertilizers instead of biological improves the overall environmental performance but also increases energy usage. Furthermore, results highlight the importance of matching biomass demands with local supplies, as the environmental benefits decrease with increasing transport distance. It is also notable that willow chip biomass has lower global warming potential and energy ratio than coal. It also causes significantly lower GHG emissions than imported biomass feedstock such as sunflower husk pellets and palm kernel shells (Murphy & McDonnell, 2017).

In summary, SRC willow production in Ireland is expanding due to multiple incentives from both private and public sectors. The research summarized here indicates substantial environmental benefits from such a development. It should be noted though that most environmental effects associated with such LUC are largely dependent on local conditions. The effectiveness of SRC willow in, for example, mitigating erosion and nutrient emissions to water, will vary from case to case based on existing land use and biotic and abiotic landscape characteristics. For example, while conversion of annual crop production to willow plantations typically enhances soil carbon sequestration, the opposite may occur by converting pastures (Clarke, Sosa, & Murphy, 2019).

2.2 | Case 2: Bioenergy and other benefits from SRC willow in Sweden

Willow has been produced commercially in Sweden since the early 1980s, after a period of intensive research focused on new varieties, management regimes, and machinery suitable for the crop and the country's conditions (Dimitriou & Aronsson, 2005). These efforts made Sweden one of the countries in Europe with the largest experience in willow cultivation. Although the area expanded quickly to reach between 14,000 and 16,000 ha at its peak (Dimitriou & Aronsson, 2005; Mola-Yudego & González-Olabarria, 2010), after the 1990s there has been a decline in area planted, mostly due to changes in the policy framework supporting establishment of plantations (Mola-Yudego, Dimitriou, Gonzalez-Garcia, Gritten, & Aronsson, 2014) combined with, for example, several agronomic reasons (Helby, Rosenqvist, & Roos, 2006), and lower yields than expected (Dimitriou, Rosenqvist, & Berndes, 2011).

Originally, the aim of these plantation systems was almost exclusively to produce bioenergy, and, despite the poor initial results, there has been a constant improvement in the productivity levels during recent decades (Mola-Yudego,- 2011). However, in addition to the high biomass potential of these plantations, there has been growing evidence of additional environmental benefits they can provide, which have been confirmed in life cycle assessments, trials, and

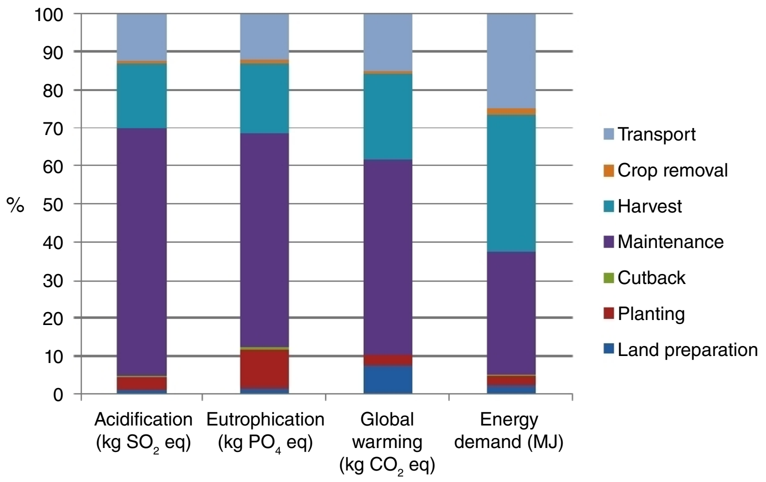

FIGURE 1 Percentage contribution of life cycle stages in SRC willow production to each impact category (Murphy et al., 2014)

experiments. In addition to the positive energy and environmental profile of plantations (González-García, Mola-Yudego, & Murphy, 2013; González-García, Mola-Yudego, Dimitriou, Aronsson, & Murphy, 2012; Nordborg et al., 2018), willow, when introduced into agricultural landscapes, results in significant benefits for groundwater water quality (Dimitriou, Mola-Yudego, & Aronsson, 2012; Dimitriou & Mola-Yudego, 2016), soil quality (Dimitriou et al., 2012) including increased soil organic carbon (SOC), and biodiversity (Langeveld et al., 2012). Knowledge about these benefits has enabled new business models that have gradually transformed the original yield-focused plantations into multifunctional systems that can provide additional ecosystem services beyond biomass for energy.

Willow plantations have proven to efficiently combine the use of sludge for fertilization in their management regimes (Sööder et al., 2013), becoming a common practice and partially replacing mineral fertilizers. The use of sludge increases the profitability of willow significantly (Dimitriou & Rosenqvist, 2011). Also, new industrial applications emerged in the late 1990s, when calculations showed the economic potential of using wastewater for irrigation (Rosenqvist, Aronsson, Hasselgren, & Perttu, 1997), and plantations started being established in combination with wastewater treatment plants (Dimitriou & Aronsson, 2005). Estimates showed that the gross profit margin increased by 39 EUR/GJ by applying sewage sludge and up to 199 EUR/GJ by applying wastewater (Dimitriou & Rosenqvist, 2011). A recent review of these applications and the expansion of these systems can be found in Zalesny et al. (2019).

Among those systems, particular attention has been focused on Nynäs Gård (Enköping), which successfully demonstrates viable multifunctional utilization of willow plantations, increasing its attractiveness and profitability. In this system, wastewater from a water treatment plant, corresponding to about 25% of the nitrogen that is treated, is used for irrigation of about 80 ha of willow plantations. In addition, sludge from nearby areas is used on another 80 ha (Sööder et al., 2013), resulting in the annual treatment of 11 t of nitrogen and 0.2 t of phosphorous (Dimitriou & Aronsson, 2005). The harvested biomass is then transported to the nearby combined heat and power plant, which is also supplied by other nearby commercial plantations, making it a hot-spot of willow cultivation in Sweden (Mola-Yudego & González-Olabarria, 2010; Mola-Yudego & Pelkonen, 2011), supplying the plant with about 10–20% of its total biomass demand (Mirck, Isebrands, Verwijst, & Ledin, 2005) (Figure 2).

These new systems are promising multifunctional alternatives that show that it is possible to combine biomass production and other ecosystem services in viable business models. This combination, however, was due to the suitable policy incentives in Sweden during the last decades, available know-how through years of collaboration with research institutions, and positive attitudes and regional partnerships between private companies, research institutions, and local government (Börjesson & Berndes, 2006; McCormick & Kåberger, 2005). Despite several similar cases of successful phytoremediation systems in Sweden (Aronsson & Perttu, 2001; Mirck et al., 2005), most are small initiatives that cannot be compared to the success and scale of the system described here, highlighting the difficulties of reproducing the model. Other benefits related to lignocellulosic crops remain even more challenging to translate into direct economic benefits to the producer, such as their potential for soil remediation, carbon sequestration, and biodiversity enhancement. However, these effects need to be considered in regional-level planning, in order to identify locations where the societal benefits of willow plantations can be maximized. The necessary tools to provide holistic landscape configurations, and the policy and economic mechanisms that would make them economically viable, need to become targets of upcoming research efforts.

FIGURE 2 Overview of the system near Enköping, Sweden, where willow fields, irrigated by a municipal wastewater plant, supply a combined, heat and power plant (from where the photo is taken) with biomass (Photo: Pär Aronsson, SLU)

2.3 | Case 3: Switchgrass for ethanol in the southeastern United States

Switchgrass is an energy crop that can be economically viable and has environmental benefits in many agricultural regions in the United States (V. H. Dale et al., 2011). It is a herbaceous and deep-rooted perennial grass native to the United States, capable of generating high yields (Jensen et al., 2007). In 1991, switchgrass was selected by the U.S. Department of Energy (USDE) as a model herbaceous bioenergy crop for the Southeast (Wright, 2007), supported by long-term research at Oak Ridge National Laboratory (ORNL). It was selected due to high productivity, low fertilizer requirements, good conservation attributes, and production and harvesting techniques that are compatible with those in conventional agriculture (McLaughlin et al., 1999; Mooney, Roberts, English, Tyler, & Larson, 2009; Post et al., 2004; Tolbert et al., 2002). Switchgrass produces relatively high and consistent yields on marginal land, and allows production on highly erodible land due to its perennial characteristics.

In 2004, a “Great Experiment” to develop the science of using switchgrass for sustainable biofuel production was launched in Tennessee in the southeastern United States (Figures 3 and 4) utilizing a $980,000 grant from the U.S. federal government. In 2007, this support was coupled with a $70 million investment by the State of Tennessee. The experiment highlighted cooperation among farmers, industry, and scientists in multiple disciplines from both the ORNL and the Institute of Agriculture at the University of Tennessee, as more than a decade of biofuels science was launched. Farmers were awarded 3-year contracts to produce switchgrass at an incentivized rate, and research was conducted on the farmers' fields. A total of 2,064 ha of this contracted bioenergy crop was grown on 66 farms in Tennessee. UT Extension and AgResearch scientists provided guidance on planting and harvesting practices. Collaboration occurred with numerous groups such as Chevron Corporation, USDE, U.S. Department of Agriculture, foreign delegations, and many others.

Topics incorporated into the Great Experiment included supply chain analysis (incorporating feedstock cultivation, harvesting, storage, and contracting and marketing products and co-products); improving genetic material; feedstock conversion; environmental and socioeconomic sustainability (detailed below); landscape design (locating plantings in places that enhance benefits and reduce costs and risks); and estimating system economic feasibility and regional impacts. Each topic resulted in an improvement of the knowledge base to enhance the development of a dedicated feedstock and sustainable fuel industry.

The Great Experiment was the basis of optimization modeling to explore potential trade-offs between soil carbon, water quality, and profit at the watershed scale using ORNL's super-computing resources (Parish et al., 2012). This analysis determined optimal locations to plant switchgrass in southeastern Tennessee based on profits and water quality projections. These optimal locations were then considered during the switchgrass farm contract selection process. Results of the “Biomass Location for Optimal Sustainability Model” efforts indicated that multiple goals—including reduced in-stream concentrations of sediment, nitrogen, and phosphorus, and increases in farmer profits—could be achieved by converting a very small proportion (~1–2%) of the 2,726 km^2 Lower Little Tennessee watershed area from traditional row crops to switchgrass.

During the Great Experiment, ORNL scientists collected information pertaining to 35 indicators of environmental and socioeconomic sustainability in 12 different categories: soil quality, water quality and quantity, air quality,

FIGURE 3 Switchgrass field in the “Great experiment.” Photo by Sam Jackson

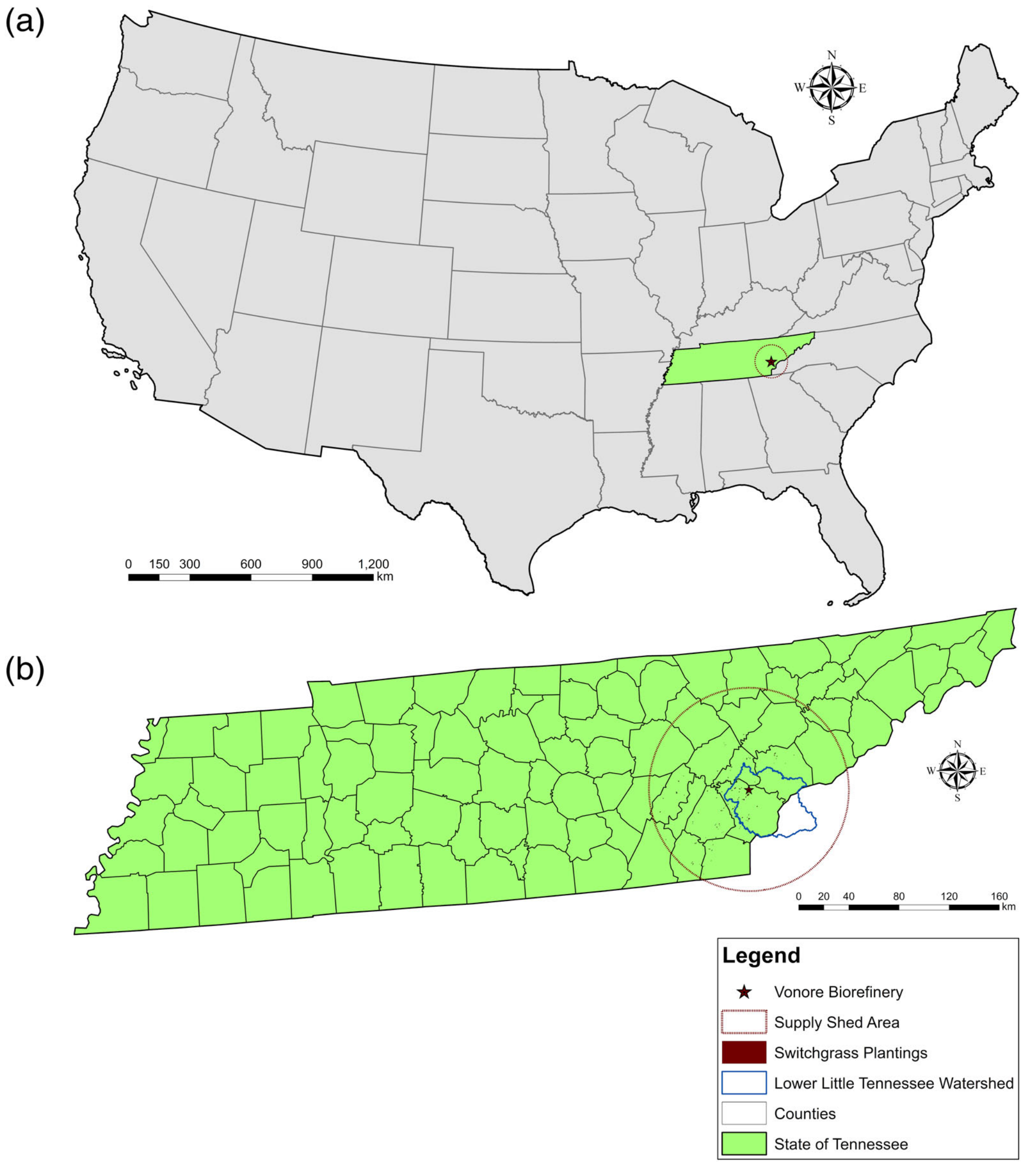

FIGURE 4 (a) Location of the Tennessee switchgrass-to-ethanol experiment within the southeastern United States. Applications for feedstock contracts were considered from Tennessee farms located within 80 km (i.e., an hour's drive) of the Vonore demonstration-scale biorefinery. (b) Optimal switchgrass planting locations were modeled for the Lower Little Tennessee watershed using a combination of water quality and profitability indicators. At the peak of the Great Experiment in 2010, a total of 2,064 ha of switchgrass were planted throughout 10 east Tennessee counties

productivity, biodiversity, greenhouse gas emissions, social well-being, resource conservation, social acceptability, and energy security (V. H. Dale, Efroymson, et al., 2013; McBride et al., 2011). The collected knowledge was used to construct a hierarchical decision tree framework that compared the overall sustainability of the no-till switchgrass production system to two current systems; tilled corn and unmanaged pasture (Parish, Dale, English, Jackson, & Tyler, 2016). The results indicated that a shift to switchgrass production could result in both local and watershed-scale environmental and socioeconomic benefits. The no-till switchgrass production system received high sustainability ratings for all environmental categories, except for greenhouse gas emissions (intermediate) due to increased transportation needs. By contrast, tilled corn received low to intermediate sustainability ratings for all categories, due to the intensive management that was needed to make it economically viable in this geographical setting. For unmanaged pasture, sustainability ratings were intermediate to high for all categories except for "productivity," but it provided little economic returns to the farmers. Overall, it was concluded that an increased production of switchgrass could improve environmental and social sustainability with only minor economic effects (Parish et al., 2016).

Although the demonstration-scale Tennessee cellulosic biorefinery did not end up receiving the investments necessary to scale up to commercial levels of production, a foundation for the future bioeconomy has been laid as local production of switchgrass and other cellulosic crops like biomass sorghum has continued. This biomass can, for example, be used as raw material for producing packaging materials and plastics, where fossil materials are becoming increasingly replaced by plant-based materials. Opportunities to produce sustainable aviation fuel may also be possible as the commercial airline industry increasingly seeks to decrease its carbon footprint, which is further discussed in the following case.

2.4 | Case 4: Eucalypts for aviation fuel in Australia

Australia has potential to produce considerable amounts of biomass from agriculture and forestry (Farine et al., 2011). However, current production falls well short of meeting national energy demands (Pearman, 2013). It is therefore necessary to identify strategically important energy applications for nationally sourced biomass.

The limited bioenergy production in Australia is due to three main factors:

- Policy limitations: policy does not fully address how energy interrelates with carbon, water, and other environmental aspects, and thus fails to promote options that provide multiple societal benefits (PMSEIC, 2010).
- Commercial limitations: Broadacre, dryland farmers have remained profitable by increasing the scale and/or intensity of grain production through innovation rather than diversification (George & Nicholas, 2012). There is a perceived risk of high opportunity costs associated with replacing annual crops with lignocellulosic crops (Goss et al., 2014).
- Unclear environmental benefits: Tree planting has been proposed as a measure to reduce dryland salinity, by increasing in situ water use. This has however not yet been possible to verify at larger scales. Revegetation in conjunction with other catchment actions is now recommended (Hatton & Nulsen, 1999; Simons & Speed, 2011).

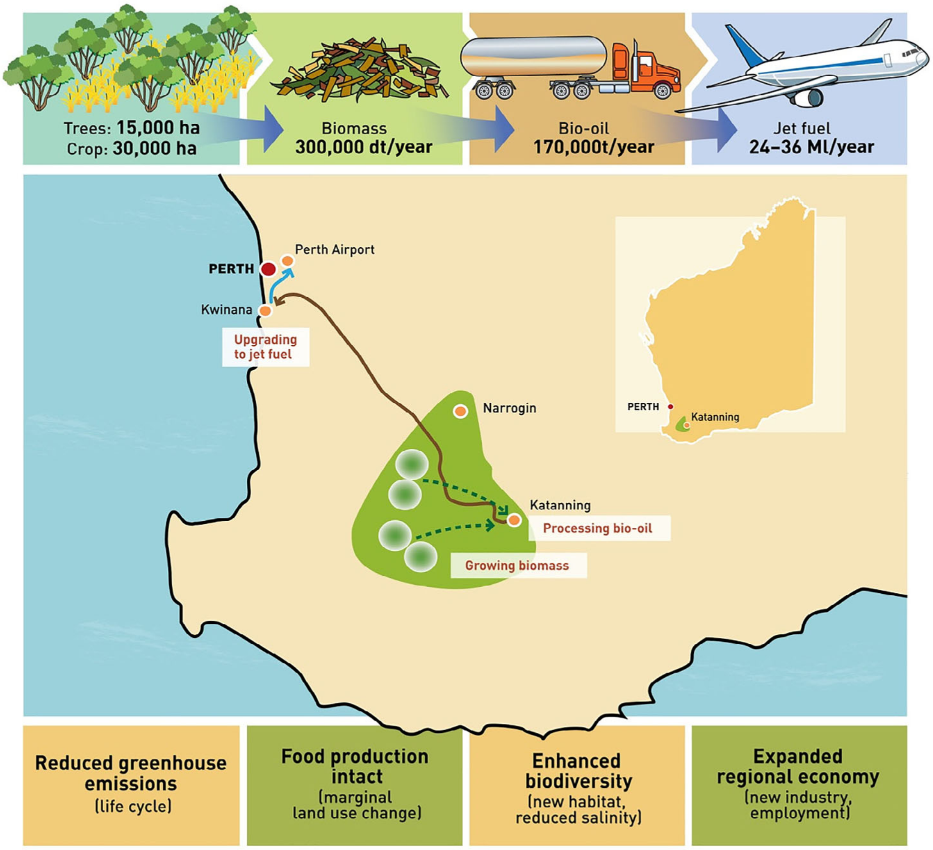

FIGURE 5 Integrated system for the supply of aviation fuel derived from mallee biomass based in the Great Southern region of WA (Goss, Abadi, Crossin, Stucley, & Turnbull, 2014)

FIGURE 6 Integrated production system with a variety of agricultural activities between rows of mallee

SRC eucalypts systems have been studied for their potential to enhance environmental and economic sustainability of dryland agriculture since 1990 (Stucley et al., 2012). Integrated with existing farming systems, such forms of woody tree cropping were shown to, for example, reduce water movement into groundwater systems relative to annual crop and pasture-based systems (Cooper, Olsen, & Bartle, 2005; Stucley et al., 2012). A system that has been evaluated specifically for production of aviation fuel uses native mallee eucalypt species, targeted to areas with lower precipitation (300–700 mm/year) in southern Australia (McGrath, Goss, Brown, Bartle, & Abadi, 2016). A well-defined business case (biomass to aviation fuel) combined with cooperation with local farmers provided reliable data to assess the viability of a commercial supply chain, as well as its environmental performance (Figures 5 and 6; Goss et al., 2014).

When evaluating the prospects for developing a sustainable aviation biofuel industry in the region (CSIRO, 2011), it was concluded that it had potential to meet multiple societal objectives. Establishing local and commercially viable supply chains was, however, identified to be a major challenge. Eucalypts, and other fast growing tree species, were suggested as a promising feedstock. Production costs were however estimated to be relatively high, due to low feedstock energy density and lack of cost-effective harvesting equipment techniques (CSIRO, 2011).

There has been a strong interest among Australian airlines in using sustainable aviation fuels. In 2019, Australia's largest carrier, Qantas, committed to capping net emissions from 2020 and achieving zero net emissions by 2050 through the development of sustainable aviation fuel and carbon offsets (Qantas, 2019). In 2018 the International Civil Aviation Organisation reaffirmed the goal of achieving “carbon neutral growth from 2020” and reducing net CO_2 emissions in 2050 by 50% relative to 2005. The deployment of sustainable aviation fuels, carbon offsets, and operational efficiencies will be used to achieve these targets (IATA, 2018). Despite this interest, implementation has been slow and the aviation fuel industry has not yet demanded these types of biomass resources. Therefore, local developers have continued to seek for other options. One alternative is to generate electricity for regional markets. A local Western Australian group is refining processing and production systems that can be used for biomass from woody crops and other biomass sources (Rainbow Bee Eater, 2018).

It is technically feasible to integrate coppicing eucalypts for bioenergy into farming systems in Western Australia. Modeling indicates that such systems could be profitable for farmers as well as beneficial for the regional economy, if infrastructure is upgraded and the biomass is processed regionally (Abadi et al., 2013). However, Australia's dry climate is limiting its capacity to produce biomass. Biomass resources therefore need to be directed to regional energy production or strategically important applications (e.g., aviation fuel). The knowledge of economic, technical, and environmental aspects of different biomass production systems is strong, indicating good development prospects. The development of new production systems to supply bioenergy industries is, however, held back by political and economic uncertainties.

3 | IDENTIFYING SUITABLE LOCATIONS FOR STRATEGIC ESTABLISHMENT OF PERENNIAL CROPS

While there is strong scientific support for claiming that the introduction of perennial crops in agricultural landscapes can have multiple environmental benefits (see Section 1 and Case 5), the effects of introducing perennials in a landscape vary, as they depend on landscape-specific biotic and abiotic properties (Efroymson et al., 2013), such as prior land use, management practices, topology, soil type, climatic conditions, and so on. It is important to understand in *which landscapes* perennialization will be particularly beneficial in order to direct implementation efforts to areas where the benefits would be maximized. Furthermore, it is important to understand *how to design and locate* perennial production systems in the landscape, so that the desired benefits are realized.

In this chapter, three cases are presented that, in different ways and in different geographical regions, explore the spatial context of strategic perennialization. See also the "Great Experiment" of switchgrass to ethanol in the previous chapter, in which optimization modeling was performed to identify optimal locations to plant switchgrass in southeast Tennessee based on profits and water quality projections (Parish et al., 2012).

3.1 | Case 5: Mapping the potential for strategic perennialization in European agricultural landscapes

Perennials can be strategically introduced into the agricultural landscape to mitigate environmental impacts from current and historic agriculture (V. H. Dale et al., 2011; Englund et al., 2019). For example, (a) windbreaks, using, for example, poplar, can result in decreased crop damages and enhanced soil fertility, thus increasing yields on sheltered cropland (Börjesson, 1999); (b) riparian buffers and filter zones with perennial grasses and/or SRC willow can reduce nutrient emissions to water (Styles et al., 2016; Berndes, Börjesson, Ostwald, & Palm, 2008; (c) strips or zones of perennial crops can be introduced in areas subject to rill erosion, particularly in hilly areas with silty and clayey soils (Börjesson, 1999), or (d) to prevent flooding events (Berndes et al., 2008). The effects of such production systems are well documented, both from experimental studies and commercial implementation (Berndes et al., 2008; Berndes, Fredrikson, & Börjesson, 2004; Börjesson, 1999; Börjesson & Berndes, 2006; Christian, Niemi, Hanowski, & Collins, 1994; Göransson, 1994; Grigal & Berguson, 1998; Gustafsson, 1987; Kort, Collins, & Ditsch, 1998; Perttu & Kowalik, 1997; Rijtema & DeVries, 1994).

A recent high-resolution land-use modeling study explored the potential for such *strategic perennialization* in mitigating impacts from the production of annual crops in the 28 member states of the EU, EU28 (Englund et al., 2019). First, each of the ~81,000 sub-watersheds ("landscapes") in EU-28 were assessed on the extent to which they were subject to a set of five environmental impacts that are typically related to production of annual crops. The extent to which these impacts could be mitigated using strategic perennialization was then estimated for each landscape individually. Finally, agricultural areas where such measures were indicated as having the highest potential in mitigating single or multiple impacts were identified.

Strategic perennialization can generally only be effective if there is a substantial degree of environmental impact(s) in the landscape combined with a high dominance of annual crop production. The latter is important since the benefits of introducing perennials into a landscape that is already dominated by perennial plants can be expected to be marginal. These factors were combined to indicate effectiveness (Figure 7). Further methodological information and additional results are available in Englund et al. (2019).

The results indicate that accumulated losses of SOC is the most common environmental impact, affecting over two-thirds of the area cultivated with annual crops in EU28. Furthermore, significant shares of the area under annual crops are located where there is a substantial risk for water erosion, nitrogen emissions to water, and recurring floods. Wind erosion is an overall less severe problem. There are also substantial overlaps between different impacts, indicating opportunities to address multiple impacts simultaneously.

Strategic perennialization was suggested as effective in addressing accumulated SOC losses on almost two-thirds of the total area under annual crop cultivation in EU-28, indicating a strong spatial correlation between the impact and the cultivation of annual crops. Reduction of soil loss by erosion from water and wind can be effective on about a quarter of the total area used for annual crop production. Figures for recurring floods and nitrogen emissions to water are 16 and 12%, respectively (Figure 7).

Mitigation of accumulated SOC losses through perennialization could be effective in agricultural areas all over Europe. Similar can be seen for soil erosion by water, although to a lesser extent. Mitigation of recurring floods could be addressed in agricultural areas around major rivers throughout the union but with the greatest potential in the Po Valley in Italy and in the Danube basin. In contrast to the other assessed impacts, significant potential for reducing nitrogen emissions to water by strategic perennialization can mainly be seen in north-western Europe.

Thus, strategic perennialization may contribute to reducing erosion, nitrogen emissions, floods, SOC losses, and related deleterious impacts on millions of managed hectares across Europe, while maintaining or increasing biomass

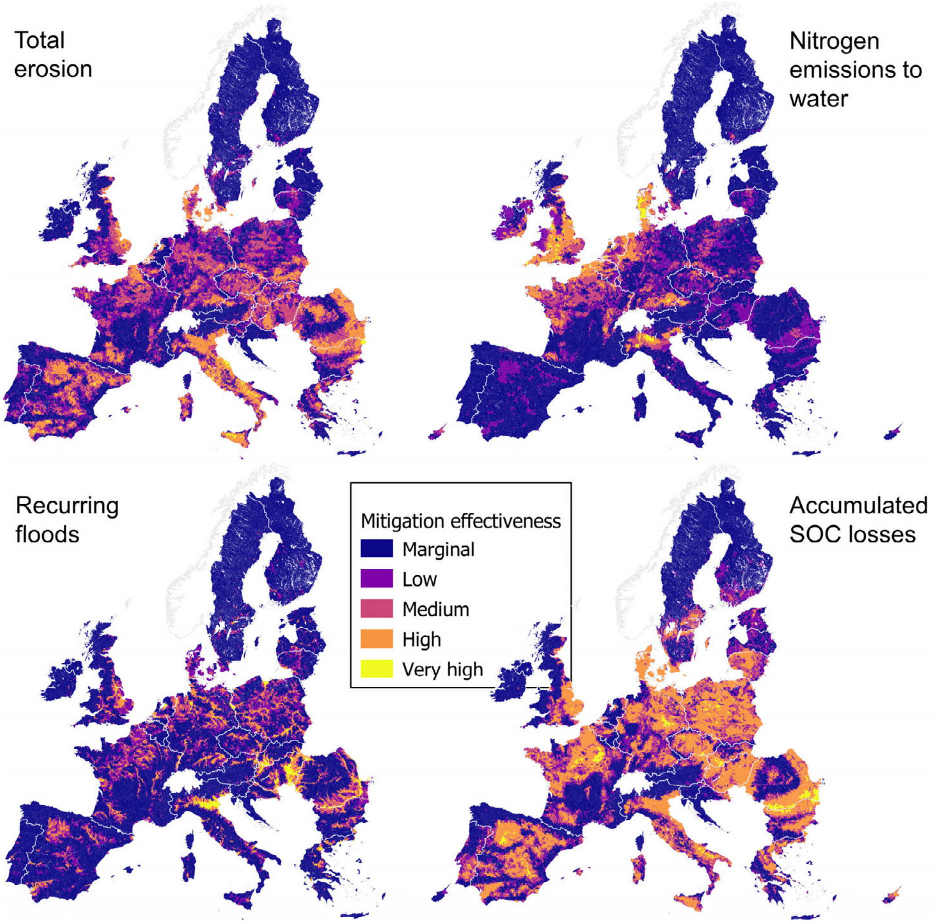

FIGURE 7 Estimated effectiveness of mitigating selected environmental impacts caused by intensive cultivation of annual crops, by a strategic introduction of perennials into the landscape (Englund et al., 2019)

production. Most of the annual crops currently cultivated in EU28 are located on land that could be subject to strategic perennialization. However, only a part of this land would need to be converted to perennial crops to achieve impact mitigation, depending, for example, on the impact that is addressed and how severe it is, to what degree mitigation is desired, and the kind of production system (e.g., woody or herbaceous crops) that could be suitable given not only the effectiveness of impact mitigation but also other factors such as stakeholder preferences and economic feasibility in the given setting. The type, and degree, of land use change that could be expected as a result of broad implementation of strategic perennialization in EU28 is therefore difficult to indicate at this point. However, studies attempting to identify and spatially model the suitability of different production systems, corresponding climate performance, the extent to which production of annual crops would need to be displaced to realize impact mitigation, and overall effects on biomass productivity, is currently underway.

While results for individual landscapes were found to be sensitive to assumptions and overall model design, general spatial patterns were not. The modeling results can therefore be used to indicate *priority areas*, that is, where the environmental benefits of strategic perennialization are expected to be relatively high. Such areas, depending on definition, sum up to a total of 15–60 Mha, containing from 10% up to almost half of the total production of annual crops in EU. Priority areas can be seen all over Europe, but with some notable regions where they are concentrated; large parts of western UK, Denmark, the Danube basin, and the Po valley in Italy, but also in northern France and several regions in Germany, Italy, and Spain.

For land use decision support in individual landscapes, further assessments are needed. The environmental effects of introducing perennials into a landscape depend on multiple parameters, for example, spatial landscape patterns, crop type, management system, and other characteristics of the landscape, such as topography and climatic conditions. To fully capture what effects that could be expected from perennialization, in both quantitative and qualitative terms, geo-explicit modeling with high resolution *within* the landscape is needed (Englund, Berndes, & Cederberg, 2017), as exemplified in the subsequent cases.

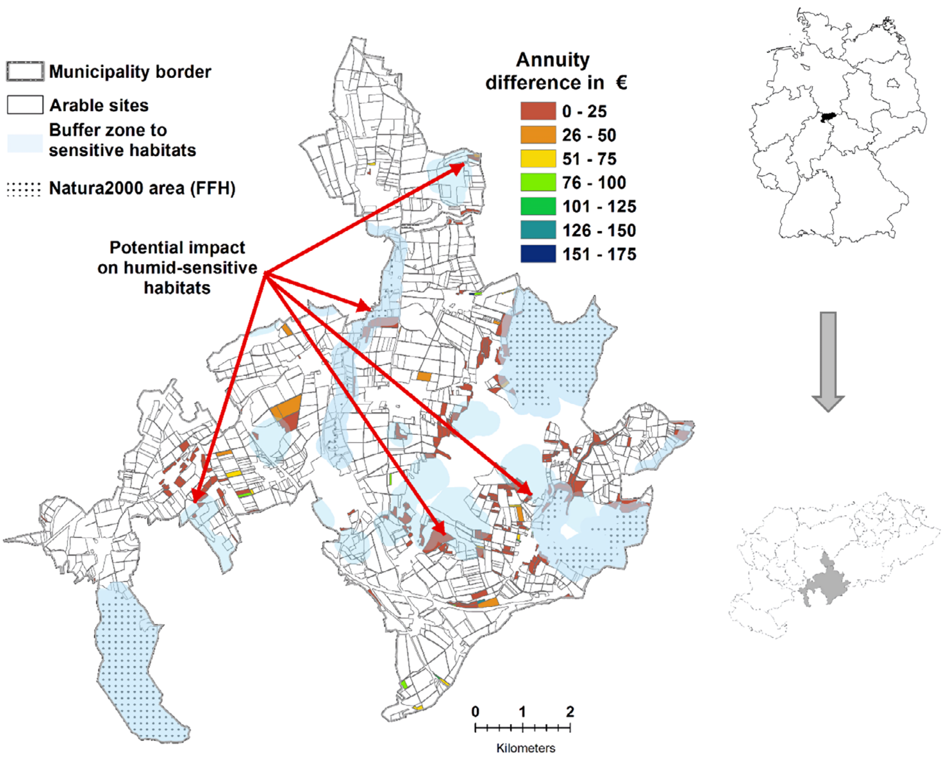

FIGURE 8 Economically competitive SRC sites that provide cross compliance-relevant erosion protection in the region of Göttingen, Germany. € = Euro, 2017 level

3.2 | Case 6: Identifying suitable fields for SRC poplar in Germany

Combating climate change is an important topic in political discussions in Germany, at both national and regional scale. Core actions have been defined at the regional scale using “Integrated Climate Protection Plans” (BMUB, 2016). In the Göttingen district, efforts have been directed to defining a roadmap towards making the energy system fully renewable by 2050 (Landkreis Göttingen, 2013). This requires a substantial decline of energy demand as well as increased production of renewable energy, in which bioenergy is expected to play a major role. However, many local farmers do not perceive farming with lignocellulosic crops a viable option (Boll, von Haaren, & Rode, 2015).

To bridge parts of this perception gap and to link climate targets with other societal objectives associated with sustainable land use, considering multiple ecosystem services, a visualization tool, BEAST (“Bio-Energy Allocation and Scenario Tool”), was constructed. It allows users to interactively create land use scenarios and investigate the effects of SRC production on ecosystem services, as well as the economic performance in relation to annual crops. Scenarios can be generated illustrating where economically viable woody biomass cultivation for renewable energy can enhance different aspects of land-use sustainability (Busch & Thiele, 2015; Thiele & Busch, 2015). For further details on the tool and methods used see Busch (2017, 2019) and Bredemeier et al. (2015).

For this case study, BEAST scenarios were generated in the municipality of Friedland in the Göttingen district, Germany (Figure 8), to identify suitable arable fields for SRC cropping. The case study area is a hilly region with sandy loamy to silty soil textures, upper-medium soil quality (median Soil Quality Index of 59 according to the German Soil Survey) and pronounced water-induced soil erosion risk (more than 70% are subject to CC2 measures; European Commission, 2009). Arable land covers 58% of the case study area. Precipitation accounts for 635 mm/year annually and the average temperature is 9.2°C (European Commission, 2009). Suitable arable fields were determined as sites where poplar SRC is economically competitive compared with annual reference crops (crop rotation of wheat–barley–oilseed rape) and could support cross compliance relevant erosion protection (see Table S1 for detailed information) while spatial restrictions were considered.

A Monte Carlo analysis (10,000 runs for each arable field) was performed on the economic scenario results (annuity differences between SRC and crop rotation) to derive probabilities of positive SRC annuities. To address farmers' reservation against SRC as a new cropping system, economic suitability was defined as a 100% probability of a positive annuity for SRC production. In the case study area, SRC outcompetes reference crops (i.e., wheat, barley, and oilseed rape) with a 100% probability on 110 ha, or 3.5% of the arable area (Figure 8). The lowest increase in expected annuity ranges between 0 and 180 € ha^{-1} year^{-1}, with a median value of 42. SRC cultivation on these fields could also reduce water-induced soil erosion. As erosion reduction is a societal goal subject to economic incentives, economic returns could be higher, possibly creating additional incentives for local farmers to opt for perennial crops on these particular sites.

Additionally, 30 ha are in neighborhoods close to humid-sensitive habitats (Figure 8). Possible trade-offs between erosion protection and negative impacts on such habitats, due to higher soil water consumption compared to annual crops, must therefore be carefully evaluated.

Scenario results thus reveal that SRC can be economically competitive, compared to common annual crops, on soils of upper-medium soil quality. Depending on the scenario setting, suitable fields constitute only a fraction of the total arable area, which emphasizes the importance of proper spatial analysis to select appropriate sites. With BEAST, it is possible to generate rapid appraisals and numerous scenarios (e.g., during stakeholder meetings) in an interactive way—allowing the user to identify suitable areas with respect to different boundary conditions. When it comes to specific planning and implementation, local consulting and reliable financial incentives are necessary to convince risk-averse farmers to add perennial crops to their portfolio. Compensation for environmental protection effects (such as erosion protection shown in this example) over the entire management period (i.e., ≥20 years), for example, within the Common Agricultural Policy framework, could provide an important additional incentive.

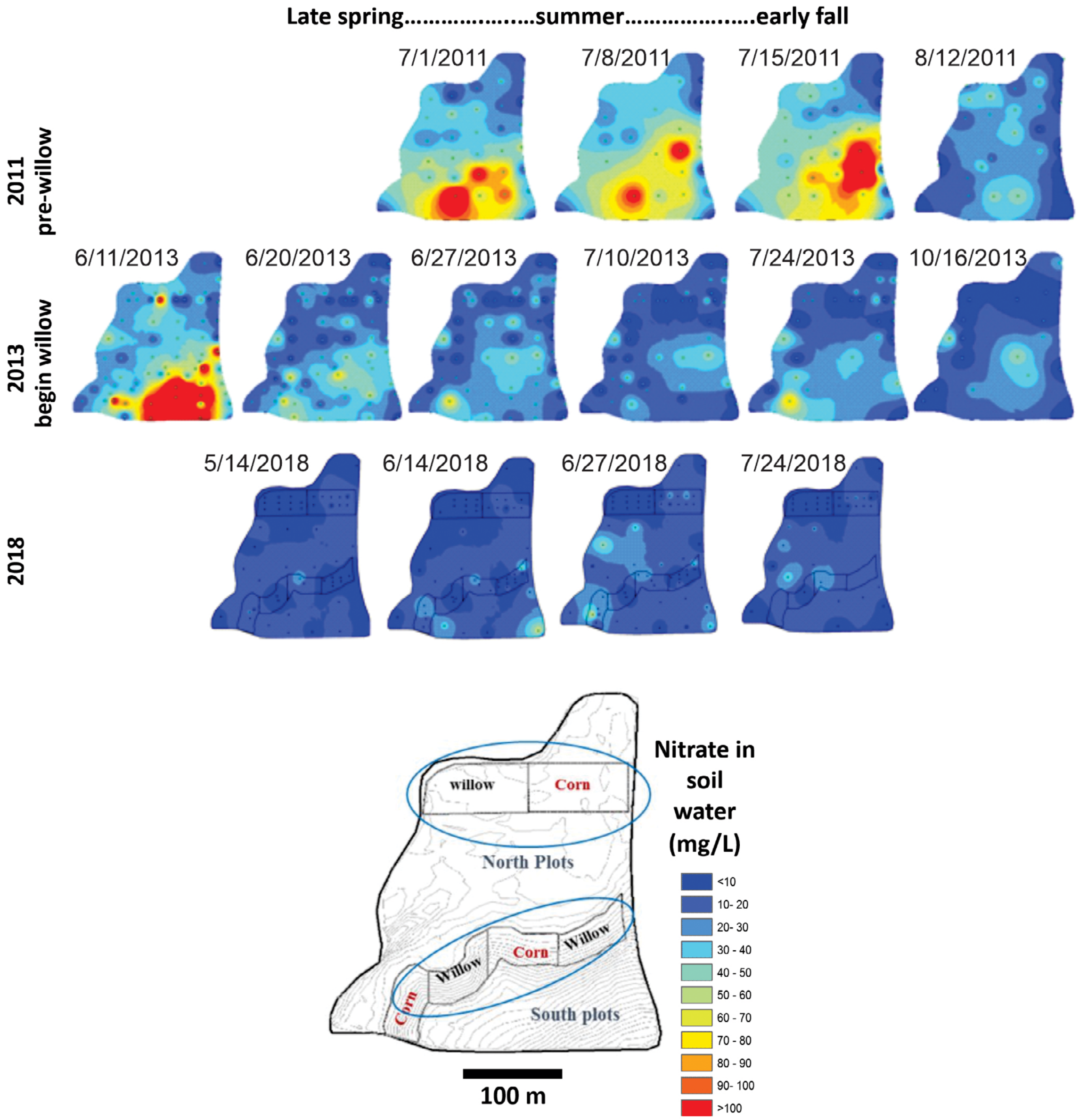

FIGURE 9 Soil-water nitrate concentration data from selected years at the Fairbury, Illinois study site

3.3 | Case 7: Beneficial locations for growing perennial crops for bioenergy in the United States

Concerns of potential indirect LUC effects of bioenergy feedstock production can be addressed by targeting subproductive areas, where establishment of perennial crops can enhance overall productivity while simultaneously reversing environmental degradation. Two major regions in the United States where biomass production has high potential in this respect are the agricultural Midwest and the managed forest lands of the Southeast. Here, we summarize outcomes of several research projects in these areas illustrating the benefits of strategically integrating perennial bioenergy crops on land considered underproductive for commodity crops, or critical for environmental quality degradation (marginal lands).

3.3.1 | Integrating perennial bioenergy crops in the U.S. Midwest agricultural landscape

Research at a corn-soybean farm in Fairbury, Illinois (Ssegane, Negri, Quinn, & Urgun-Demirtas, 2015) demonstrates that integration of shrub willow (*Salix miyabeana* "*SX61*"), into areas with marginal soils or as a riparian buffer, could produce biomass and provide environmental benefits, especially water quality improvement (Zumpf, Ssegane, Negri, Campbell, & Cacho, 2017). Willow can intercept nitrate applied to hydraulically upgradient portions of the field, thereby promoting biomass growth without direct fertilizer application. The soil-water nitrate concentration has dropped significantly since establishment of the trees (Figure 9). Through biophysical modeling based on the Soil and Water Assessment Tool, the projected reductions in sediment and nitrate losses from implementing this approach (integrated production system) to a larger area (Hydrologic Unite Code 10 tile-drained agricultural watershed) were up to 33% and 26%, respectively, for switchgrass relative to the business-as-usual (BAU) case. Even greater reduction in nitrate was found for willow (Ssegane & Negri, 2016). Integrated systems in the same agricultural watershed are also expected to enhance habitats for pollinators, compared to BAU (Graham, Nassauer, Currie, Ssegane, & Negri, 2017).

An analysis of an integrated production system, considering the complex logistics from producing biomass over small distribution areas (particularly biomass transport from farms to nearest storage areas), highlighted factors that are critical for adopting such systems as economically viable alternatives over BAU (Ssegane et al., 2016). These factors included intra-field commodity crop productivity, commodity crop market price, availability of biomass markets, biomass market price, and valuation of ecosystem services. High land prices limit the profitability of willow production in the Midwest compared to commodity crops (Ssegane et al., 2016). However, if local markets for biomass offer competitive prices and monetary compensation for enhanced ecosystem services, targeting willow production on land that is economically marginal for producing commodity crops may provide a good business case for farmers. To support the development of a scheme for monetary valuation of ecosystem services derived from an integrated agricultural system in the context of an agricultural Midwest landscape, a watershed-scale biophysical model was coupled with an economic analysis (Mishra et al., 2019) based on the Millennium Ecosystem Assessment framework (MEA, 2005). Ecosystem services considered in this 1,500-km^2 study area included commodity crop and biomass production (provisioning services); water quality protection and greenhouse gas emissions reduction (regulating services); and water-based recreation, wildlife viewing, and hunting (cultural services). The results indicate that, in this particular Illinois landscape, annual reductions in nitrate leaching, sediment loss, and carbon dioxide emissions of an integrated production system can be valued up to $97 million, $197,000, and $6.1 million, respectively. Additionally, annual estimated revenues from wildlife viewing, water-based recreation, and pheasant hunting were $1.24 million, $170,000, and $300,000, respectively.

3.3.2 | Integrating switchgrass in managed forests in the southeastern United States

Approximately 21% (almost 14 Mha in 2014) of the forest area in the southeastern United States is covered by managed loblolly pine (Huggett, Wear, Li, Coulston, & Liu, 2013). As such, it can have high potential to contribute in satisfying the bioenergy feedstock supply needed for the emerging bioeconomy. Study sites in the Coastal Plains of North Carolina (Cacho et al., 2015; Tian et al., 2015, 2017) showed that by extending the tree bed spacing from 2.65 m (traditional practice) to 6.1 m, the space in-between rows of trees could be utilized to grow switchgrass for about 8–9 years before

BOX 2 GENERAL INCENTIVES AND BARRIERS FOR BIOENERGY EXPANSION

Incentives for wider implementation of bioenergy include replacement of fossil fuels, enhancement of energy security, making better use of agricultural and urban wastes, providing jobs and supporting rural development, increasing food security, and retaining land in agriculture or forests while improving upon established infrastructure, knowledge, and technologies (Dimitriou et al., 2018; Smith et al., 2015). Expanding the bioeconomy offers synergistic opportunities in support of most other SDGs (IPCC, 2018).

Main barriers to bioenergy expansion include the inertia of existing practices, low profitability relative to competing land-use and energy systems, lack of scale-appropriate technologies, lack of appropriate equipment and infrastructure, policies that favor fossil-based products, uncertainties associated with environmental impacts and LUC, and overly optimistic forecasts and timetables (Dimitriou et al., 2018; Smith et al., 2015). Many formidable barriers are represented by the challenges associated with establishing reliable demand and stable markets for bio-based products.

canopy closure (Cacho, Youssef, Chescheir, et al., 2018), allowing for co-production of herbaceous biomass and timber. Such intercropping did not significantly impact drainage water quality (Muwamba et al., 2015; Muwamba et al., 2017), shallow groundwater quality (Cacho, Youssef, Chescheir, et al., 2018), or soil nitrogen cycling (Cacho, Youssef, Shi, et al., 2018). Some environmental impacts were observed in response to additional operations, but these were considered small and short-lived (Chescheir et al., 2018). The extended tree bed spacing is likely to affect overall timber yields, but such effects cannot yet be determined.

4 | DISCUSSION

Multifunctional perennial bioenergy systems, as described in this article, can support essential ecosystem services, mitigate environmental impacts of current and historic land use, and maintain or enhance total biomass productivity (V. H. Dale, Parish, & Kline, 2014; Englund et al., 2019). While some of the cases in this paper can be considered success stories (e.g., the Swedish case), most merely demonstrate promising opportunities, experimentally or theoretically. For multifunctional production systems to play a substantial role in developing a sustainable bioeconomy, effective incentives need to be identified and implemented, and barriers need to be overcome. While many incentives and barriers are related to bioenergy in general (Box 2), approaches to implement promising production systems, and to produce and use bioenergy and biobased products, will be context specific (Efroymson et al., 2013). Production systems have site-specific constraints and opportunities, ranging from biophysical and environmental conditions to socioeconomic and political factors (van der Hilst, 2018).

4.1 | Barriers to wider implementation

An important barrier is the lack of markets, or policies, compensating producers for enhanced ecosystem services and other environmental benefits. This absence is particularly important since prices for fossil-based fuels are low relative to bioenergy production costs. Without such compensation, producers have weak incentives to implement multifunctional perennial production systems. Developing a new bioenergy industry based on (ligno-)cellulosic biomass from perennials involves large start-up costs that are difficult to recuperate without subsidies. Furthermore, technologies, efficient handling and logistic systems, and best practices for advanced bioenergy are still under development.

Limited social acceptance of bioenergy expansion is increasingly perceived as a major barrier, as broad support from consumers and policymakers is required for leveling the playing field with fossil alternatives. Perceptions about impacts on forests, soils, air quality, and water quality, and concerns about biodiversity and food security, continue to undermine societal support for bioenergy in general. Polarized positions and simplified assertions about benefits and impacts of bioenergy are particularly problematic. Decision makers need valid and consistent information on the economics, societal (including environmental) benefits, and possible trade-offs of producing and using bioenergy, so that it can play an appropriate role in meeting climate targets. Bioenergy proponents and opponents must be careful not to overstate expected benefits or costs, or to understate or embellish possible trade-offs. For example, overly optimistic timetables for advanced bioenergy production have begun to create a perspective that lignocellulosic biofuel will always be "a future option, not yet viable." This perception is reinforced by the many bottlenecks and limitations associated with the infrastructure required for scaling-up bioenergy production. Instead, evidence-based analysis and projections must be based on realistic assumptions and counterfactuals.

4.2 | Paths forward

Implementing incentives and achieving the benefits of an expanding bioeconomy require that it be "done right" (V. H. Dale, Parish, et al., 2014; Kline, Dale, Lee, & Leiby, 2009). Because bioenergy has been intensively scrutinized over the last decade, major efforts have been undertaken to define sustainable practices for its production and use. While successful practices are location specific (Efroymson et al., 2013), some general features have been identified (Joly et al., 2015; Souza et al., 2017):

- Investments in technology and innovation, as well as rural extension, are needed to establish infrastructure and sufficient capacity.
- Stable long-term prices and demand incentivizes local feedstock production.
- Use of multiple-cropping, inter-cropping, and flex crop systems (which include perennials that can provide food, feed, fiber, fodder, and biomass for other markets) offers more resilient options to balance weather-related variability in production with changing human provisioning needs, while also supporting other ecosystems services.
- Paths towards successful establishment of a bioeconomy integrate lignocellulosic crops into agricultural and forest systems in a way that addresses market needs and concerns while providing a low cost and consistent supply of energy.
- Integrated resource management practices support nutrient and water conservation and preserve biodiversity at field, watershed, and regional scales.

Research is required to help landowners, policymakers, and other stakeholders understand and adapt the appropriate approach for each set of unique local conditions (V. H. Dale, Kline, Perla, & Lucier, 2013). This research needs to consider socioeconomic factors and trends while helping stakeholders to determine how to optimize land management to meet different societal objectives by considering biodiversity improvements, productive soils, water flow regulation, reductions in nitrogen and phosphorus pollution, site decontamination, and so on, as well as carbon sequestration and related climate effects (V. H. Dale, Kline, Parish, & Eichler, 2019). Research also needs to better inform practices and policies that reduce the risks to society related to increasing extreme weather events.

Given the incentives and barriers described above, one important line of research relates to generation of reliable and valid documentation of the actual effects of choices related to fossil resource extraction and renewable alternatives, including bio-based perennial production systems. Solid reporting on costs, impacts and benefits requires transparent sharing of information across all steps of supply chains for each system being used or proposed. Researchers should agree on methods for estimating, measuring, and reporting the performance of different energy options, so that decision makers can make fair comparisons (V. H. Dale, Kline, et al., 2013). Furthermore, research is needed to more effectively inform and engage stakeholders throughout the planning and implementation of processes that impact bioenergy and fossil energy choices and to assure that key concerns are identified and addressed (V. H. Dale, Kline, Richard, Karlen, & Belden, 2018).

Production and use of jet fuel made from biobased material is a path forward being pursued by the aviation industry and U.S. military. While concerns remain about adequate supply, price stability, and environmental issues (including competition for land, net GHG reductions, and local air quality emissions), the aviation industry has the advantage of being a large and specialized market with a modest amount of purchasers/distributors and point-usage that is highly concentrated (B. Dale, Anderson, et al., 2014). Hence aviation may be the first industry to rely on sustainably produced biofuels largely derived from perennial production systems.

There are a variety of governance instruments that could create incentives for enabling a wider implementation of multifunctional perennial bioenergy systems. A prerequisite for developing this business opportunity is that investors, land owners, and energy producers are confident that there is a stable market demand and willingness-to-pay for lignocellulosic feedstock and additional benefits, such as enhanced ecosystem services. The demand needs to be at a sufficient level over a sufficient amount of time to allow cost recuperation. This stability requires broad public and science-based support for strategies that enable the long-term planning and investments required for bioenergy systems to fulfill their potential roles in support of sustainable development and climate change mitigation.

5 | CONCLUSIONS

This article reviews options for integrating lignocellulosic crops into agricultural landscapes, in order to provide biomass for the bioeconomy while providing additional environmental benefits. Seven different cases in different world regions are reviewed to exemplify and evaluate (a) multifunctional production systems that have been established to meet emerging bioenergy demands and (b) efforts to identify locations where the establishment of perennial crops will be particularly beneficial.

Many multifunctional perennial bioenergy systems entail modifications to agricultural or forestry practices that are not changes in the predominant use of land but rather involve changes in land management. Indeed, better management practices are widely recognized as being needed to address negative impacts of current land uses, for example, eutrophication, soil erosion, and soil carbon losses (Englund et al., 2019), and to contribute to meeting climate targets (Fargione et al., 2018). Improved land and water management practices are often an explicit part of perennial bioenergy production systems (Englund et al., 2019).

Landscape design provides a strategy to plan for establishment of perennial production systems that enable bioenergy feedstock production while also providing environmental, social, and economic benefits (V. H. Dale et al., 2016). This approach takes into account context, trends, and current conditions by combining spatially explicit planning with adaptive management (Jones et al., 2012). It thereby provides a means to evaluate tradeoffs that are inherent in developing pathways to simultaneously address multiple needs by identifying places in the landscape where food, energy, biodiversity, and ecosystem services can best be targeted.

Further scientific attention is required on assessing the environmental performance of different production systems, not the least concerning climate and imacts associated with LUC. Strong, science-based analyses need to document when, how, and where multifunctional perennial production systems can contribute to meeting current and future biomass needs as well as other SDGs, related to, for example, employment, health, equality, life on land, and climate change.

Perennial systems will likely continue to rely on incentives and subsidies for environmental and cultural services that do not involve market commodities, unless strong consumer demand develops around confidence that such systems (and/or bioenergy or biomaterials in general) provide beneficial services to society. In such case, non-market services, for example, enhanced conditions for biodiversity, could provide a price premium. This may be most likely to occur on the market for voluntary sustainability certification, as it can provide third-party verification of such benefits. Finally, the costs and benefits of renewables compared to fossil energy could become more balanced if the environmental externalities and societal costs of consuming fossil fuels are quantified and considered.

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CONFLICT OF INTEREST

The authors have declared no conflicts of interest for this article.

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FURTHER READING

Abadi, A., Bartle, J., Giles, R., & Thomas, Q. (2013). *Delivered cost of biomass from shortcycle coppiced mallee eucalypts, bioenergy*. Canberra: RIRDC.

Asbjornsen, H., Hernandez-Santana, V., Liebman, M., Bayala, J., Chen, J., Helmers, M., … Schulte, L. A. (2014). Targeting perennial vegetation in agricultural landscapes for enhancing ecosystem services. *Renewable Agriculture and Food Systems*, *29*, 101–125.

Berndes, G., & Fritsche, U. (2016). May we have some more land use change, please? *Biofuels, Bioproducts and Biorefining*, *10*(3), 195–197.

Buchholz, T., Prisley, S., Marland, G., Canham, C., & Sampson, N. (2014). Uncertainty in projecting GHG emissions from bioenergy. *Nature Climate Change*, *4*, 1045–1047.

Busch, G., & Thiele, J. C. (2015). The bioenergy allocation and scenario tool (BEAST) to assess options for the siting of short rotation coppice in agricultural landscapes: Tool development and case study results from the Göttingen district. In D. B. Manning, A. Bemmann, M. Bredemeier, N. Lamersdorf, & C. Ammer (Eds.), *Bioenergy from dendromass for the sustainable development of rural areas* (pp. 23–43). Weinheim, Germany: Wiley-VCH Verlag GmbH & Co. KGaA ISBN: 978-3-527-33764-4.

Cardinale, B. J., Duffy, J. E., Gonzalez, A., Hooper, D. U., Perrings, C., Venail, P., … Naeem, S. (2012). Biodiversity loss and its impact on humanity. *Nature*, *486*, 59–67.

Christen, B., & Dalgaard, T. (2013). Buffers for biomass production in temperate European agriculture: A review and synthesis on function, ecosystem services and implementation. *Biomass and Bioenergy*, *55*, 53–67.

Dauber, J., & Miyake, S. (2016). To integrate or to segregate food crop and energy crop cultivation at the landscape scale? Perspectives on biodiversity conservation in agriculture in Europe. *Energy, Sustainability and Society*, *6*, 25.

Dimitriou, I., & Aronsson, P. (2010). Landfill leachate treatment with willows and poplars – Efficiency and plant response. *Waste Management*, *30*(11), 2137–2145.

Dodds, W. K., Perkin, J. S., & Gerken, J. E. (2013). Human impact on freshwater ecosystem services: A global perspective. *Environmental Science & Technology*, *47*(16), 9061–9068.

DWD. (2013). *Precipitation and temperature data*. German Weather Service (DWD). Available at http://www.dwd.de/

Efroymson, R. A., Kline, K. L., Angelsen, A., Verburg, P. H., Dale, V. H., Langeveld, J. W. A., & McBride, A. (2016). A causal analysis framework for land-use change and the potential role of bioenergy policy. *Land Use Policy*, *59*, 516–527. https://doi.org/10.1016/j.landusepol.2016.09.009

Holland, R. A., Eigenbrod, F., Muggeridge, A., Brown, G., Clarke, D., & Taylor, G. (2015). A synthesis of the ecosystem services impact of second generation bioenergy crop production. *Renewable and Sustainable Energy Reviews*, *46*, 30–40.

IPCC (2014). In Core Writing Team, R. K. Pachauri, & L. A. Meyer (Eds.), *Climate change 2014: Synthesis report. Contribution of working groups I, II and III to the fifth assessment report of the intergovernmental panel on climate change*. Geneva, Switzerland: IPCC 151 pp.

Kilkenny, M., & Partridge, M. D. (2009). Export sectors and rural development. *Am. J. Agric. Econ.*, *91*(4), 910–929.

Kline, K. L., Martinelli, F. S., Mayer, A. L., Medeiros, R., Oliveira, C. O., Sparovek, G., … Venier, L. A. (2015). Bioenergy and biodiversity: Key lessons from the Pan American region. *Environmental Management*, *56*(6), 1377–1396.

Kline, K. L., Msangi, S., Dale, V. H., Woods, J., Souza, G., Osseweijer, P., … Johnson, F. (2017). Reconciling food security and bioenergy: Priorities for action. *GCB Bioenergy*, *9*(3), 557–576. https://doi.org/10.1111/gcbb.12366

Kline, K. L., Oladosu, G. A., Dale, V. H., & McBride, M. C. (2011). Scientific analysis is essential to assess biofuel policy effects: In response to the paper by Kim and Dale on "Indirect land use change for biofuels: Testing predictions and improving analytical methodologies". *Biomass and Bioenergy*, *35*, 4488–4491. https://doi.org/10.1016/j.biombioe.2011.08.011

Martin, P., Thompson, T., Phillips, P., & Shafron, W. (2015). Farm performance: Broadacre and dairy farms, 2012–13 to 2014–15. In: Australian Bureau of Agricultural and resource Economics and Sciences, *Agricultural Commodities, March Quarter 2015*. ISBN: 978-1-74323-226-2.

Milner, S., Holland, R. A., Lovett, A., Sunnenberg, G., Hastings, A., Smith, P., … Taylor, G. (2016). Potential impacts on ecosystem services of land use transitions to second-generation bioenergy crops in GB. *GCB Bioenergy*, *8*, 317–333.

Nuffield Council on Bioethics. (2011). *Biofuels: Ethical issues*. London, England: Nuffield Council on Bioethics. ISBN: 978-1-904384-22-9.

Parish, E. S., Efroymson, R. A., Dale, V. H., Kline, K. L., McBride, A. C., Johnson, T., … Bielicki, J. M. (2013). Comparing scales of environmental effects from gasoline and ethanol production. *Environmental Management*, *51*(2), 307–338.

Searchinger, T., Wirsenius, S., Beringer, T., & Dumas, P. (2019). Assessing the efficiency of changes in land use for mitigating climate change. *Nature*, *564*, 249–253.

Smith, C. S., & McDonald, G. T. (1998). Assessing the sustainability of agriculture in the planning stage. *Journal of Environmental Management*, *52*, 15–37.

Szabo, Z. (2019). Can biofuel policies reduce uncertainty and increase agricultural yields thought stimulating investments? *Biofuels, Bioproducts and Biorefining*, *13*(5), 1224–1233. https://doi.org/10.1002/bbb.2011

UNCCD. (2017). *Global land report. United Nations convention to combat desertification*. Available at: https://global-land-outlook.squarespace.com/#glo-intro

REFERENCES

Aronsson, P., & Perttu, K. (2001). Willow vegetation filters for wastewater treatment and soil remediation combined with biomass production. *The Forestry Chronicle*, *77*(2), 293–299.

Augustenborg, C. A., Finnan, J., Mcbennett, L., Connolly, V., Priegnitz, U., & Müller, C. (2012). Farmers' perspectives for the development of a bioenergy industry in Ireland. *GCB Bioenergy*, *4*, 597–610.

Berndes, G. (2002). Bioenergy and water – The implications of large-scale bioenergy production for water use and supply. *Global Environmental Change*, *12*(4), 7–25.

Berndes, G., Ahlgren, S., Börjesson, P., & Cowie, A. (2013). Bioenergy and land use change – State of the art. *WIREs Energy and Environment*, *2*, 282–303. https://doi.org/10.1002/wene.41

Berndes, G., Börjesson, P., Ostwald, M., & Palm, M. (2008). Multifunctional biomass production systems –an overview with presentation of specific applications in India and Sweden. *Biofuels, Bioproducts and Biorefining*, *2*, 16–25.

Berndes, G., Fredrikson, F., & Börjesson, P. (2004). Cadmium accumulation and Salix-based phytoextraction on arable land in Sweden. *Agriculture, Ecosystems & Environment*, *103*, 207–223.

Berndes, G., Hoogwijk, M., & van den Broek, R. (2003). The contribution of biomass in the future global energy supply: A review of 17 studies. *Biomass and Bioenergy*, *25*, 1–28.

BMUB. (2016). *Climate action plan 2050. Principles and goals of the German government's climate policy*. Berlin, Germany: Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (BMUB) Available at: https://www.bmu.de/fileadmin/Daten_BMU/Pools/Broschueren/klimaschutzplan_2050_en_bf.pdf

Boll, T., von Haaren, C., & Rode, M. (2015). The effects of short rotation coppice on the visual landscape. In D. B. Manning, A. Bemmann, M. Bredemeier, N. Lamersdorf, & C. Ammer (Eds.), *Bioenergy from dendromass for the sustainable development of rural areas* (pp. 105–119). Weinheim, Germany: Wiley-VCH Verlag GmbH & Co. KGaA ISBN: 978-3-527-33764-4.

Börjesson, P. (1999). Environmental effects of energy crop cultivation in Sweden – I: Identification and quantification. *Biomass and Bioenergy*, *16*, 137–154.

Börjesson, P., & Berndes, G. (2006). The prospects for willow plantations for wastewater treatment in Sweden. *Biomass and Bioenergy*, *30*, 428–438.

Bredemeier, M., Busch, G., Hartmann, L., Jansen, M., Richter, F., & Lamersdorf, N. P. (2015). Fast growing plantations for wood production and integration of ecological effects and economic perspectives. *Frontiers in Bioengineering and Biotechnology*, *3*. https://doi.org/10.3389/fbioe.2015.00072

Busch, G. (2017). A spatial explicit scenario method to support participative regional land-use decisions regarding economic and ecological options of short rotation coppice (SRC) for renewable energy production on arable land: Case study application for the Göttingen district, Germany. *Energy, Sustainability and Society*, *7*, 2. https://doi.org/10.1186/s13705-017-0105-4

Busch, G. (2019). *Using "BEAST" to support the local dialogue on lignocellulosic cropping for energy use, climate protection and sustaining ecosystem services. Tool description and case study scenario application for the Göttingen district, Germany*. IEA Bioenergy Task 43 report: TR2019-03. Available at: http://task43.ieabioenergy.com/publications/using-beast-to-support-the-local-dialogue-on-lignocellulosic-cropping-for-energy-use-climate-protection-and-sustaining-ecosystem-services-tr2019-05/

Cacho, J. F., Youssef, M. A., Chescheir, G. M., Skaggs, R. W., Appelboom, T. W., Leggett, Z. H., … Arellano, C. (2018). Effects of forest-based bioenergy feedstock production on shallow groundwater quality of a drained forest soil. *Science of the Total Environment*, *631*, 13–22.

Cacho, J. F., Youssef, M. A., Chescheir, G. M., Skaggs, R. W., Leggett, Z. H., Sucre, E. B., … Arellano, C. (2015). Impacts of switchgrass-loblolly pine intercropping on soil physical properties of a drained forest. *Transactions of the ASABE*, *58*(6), 1573–1583.

Cacho, J. F., Youssef, M. A., Shi, W., Chescheir, G. M., Skaggs, R. W., Tian, S., … Arellano, C. (2018). Impacts of forest-based bioenergy feedstock production on soil nitrogen cycling. *Forest Ecology and Management*, *419*, 227–239.

Chescheir, G.M., Nettles, J.E., Youssef, M.A., Birgand, F., Amatya, D.M, Miller, D.A, …, Allen, E. (2018). *Optimization of southeastern forest biomass crop production: A watershed scale evaluation of the sustainability and productivity of dedicated energy crop and woody biomass operations* (No. DOE-NCSU-04395). North Carolina State University, Raleigh, NC. Available at: https://www.researchgate.net/publication/329127199_Optimization_of_Southeastern_Forest_Biomass_Crop_Production_A_Watershed_Scale_Evaluation_of_the_Sustainability_and_Productivity_of_Dedicated_Energy_Crop_and_Woody_Biomass_Operations

Christian, D. P., Niemi, G. J., Hanowski, J. M., & Collins, P. (1994). Perspectives on biomass energy tree plantations and changes in habitat for biological organisms. *Biomass and Bioenergy*, *6*, 31–39.

Clarke, L., Jiang, K., Akimoto, K., Babiker, M., Blanford, G., Fisher-Vanden, K., … Van Vuuren, D. P. (2014). Assessing transformation pathways. In O. Edenhofer, R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, et al. (Eds.), *Climate change mitigation of climate change. Contribution of working group III to the fifth assessment report of the intergovernmental panel on climate change* (pp. 413–510). Cambridge, England/New York, NY: Cambridge University Press.

Clarke, R., Sosa, A., & Murphy, F. (2019). Spatial and life cycle assessment of bioenergy-driven land-use changes in Ireland. *Science of the Total Environment*, *664*, 262–275.

Cooper, D., Olsen, G., & Bartle, J. (2005). Capture of agricultural surplus water determines the productivity and scale of new low-rainfall woody crop industries. *Australian Journal of Experimental Agriculture*, *45*, 1369–1388.

Creutzig, F., Ravindranath, N. H., Berndes, G., Bolwig, S., Bright, R., Cherubini, F., … Masera, O. (2014). Bioenergy and climate change mitigation: An assessment. *GCB Bioenergy*, *7*(5), 916–944. https://doi.org/10.1111/gcbb.12205

CSIRO. (2011). *Flight path to sustainable aviation: Towards establishing a sustainable aviation fuels industry in Australia and New Zealand*. Commonwealth Scientific and Industrial Research Organisation (CSIRO), Newcastle, NSW. Available at: https://publications.csiro.au/rpr/download?pid=csiro:EP107203&dsid=DS3

Dáil Éireann. (2015). *Debate, Vol. 884 No. 1, Written Answer No. 149 'Alternative Farm Enterprises'*, 24th June 2015.

Dáil Éireann. (2019a). *Debate: Renewable energy projects*, 27th March 2019.

Dáil Éireann. (2019b). *Debate: Renewable heat incentive*, 8th May 2019.

Daioglou, V., Doelman, J. C., Wicke, B., Faaji, A., & van Vuuren, D. P. (2019). Integrated assessment of biomass supply and demand in climate change mitigation scenarios. *Global Environmental Change*, *54*, 88–101. https://doi.org/10.1016/j.gloenvcha.2018.11.012

Dale, B., Anderson, J., Brown, R., Csonka, S., Dale, V. H., Herwick, G., … Wang, M. (2014). Take a closer look: Biofuels can support environmental, economic and social goals. *Environmental Science & Technology*, *48*(13), 7200–7203.

Dale, V. H., Efroymson, R. A., Kline, K. L., Langholtz, M. H., Leiby, P. N., Oladosu, G. A., … Hilliard, M. R. (2013). Indicators for assessing socioeconomic sustainability of bioenergy systems: A short list of practical measures. *Ecological Indicators*, *26*, 87–102.

Dale, V. H., Kline, K. L., Buford, M. A., Volk, T. A., Smith, C. T., & Stupak, I. (2016). Incorporating bioenergy into sustainable landscape designs. *Renewable & Sustainable Energy Reviews*, *56*, 1158–1171.

Dale, V. H., Kline, K. L., Parish, E. S., & Eichler, S. E. (2019). Engaging stakeholders to assess ability. *Landscape Ecology*, *34*(6), 1199–1218. https://doi.org/10.1007/s10980-019-00848-1, http://link.springer.com/article/10.1007/s10980-019-00848-1

Dale, V. H., Kline, K. L., Perla, D., & Lucier, A. (2013). Communicating about bioenergy sustainability. *Environmental Management*, *51*(2), 279–290. https://doi.org/10.1007/s00267-012-0014-4

Dale, V. H., Kline, K. L., Richard, T. L., Karlen, D. L., & Belden, W. W. (2018). Bridging biofuel sustainability indicators and ecosystem services through stakeholder engagement. *Biomass and Bioenergy*, *114*, 143–156. https://doi.org/10.1016/j.biombioe.2017.09.016

Dale, V. H., Kline, K. L., Wright, L. L., Perlack, R. D., Downing, M., & Graham, R. L. (2011). Interactions among bioenergy feedstock choices, landscape dynamics, and land use. *Ecological Applications*, *21*, 1039–1054.

Dale, V. H., Parish, E. S., & Kline, K. L. (2014). Risks to global biodiversity from fossil-fuel production exceed those from biofuel production. *Biofuels, Bioproducts and Biorefining*, *9*(2), 177–189.

DCCAE. (2010). *National Renewable Energy Action Plan – Ireland. Submitted under Article 4 of Directive 2009/28/EC*. Department of Communications Energy and Natural Resources (DCCAE), Ireland. Available at: https://www.dccae.gov.ie/documents/The%20National%20Renewable%20Energy%20Action%20Plan%20(PDF).pdf

Dimitriou, I., & Aronsson, P. (2005). Willows for energy and phytoremediation in Sweden. *Unasylva*, *221*(56), 47–50.

Dimitriou, I., Berndes, G., Englund, O., Brown, M., Busch, G., Dale, V., Devlin, G., English, B., Goss, K., Jackson, S., Kline, K.L., McDonnell, K., McGrath, J., Mola-Yudego, B., Murphy, F., Negri, M.C., Parish, E.S., Ssegane, H., & Tyler, D. (2018). *Lignocellulosic crops in agricultural landscapes: Production systems for biomass and other environmental benefits – Examples, incentives, and barriers*. IEA Bioenergy Task 43 report: 2018-05. Available at: https://www.ieabioenergy.com/wp-content/uploads/2019/01/TR2018-05.pdf

Dimitriou, I., & Mola-Yudego, B. (2016). Poplar and willow plantations on agricultural land in Sweden: Area, yield, groundwater quality and soil organic carbon. *Forest Ecology and Management*, *383*, 99–107. https://doi.org/10.1016/j.foreco.2016.08.022

Dimitriou, I., Mola-Yudego, B., & Aronsson, P. (2012). Impact of willow short rotation coppice on water quality. *Bioenergy Research*, *5*(3), 537–545.

Dimitriou, I., & Rosenqvist, H. (2011). Sewage sludge and wastewater fertilisation of short rotation coppice (SRC) for increased bioenergy production – Biological and economic potential. *Biomass and Bioenergy*, *35*(2), 835–842.

Dimitriou, I., Rosenqvist, H., & Berndes, G. (2011). Slow expansion and low yields of willow short rotation coppice in Sweden; implications for future strategies. *Biomass and Bioenergy*, *35*(11), 4613–4618.

Efroymson, R. A., Dale, V. H., Kline, K. L., McBride, A. C., Bielicki, J. M., Smith, R. L., … Shaw, D. M. (2013). Environmental indicators of biofuel sustainability: What about context? *Environmental Management*, *51*(2), 291–306.

Englund, O., Berndes, G., & Cederberg, C. (2017). How to analyse ecosystem services in landscapes – A systematic review. *Ecological Indicators*, *73*, 492–504. https://doi.org/10.1016/j.ecolind.2016.10.009

Englund, O., Börjesson, P., Berndes, G., Scarlat, N., Dallemand, J.-F., Grizzetti, B., … Fahl, F. (2019). Beneficial land use change: Strategic expansion of new biomass plantations can reduce environmental impacts from EU agriculture. *Global Environmental Change*, *60*, 101990. https://doi.org/10.1016/j.gloenvcha.2019.101990

European Commission. (2009). Council Regulation (EC) No 73/2009 of 19 January 2009 establishing common rules for direct support schemes for farmers under the common agricultural policy and establishing certain support schemes for farmers, amending Regulations (EC) No 1290/2005, (EC) No 247/2006, (EC) No 378/2007 and repealing Regulation (EC) No 1782/2003.

Fargione, J. E., Bassett, S., Boucher, T., Bridgham, S. D., Conant, R. T, Cook-Patton, S. C., …, Griscom, B. W. (2018). Natural climate solutions. *Science Advances*, *4*, eaat1869.

Farine, D. R., O'Connell, D. A., Raison, J. R., May, B. M., O'Connor, M. H., Crawford, D. F., … Kriticos, D. (2011). An assessment of biomass for bioelectricity and biofuel, and for greenhouse gas emission reduction in Australia. *GCB Bioenergy*, *4*(2), 148–175. https://doi.org/10.1111/j.1757-1707.2011.01115.x

George, B. H., & Nicholas, I. (2012). Developing Options for Integrated Food-Energy Systems – Volume 1. Rationale for industry development, species criteria and selection of woody species in agricultural production areas for bioenergy in Australia. *Promising resources and systems for producing bioenergy feed stocks, International Energy Agency Bioenergy Task*, **43**, PR02. Available from http://ieabioenergytask43.org/wp-content/uploads/2013/09/IEA_Bioenergy_Task43_PR2012-02.pdf

González-García, S., Mola-Yudego, B., Dimitriou, I., Aronsson, P., & Murphy, R. (2012). Environmental assessment of energy production based on long term commercial willow plantations in Sweden. *Science of the Total Environment*, *421*, 210–219.

González-García, S., Mola-Yudego, B., & Murphy, R. J. (2013). Life cycle assessment of potential energy uses for short rotation willow biomass in Sweden. *International Journal of Life Cycle Assessment*, *18*(4), 783–795. https://doi.org/10.1007/s11367-012-0536-2

Göransson, G. (1994). Bird fauna of cultivated energy shrub forests at different heights. *Biomass and Bioenergy*, *6*, 49–52.

Goss, K., Abadi, A., Crossin, E., Stucley, C., & Turnbull, P. (2014). *Sustainable mallee jet fuel, sustainability and life cycle assessment for supply to Perth airport, Western Australia*. Crawley, Australia: Future Farm Industries Cooperative Research Centre ISBN: 9780987156273.

Graham, J. B., Nassauer, J. I., Currie, W. S., Ssegane, H., & Negri, M. C. (2017). Assessing wild bees in perennial bioenergy landscapes: Effects of bioenergy crop composition, landscape configuration, and bioenergy crop area. *Landscape Ecology*, *32*(5), 1023–1037.

Grigal, D. F., & Berguson, W. E. (1998). Soil carbon changes associated with short-rotation systems. *Biomass and Bioenergy*, *14*, 371–377.

Gustafsson, L. (1987). Plant conservation aspects of energy forestry – A new type of land-use in Sweden. *Forest Ecology and Management*, *21*, 141–161.

Haberl, H., Erb, K.-H., Krausmann, F., Bondeau, A., Lauk, C., Müller, C., … Steinberger, J. K. (2011). Global bioenergy potentials from agricultural land in 2050: Sensitivity to climate change, diets and yields. *Biomass and Bioenergy*, *35*, 4753–4769.

Hatton, T. J., & Nulsen, R. A. (1999). Towards achieving functional ecosystem mimicry with respect to water cycling in southern Australian agriculture. *Agroforestry Systems*, *45*, 203–214.

Helby, P., Rosenqvist, H., & Roos, A. (2006). Retreat from Salix – Swedish experience with energy crops in the 1990s. *Biomass and Bioenergy*, *30*(5), 422–427.

Huggett, R., Wear, D. N., Li, R., Coulston, J., & Liu, S. (2013). Forecasts of forest conditions. In D. N. Wear & J. G. Greis (Eds.), *The Southern Forest Futures Project. Gen. Tech. Rep. SRS-GTR-178 USDA-Forest Service* (pp. 73–101). Ashville, NC: Southern Research Station.

IATA. (2018). *Fact Sheet Climate Change & CORSIA*. Available at: https://www.iata.org/pressroom/facts_figures/fact_sheets/Documents/fact-sheet-climate-change.pdf

IPCC (2018). In V. Masson-Delmotte, P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P. R. Shukla, et al. (Eds.), *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty*. Geneva, Switzerland: World Meteorological Organization 32 pp.

Jensen, K., Clark, C. D., Ellis, P., English, B. C., Menard, R. J., Walsh, M., & de la Torre Ugarte, D. (2007). Farmer's willingness to grow switchgrass for energy production. *Biomass and Bioenergy*, *31*, 773–781.

Joly, C. A., Verdade, L. M., Huntley, B. J., Dale, V. H., Mace, G., Muck, B., & Ravindranath, N. H. (2015). Biofuel Impacts on Biodiversity and Ecosystem Services. In G. M. Souza, R. L. Victoria, C. A. Joly & L. M. Verdade (Eds.), *Bioenergy & Sustainability: bridging the gaps*, Chapter 16. Paris, France: Scientific Committee on Problems of the Environment (SCOPE).

Jones, K. B., Zurlini, G., Kienast, F., Petrosillo, I., Edwards, T., Wade, T. G., … Zaccarelli, N. (2012). Informing landscape planning and design for sustaining ecosystem services from existing spatial patterns and knowledge. *Landscape Ecology*, *28*, 1175–1192.

Kline, K. L., & Dale, V. H. (2008). Biofuels: Effects on land and fire. *Science*, *321*(5886), 199. https://doi.org/10.1126/science.321.5886.199

Kline, K. L., Dale, V. H., Lee, R., & Leiby, P. (2009). In defense of biofuels, done right. *Issues in Science and Technology*, *25*(3), 75–84.

Kort, J., Collins, M., & Ditsch, D. (1998). A review of soil erosion potential associated with biomass crops. *Biomass and Bioenergy*, *14*, 351–359.

Landkreis Göttingen. (2013). *Landkreis Göttingen – Integriertes Klimaschutzkonzept für den Landkreis*. Available at: http://www.landkreis-goettingen.de

Langeveld, H., Quist-Wessel, F., Dimitriou, I., Aronsson, P., Baum, C., Schulz, U., … Berndes, G. (2012). Assessing environmental impacts of short rotation coppice (SRC) expansion: Model definition and preliminary results. *Bioenergy Research*, *5*(3), 621–635.

McBride, A., Dale, V. H., Baskaran, L., Downing, M., Eaton, L., Efroymson, R. A., … Storey, J. (2011). Indicators to support environmental sustainability of bioenergy systems. *Ecological Indicators*, *11*(5), 1277–1289.

McCormick, K., & Kåberger, T. (2005). Exploring a pioneering bioenergy system: The case of Enköping in Sweden. *Journal of Cleaner Production*, *13*(10–11), 1003–1014.

McGrath, J. F., Goss, K. F., Brown, M. W., Bartle, J. R., & Abadi, A. (2016). Aviation biofuel from integrated woody biomass in southern Australia. *WIREs Energy and Environment*, *6*, e221. https://doi.org/10.1002/wene.221

McLaughlin, S., Bouton, J., Bransby, D., Conger, B., Ocumpaugh, W., Parrish, D., … Wullschleger, S. (1999). Developing switchgrass as a bioenergy crop. In J. Janick (Ed.), *Perspectives on new crops and new uses*. Alexandria, VA: ASHS Press.

MEA. (2005). *Millennium ecosystem assessment: Ecosystems and human well-being: Synthesis*. Washington, DC: Island Press.

Mirck, J., Isebrands, J., Verwijst, T., & Ledin, S. (2005). Development of short rotation willow coppice systems for environmental purposes in Sweden. *Biomass & Bioenergy*, *28*(2), 219–228.

Mishra, S. K., Negri, M. C., Kozak, J., Cacho, J. F., Quinn, J., Secchi, S., & Ssegane, H. (2019). Valuation of ecosystem services in alternative bioenergy landscape scenarios. *GCB Bioenergy*. https://doi.org/10.1111/gcbb.12602

Mola-Yudego, B. (2011). Trends and productivity improvements from commercial willow plantations in Sweden during the period 1986–2000. *Biomass & Bioenergy*, *35*, 446–453. https://doi.org/10.1016/j.biombioe.2010.09.004

Mola-Yudego, B., Dimitriou, I., Gonzalez-Garcia, S., Gritten, D., & Aronsson, P. (2014). A conceptual framework for the introduction of energy crops. *Renewable Energy*, *72*, 29–38.

Mola-Yudego, B., & González-Olabarria, J. R. (2010). Mapping the expansion and distribution of willow plantations for bioenergy in Sweden: Lessons to be learned about the spread of energy crops. *Biomass & Bioenergy*, *34*, 442–448. https://doi.org/10.1016/j.biombioe.2009.12.008

Mola-Yudego, B., & Pelkonen, P. (2011). Pulling effects of district heating plants on the adoption and spread of willow plantations for biomass: The power plant in Enköping (Sweden). *Biomass & Bioenergy*, *35*(7), 2986–2992.

Mooney, D. F., Roberts, R. K., English, B. C., Tyler, D. D., & Larson, J. A. (2009). Yield and breakeven price of "Alamo" switchgrass for biofuels in Tennessee. *Agronomy Journal*, *101*, 1234–1242.

Murphy, F., Devlin, G., & Mcdonnell, K. (2014). Energy requirements and environmental impacts associated with the production of short rotation willow (Salix sp.) chip in Ireland. *GCB Bioenergy*, *6*, 727–739.

Murphy, F., & McDonnell, K. (2017). Investigation of the potential impact of the Paris Agreement on national mitigation policies and the risk of carbon leakage; an analysis of the Irish bioenergy industry. *Energy Policy*, *104*, 80–88.

Muwamba, A., Amatya, D., Ssegane, H., Chescheir, G. M., Appleboom, T, Tollner, E. W., … Tian, S. (2015). Effects of site preparation for pine forest/switchgrass intercropping on water quality. *Journal of Environmental Quality*, *44*(4), 1263–1272.

Muwamba, A., Amatya, D., Chescheir, G. M., Nettles, J., Appleboom, T, Ssegane, H., … Tian, S. (2017). Water quality effects of switchgrass intercropping on pine forest in coastal North Carolina. *Transactions of the ASABE*, *60*(5), 1607–1620.

Nordborg, M., Berndes, G., Dimitriou, I., Henriksson, A., Mola-Yudego, B., & Rosenqvist, H. (2018). Energy analysis of willow production for bioenergy in Sweden. *Renewable and Sustainable Energy Reviews*, *93*, 473–482. https://doi.org/10.1016/j.rser.2018.05.045

Parish, E. S., Dale, V. H., English, B. C., Jackson, S. W., & Tyler, D. D. (2016). Assessing multimetric aspects of sustainability: Application to a bioenergy crop production system in East Tennessee. *Ecosphere*, *7*(2), e01206.

Parish, E. S., Hilliard, M., Baskaran, L. M., Dale, V. H., Griffiths, N. A., Mulholland, P. J., … Middleton, R. (2012). Multimetric spatial optimization of switchgrass plantings across a watershed. *Biofuels, Bioproducts and Biorefining*, *6*, 58–72.

Pearman, G I. (2013). Limits to the potential of bio-fuels and bio-sequestration of carbon. *Energy Policy*, *59*, 523–535.

Perttu, K. L., & Kowalik, P. J. (1997). Salix vegetation filters for purification of waters and soils. *Biomass & Bioenergy*, *12*, 9–19.

PMSEIC. (2010). *Challenges at energy-water-carbon intersections* (p. 88). Canberra, Australia: Prime Minister's Science, Engineering and Innovation Council (PMSEIC).

Post, W. M., Izaurralde, R. C., Jastrow, J. D., McCarl, B. A., Amonette, J. E., Bailey, V. L., … Zhou, J. (2004). Enhancement of carbon sequestration in US soils. *BioScience*, *54*, 895–908.

Qantas Group. (2019). *Qantas Group net zero emissions commitment fact sheet*. Available at: https://www.qantasnewsroom.com.au/wp-content/uploads/2019/11/191111-Qantas-Group-Sustainability-Fact-Sheet.pdf

Rainbow Bee Eater. (2018). *Rainbow bee eater website*. Available at: http://rainbowbeeeater.com.au/

Rijtema, P. E., & DeVries, W. (1994). Differences in precipitation excess and nitrogen leaching from agricultural lands and forest plantations. *Biomass & Bioenergy*, *6*, 103–113.

Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin III, F. S., Lambin, E., … & Foley, J. (2009). Planetary boundaries: Exploring the safe operating space for humanity. *Ecology and Society*, *14*(2), 32.

Rosenqvist, H., Aronsson, P., Hasselgren, K., & Perttu, K. (1997). Economics of using municipal wastewater irrigation of willow coppice crops. *Biomass & Bioenergy*, *12*(1), 1–8.

Searchinger, T., Heimlich, R., Houghton, R. A., Dong, F. X., Elobeid, A., Fabiosa, J., … Yu, T. H. (2008). Use of US croplands for biofuels increases greenhouse gases through emissions from land-use change. *Science*, *319*, 1238–1240.

Simons, J., & Speed, R. (2011). *Hydrological impacts of integrated oil mallee farming systems*. Resource Management Technical Report 377, Department of Agriculture and Food, Perth, Western Australia.

Slade, R., Bauen, A., & Gross, R. (2014). Global bioenergy resources. *Nature Climate Change*, *4*, 99–105. https://doi.org/10.1038/nclimate2097

Smeets, E. M. W., Faaij, A. P. C., Lewandowski, I. M., & Turkenburg, W. C. (2006). A bottom-up assessment and review of global bioenergy potentials to 2050. *Progress in Energy and Combustion Science*, *33*, 56–106.

Smith, T., Lattimore, B., & Atkin, E. (Eds.) (2015). *Mobilizing sustainable bioenergy supply chains*. Inter-Task Project Synthesis Report, IEA Bioenergy ExCo:2015:04. Available at: http://www.ieabioenergy.com/publications/mobilizing-sustainable-bioenergy-supply-chains/

Smith, P., Haberl, H., Popp, A., Erb, K.-h., Lauk, C., Harper, R., … Rose, S. (2013). How much land-based greenhouse gas mitigation can be achieved without compromising food security and environmental goals? *Global Change Biology*, *19*(8), 2285–2302.

Sööder, F., Nilsson, M., Olevik, J., Forsberg, J., Jacobsson, A., Holm, L., … Ekman, O. (2013). Industrial symbiosis in Enköping (p. 8). Linköping, Sweden: Linköping University.

Souza, G., Ballester, M. V. R., Cruz, C. H. B., Chum, H., Dale, B., Dale, V. H., … van der Wielen, L. (2017). The role of bioenergy in a climate-changing world. *Environmental Development*, *23*, 57–64.

Ssegane, H., & Negri, M. C. (2016). An integrated landscape designed for commodity and bioenergy crops for a tile-drained agricultural watershed. *Journal of Environmental Quality*, *45*(5), 1588–1596.

Ssegane, H., Negri, M. C., Quinn, J., & Urgun-Demirtas, M. (2015). Multifunctional landscapes: Site characterization and field-scale design to incorporate biomass production into an agricultural system. *Biomass & Bioenergy*, *80*, 179–190.

Ssegane, H., Zumpf, C., Negri, M. C., Campbell, P., Heavey, J. P., & Volk, T. A. (2016). The economics of growing shrub willow as a bioenergy buffer on agricultural fields: A case study in the Midwest Corn Belt. *Biofuels, Bioproducts and Biorefining*, *10*(6), 776–789.

Stucley, C., Schuck, S., Sims, S., Bland, J., Marino, B., Borowitzka, M., … Thomas, Q. (2012). *Bioenergy in Australia: Status and opportunities, chapter 9: Supply and delivery of mallees*. St Leonards: Bioenergy Australia Available at: http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.694.4104&rep=rep1&type=pdf

Styles, D., Börjesson, P., D'Hertefeldt, T., Birkhofer, K., Dauber, J., Adams, P., … Rosenqvist, H. (2016). Climate regulation, energy provisioning and water purification: Quantifying ecosystem service delivery of bioenergy willow grown on riparian buffer zones using life cycle assessment. *Ambio*, *45*, 872–884.

Thiele, J. C., & Busch, G. (2015). A decision support system to link stakeholder perception with regional renewable energy goals for woody biomass. In D. B. Manning, A. Bemmann, M. Bredemeier, N. Lamersdorf, & C. Ammer (Eds.), *Bioenergy from dendromass for the sustainable development of rural areas* (pp. 433–445). Weinheim, Germany: Wiley-VCH Verlag GmbH & Co. KGaA ISBN: 978-3-527-33764-4.

Tian, S., Cacho, J. F., Youssef, M. A., Chescheir, G. M., Fischer, M., Nettles, J. E., & King, J. S. (2017). Switchgrass growth and pine–switchgrass interactions in established intercropping systems. *GCB Bioenergy*, *9*(5), 845–857.

Tolbert, V. R., Todd, D. E., Jr., Mann, L. K., Jawdy, C. M., Mays, D. A., Malik, R., … Pettry, D. E. (2002). Changes in soil quality and below-ground carbon storage with conversion of traditional agricultural crop lands to bioenergy crop production. *Environmental Pollution*, *116*, 97–106.

van der Hilst, F. (2018). Location, location, location. *Nature Energy*, *3*, 164–165. https://www.nature.com/articles/s41560-018-0094-3

Wright, L. (2007). *historical perspective on how and why switchgrass was selected as a "model" high-potential energy crop*. Oak Ridge National Laboratory, ORNL/TM-2007/109.

Zalesny, R. S., Berndes, G., Dimitriou, I., Fritsche, U., Miller, C., Eisenbies, M., … Zumpf, C. R. (2019). Positive water linkages of producing short rotation poplars and willows for bioenergy and phytotechnologies. *WIREs Energy and Environment*. https://doi.org/10.1002/wene.345

Zumpf, C., Ssegane, H., Negri, M. C., Campbell, P., & Cacho, J. (2017). Yield and water quality iImpacts of field-scale integration of willow into a continuous corn rotation system. *Journal of Environmental Quality*, *46*(4), 811–818.

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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