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CROPS OF THE BIOFRONTIER: IN SEARCH OF OPPORTUNITIES FOR SUSTAINABLE ENERGY CROPPING

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The International Council on Clean Transportation is an independent nonprofit organization founded to provide first-rate, unbiased research and technical and scientific analysis to environmental regulators. Our mission is to improve the environmental performance and energy efficiency of road, marine, and air transportation, in order to benefit public health and mitigate climate change.

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PREFACE BY THE EUROPEAN CLIMATE FOUNDATION

In December 2015, world leaders agreed a new deal for tackling the risks of climate change. Countries will now need to develop strategies for meeting their commitments under the Paris Agreement, largely via efforts to limit deforestation and to reduce the carbon intensity of their economies. In Europe, these climate protection strategies will be developed via the EU's 2030 climate and energy framework, with a view to ensuring an integrated single market for emissions reduction technologies.

Existing EU energy policy for 2020 foresees an important role for bioenergy as a means of reducing carbon emissions from heating, power, and transport, and yet there are concerns that this has led to a number of negative consequences related to the intensification of resource use. If bioenergy is to continue to play a role in EU energy strategies for 2030, it seems wise to learn from the past to ensure that this is done in a manner that is consistent with the EU's environmental goals, including the objective of limiting temperature rise to no more than 2 degrees C.

With this in mind, the European Climate Foundation has convened the BioFrontiers platform, bringing together stakeholders from industry and civil society to explore the conditions and boundaries under which supply chains for advanced biofuels for transport might be developed in a sustainable manner. This builds on work developed in the ECF's Wasted platform in 2013-2014, which focused on waste- and residue-based feedstocks for advanced biofuels. This time around, there is an additional focus on considering land-using feedstocks and novel fuel technologies.

As the name BioFrontiers suggests, this discussion enters new territory and is faced with numerous gaps in knowledge. To facilitate a transparent and constructive debate between industry and civil society, the ECF has commissioned a number of studies to help fill such knowledge gaps. This is one such study. It does not represent the views of the members of the BioFrontiers platform, merely an input to their discussions. If this research also helps inform the wider debate on the sustainability of bioenergy, that is a bonus. I would like to thank the IEEP for using the resources provided by the ECF to improve our understanding of these important issues.

Pete Harrison

Programme Director, Transport

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EXECUTIVE SUMMARY

Since the Renewable Energy Directive and Fuel Quality Directive were adopted in 2009, European biofuel policy has been dominated by discussions about the indirect effects of biofuel consumption, and in particular indirect land use change and impacts on food prices and security. One widely considered option to reduce or avoid these risks is to move towards second-generation biofuels from cellulosic feedstocks. It has been shown that it would be possible to deliver a significant fraction of European transport energy requirements using cellulosic biofuels from sustainably available wastes and residues, with minimal indirect impact (Harrison et al., 2014). However, these risks are not necessarily avoided when cellulosic biofuels are produced from energy crops, grown for their high cellulosic biomass yield. Growing land-based energy crops on land currently used for the production of other crops will generally lead to indirect land use change, and pressure on existing food and feed markets. Converting natural forest and grassland to biomass crops will generally cause environmental damage.

There is no consensus to date on the magnitude of indirect effects likely if biomass crops displace existing food or feed production, and that question is beyond the scope of this report. Instead, this report investigates instances in which energy crops could be grown sustainably and with minimal or no indirect impacts. That could mean using land that can be converted with minimal environmental costs, or even with environmental benefits (land that is unused or underutilized and has low productivity, low carbon stocks, and low biodiversity). It could also mean introducing systems such as double cropping that could increase overall biomass productivity on areas already harvested, or sustainable harvesting of biomass from existing systems.

With this research, we seek to identify and describe the opportunity for sustainable energy cropping through fieldwork and literature review, including case studies of early energy crop projects in Europe. Two case studies, supported by fieldwork, consider cropping on land that is marginal for agriculture, and one of the cases also looks at the potential for double cropping. The third case study, based on literature review, considers the environmental benefits that could be achieved through the wet cultivation of peatlands for biomass in Europe. These case studies augment a sparse literature base on the environmental risks and benefits of an emerging and rapidly evolving industry.

There is reason to believe that energy crops could potentially deliver environmental benefits when grown on previously disturbed, abandoned agricultural land. While literature studies comparing biodiversity and carbon stocks in energy crop plantations to marginal land are scant, it is clear that in many cases perennial energy crops can improve agricultural land previously used for annual row crops and may offer similar environmental benefits to existing unmanaged grassland. The literature suggests that growing perennial energy crops may rehabilitate agricultural land faster than simple abandonment. Perennial grasses, including switchgrass, giant reed, and Miscanthus, may be successfully grown on semi-arid marginal land without irrigation, while poplar and willow likely require wetter environments. Data on annual energy crops such as biomass sorghum is scarcer, but they may be sustainably cultivable in many areas. The environmental effects of these different categories of energy crops grown on marginal land are shown in Table 1.

Table 1. Summary of environmental effects of energy crops from literature review

Environmental effect on marginal land	Perennial grasses	Woody crops	Annual energy crops
Biodiversity	Potentially higher	Potentially higher	No evidence
Biomass productivity	Likely higher	Likely higher	Likely higher
Biomass stocks	Potentially higher	Likely higher	Not clear
Soil carbon	Not clear	Not clear	Not clear
Water requirements (are crops viable in dry regions)	Potentially yes	Likely no	Maybe

To investigate how energy crops grown on marginal land affect the environment in practice, we conducted on-the-ground observations and environmental measurements at two biomass crop projects currently under development in Europe.

We visited three sites in the Carbonia region of Sardinia, Italy, where Biochemtex is conducting trials of *Arundo donax* (giant reed) on underutilized agricultural land. This region has large areas of semi-arid, low-productivity abandoned agricultural land with very little biomass stock and biodiversity. *A. donax* is invasive in Sardinia and has already colonized most waterways on the island. The project will take measures to prevent spread to uninvaded, sensitive areas, and could aid management by harvesting existing stands. Most of the land in the region has been classified as having low ecological importance. We conducted a cursory biodiversity assessment, during which we observed only common birds and agricultural weeds in the areas surrounding the energy crop fields. This assessment did not identify any major biodiversity concerns related to cultivation of *A. donax* in this area, but additional surveys would be necessary to confirm this result. Regarding potential productivity of the system, it was clear that *A. donax* produced far higher biomass stocks than the surrounding landscape. *A. donax* requires irrigation in this arid region, and it appears that sufficient water will be available without having an impact on other uses in most years; the project developers state that irrigation would be halted during periods of drought. The project plan also includes using *A. donax* to remediate industrial land contaminated with heavy metals that is currently unfit for growing other crops. Overall, we conclude that the Biochemtex project has the potential to deliver some environmental benefits, including increased biomass stocks, invasive species management, and soil remediation, while posing little risk to soil carbon stocks, water use, or displacement of other crops.

The second case study we examined is in the Pelagonia region of Macedonia. Here, Ethanol Europe is collaborating with DuPont and NexSteppe to test biomass sorghum and switchgrass on two types of land: (1) actively used agricultural land, during what would otherwise be the short summer fallow period of winter wheat, and (2) arid, abandoned agricultural land in a dry region. During our site visit, we witnessed challenges in project implementation in this first year of trials. It was not clear whether biomass sorghum was displacing food production in the actively used areas. However, the project leaders have stated their commitment to avoiding displacement of food production if the associated biorefining facility becomes operational. Some sites only achieved poor yields in this first year due to planting delays and establishment losses. Biodiversity and biomass stocks appeared to be very low in the abandoned region based on a cursory assessment. The Macedonian trials are at an earlier stage of development than the Sardinian case, and it was apparent that the project has experienced challenges in coordination and planning in its first year. There seem to be real opportunities for both the use of abandoned land and for the introduction of double cropping, but it is not yet possible to be confident that commercially viable yields can be achieved without environmental impact or displacement of food production.

Through literature review, we also investigated a different type of energy crop system that could potentially deliver associated environmental benefits. "Paludiculture," the wet cultivation of peatlands, could be used to produce biomass for energy while actively rehabilitating degraded peatlands in Europe, sequestering soil carbon and supporting native plant and animal species. In the Biebrza Valley of Poland, the Polish Society for the Protection of Birds (OTOP) has restored large areas of an abandoned fen as habitat for threatened birds by mowing vegetation, producing biomass for pelleting. Another project in Belarus is rewetting and restoring degraded sites while replacing mined peat used for energy with briquettes from natural vegetation. Paludiculture is still in the early stages of adoption, and challenges remain for more sustainable harvesting technologies and economic viability of projects—but in cases where there is an economic case for biomass production, paludiculture could deliver a win-win-win for climate mitigation, wildlife conservation, and renewable energy.

Through on-the-ground verification, this report supports much of what is shown in the literature: that there is a real potential to cultivate energy crops sustainably with little environmental risk, and in some cases while delivering substantial direct environmental benefits beyond renewable energy production. At the same time, we highlight challenges in the implementation of energy crop projects and hurdles that must be overcome before sustainability can be assured, particularly the difficulty in managing energy crop production's impact on other agricultural output, and preventing overuse of water resources.

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INTRODUCTION

Since they were adopted in 2009, the EU's Renewable Energy Directive and Fuel Quality Directive have incentivized consumption of biofuels. However, the first-generation biofuels produced largely from food crops used to meet the targets in these Directives have been strongly criticized for driving indirect land use change (ILUC) and for contributing to global food price increases and food insecurity. The EU now seeks to move beyond food-based biofuels with the 0.5% advanced biofuel blending target introduced in the ILUC Directive, and there are indications that post-2020 renewable energy policy will not support biofuels from food crops. The focus is turning to second-generation biofuels from cellulosic feedstocks with low indirect impacts. One option is to mobilize wastes and residues that, if sustainably harvested, could produce low-carbon biofuel with minimal indirect impacts—this source could potentially contribute a significant fraction to the EU's transport fuel supply (Harrison et al., 2014).

Cellulosic biofuel feedstocks could also be sourced from energy crops that produce high biomass yields. Studies that estimate the global technical potential for bioenergy tend to assume that energy crops would provide the bulk of the world's biomass (reviewed in Searle and Malins, 2014a). However, because energy crops use land, they carry some of the same risks as food-based biofuel feedstocks. If grown on currently used agricultural land, energy crops could displace food production, which could increase food prices and cause indirect land use change, much the same as with food-based biofuel feedstocks. For example, the US EPA has estimated that ILUC emissions from switchgrass production would add 12 $gCO_2e\ MJ^{-1}$ to the lifecycle carbon intensity of switchgrass ethanol, reducing its GHG benefit compared to gasoline by around 12%. On the other hand, other studies have estimated zero or negative ILUC emissions for perennial grass crops (Dunn et al., 2013, Wang et al., 2012),[1] so as with any type of crop, there is no consensus on the magnitude of ILUC emissions for energy crops.

A potential solution for avoiding ILUC with energy crops is to cultivate them on unused land that has low biomass stocks and low biodiversity. Converting unmanaged forest and grassland to energy crop plantations would likely result in biodiversity losses, and in the case of forest, standing biomass stocks, which would not be a desirable environmental outcome. In particular, land that was previously disturbed for agriculture or industry but has now been abandoned due to low productivity and that has low biodiversity and low carbon stocks (sometimes referred to as "marginal land") may generally offer an opportunity for energy cropping with low environmental risks. Allen et al. (2014) estimate that at least 1.35 million hectares of unused, degraded land may be available for biomass production in the EU—a small fraction of the more than 400 million hectares of total land area in the EU, but enough to produce a significant amount of biomass. This estimate may be conservative, as this study was highly selective in the types of land areas considered available. Alexopoulou and Kretschmer (2011) provide a higher estimate, concluding that 20.5 million hectares of unused land may be available for energy crop production in 2020. The latter estimate assumes several million hectares that are currently used for production of cereals and other food crops will become available as yields increase and the EU's population changes—this study may thus represent a high-end estimate of potential land availability. In any case, it is clear that there is the potential for significant areas in the EU to be used for energy cropping.

1 In these studies, increased carbon sequestration in biomass and soils offsets ILUC from displacing other land uses.

In this report, we focus on specific case studies where energy crop projects are being piloted with low environmental risks, and that could potentially provide some environmental benefits. The next chapter investigates the environmental impacts of energy cropping on abandoned land generally through literature review, discussing impacts on biodiversity, biomass stocks, soil carbon, and water consumption. Then we describe two in-depth case studies: one in Sardinia and one in Macedonia. In the Sardinia project, Biochemtex is growing trial plots of *Arundo donax* for potential cellulosic biofuel production on underutilized agricultural land. In Macedonia, Ethanol Europe, DuPont, and NexSteppe are partnering to conduct trials of biomass sorghum. In the final chapter, we discuss the opportunity for biomass production through paludiculture, the wet cultivation of peatlands. In each of these case studies, there is an opportunity to produce significant quantities of cellulosic biofuel feedstock with minimal environmental harm, as long as sustainability controls are implemented.

LITERATURE REVIEW ON ENVIRONMENTAL IMPACTS OF ENERGY CROPPING

SUMMARY OF LITERATURE REVIEW

In this review, we focus on the environmental impacts that would be expected from energy crop cultivation on abandoned agricultural land that is marginal for production. This is considered an important opportunity to produce biomass without the direct environmental damage of converting natural land and without the indirect environmental risks of displacing food production.

The environmental impacts of energy crop cultivation depend strongly on the type of land on which these crops are grown, and its status before conversion to energy cropping. When compared to naturally occurring systems, traditional agriculture producing annual food crops generally has strongly negative impacts on biodiversity, soil carbon, and water consumption, as well as leading to water pollution. Compared with annual food crops, perennial energy crop production shows consistently better performance on all these parameters. But, as may be expected, converting natural systems to energy crops would likely lead to significant environmental damage in many cases. Few studies have directly examined the environmental impacts of energy crops on marginal land specifically, so we highlight the information that does exist and in some cases must infer from comparisons of energy crop systems and abandoned agricultural land in general.

Energy crops may offer benefits in terms of biodiversity compared to abandoned land or similar unused land. Both perennial grasses and short rotation coppice (SRC) woody crops have generally been found to support similar or even greater levels of diversity of birds and insects compared with grasslands and set-aside land. For SRC crops in particular, bird diversity may even be similar to that of undisturbed forest, although the composition of the community changes. Perennial grasses are thought to support biodiversity by offering the same grassy habitat structure as unmanaged grasslands, and SRC crops offer a variety of habitats through their vertical structure. Both types of crops can support understory vegetation and ground-dwelling wildlife as the soil is only disturbed every several years. It should be noted that the perennial energy crops discussed here require two to three years for establishment and to reach maximum yields, and during the initial establishment phase the crops may be more closely managed to limit floral diversity. There is less evidence available regarding the biodiversity implications of annual energy crops such as biomass sorghum. It is likely that these crops would deliver lower levels of ecosystem services than perennials, but there may be other reasons to consider annual systems, such as the faster establishment timeline and the potential for more rapid development of high-yielding cultivars.

All types of energy crops can generally be expected almost by definition to deliver higher biomass productivity—and thus higher rates of carbon sequestration—than unmanaged land, because energy crop species are selected based on high growth rates. Standing biomass stocks will typically be higher in energy crop plantations than they will on abandoned agricultural land, unless the land has developed into forest under natural succession. The impact of energy crop cultivation on soil carbon levels is less clear. While all types of perennial energy crops considered here will increase soil carbon compared with annual row crops, results are highly variable and mixed when comparing energy crops with abandoned land and to grassland. It appears likely that energy crops will increase soil carbon on abandoned agricultural land in some locations but decrease it in others. On newly abandoned agricultural land, it is possible that some energy crops could achieve a level of soil carbon sequestration on the order of half the GHG benefit the same crops would realize from petroleum displacement.[2]

Perennial grasses and biomass sorghum are at least somewhat drought-tolerant, and under some conditions can produce viable yields in semi-arid locations without irrigation. In particular, some cultivars of switchgrass can be grown with little water availability year-round, and Miscanthus, *Arundo donax*, and biomass sorghum can tolerate dry periods. Willow and poplar, the two species most often considered for SRC in Europe, fare less well without sufficient water.

BIODIVERSITY IMPACTS

Introduction to biodiversity

Biodiversity encompasses all plant and animal species and is tightly connected to the well-being and function of ecosystems. Many species threatened with extinction could have unique ecological functions, medicinal properties, or other functions valuable to society (Maclaurin & Sterelny, 2008; Sala et al. 2000).

Biodiversity is difficult to measure, and any particular metric does not tell the whole story. The most basic metric is "species richness," which is simply a count of the number of species present in any particular area. Other metrics may take into account population sizes, species density, and trends over time.

These metrics by themselves do not necessarily indicate overall ecosystem health or conservation value. Some types of ecosystems (such as the temperate Nothofagus forests in New Zealand) have very few species and yet are highly stable. Sometimes the presence of invasive plants or animals can inflate the species richness in an area, but to the detriment of ecosystem health. In some cases, areas with high numbers of a threatened or endangered species may have greater conservation value than areas with higher species richness. Lastly, measuring biodiversity at different taxonomic levels may complicate the picture, for example in an area with only a few families of plants but a high number of species within each family.

Still, biodiversity metrics can be useful in painting a broad picture of the overall health of an ecosystem, especially when reflecting on the impact that agriculture has on a landscape compared with its undisturbed (or less disturbed) surroundings.

It is important to keep in in mind that ecosystems are highly variable through time and space. The effect of energy cropping on the biodiversity of a landscape depends strongly on the location of a landscape; the surrounding areas; the type of energy crop; which groups of plants, animals, or fungi are assessed and at what taxonomic level; the time of year of the assessment; and the age of the energy cropping system. It is thus fairly common and unsurprising to get contradictory results for an energy crop's impact on biodiversity across different studies.

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2 Calculated assuming soil carbon sequestration of 1 tC ha^{-1} yr^{-1} which is on the high end of values reported in the literature for perennial grasses, harvested crop yields of 10 dry t ha^{-1} yr^{-1}, ethanol yields of 1 tonne per 5 tonnes biomass, and 100% GHG reduction compared with fossil gasoline.

Perennial energy crops compared with annual row crops

A number of review papers compare biodiversity in perennial energy cropping systems to conventional annual cropping systems (typically food crops) and undisturbed landscapes. The most comprehensive of these review papers (Dauber et al., 2010) assessed 47 publications on biodiversity in SRC (poplar and willow) and perennial grasses (Miscanthus, switchgrass, and reed canary grass) compared with other landscapes in countries across Europe and North America.

All studies reviewed in Dauber et al. (2010) found that perennial biomass crop systems had greater species richness compared with annual crop systems for almost all taxa studied,[3] although it should be noted that this measure does not reflect the ecological importance of various species and thus gives only a partial picture of the biodiversity support role of an ecosystem. Hypothesized drivers include:

- Longer rotation periods
- Low fertilizer and pesticide requirements
- Better soil protection
- Greater richness of spatial structures
- Exposed to fewer disturbances during growing period
- Harvesting carried out in winter or after breeding period of birds

It should be noted that no-till practices for annual crops may provide some of the same benefits of soil protection and reduced soil disturbance that could benefit biodiversity, but no-till agriculture is very uncommon in the EU at present (EUROSTAT, 2014) and may or may not be environmentally preferable depending on local conditions.

Werling et al. (2014), a large field study conducted in the United States, found that switchgrass and prairie grass plantations have higher biodiversity (measured as plants, arthropods, birds, and some types of bacteria) than annual grain fields, such as maize. The perennial grass fields also delivered greater ecosystem services compared to maize fields, including lower levels of pests and higher methane consumption. Other studies have found that SRC supports greater plant diversity and abundance than annual crops because the ground is not disturbed every year and because the vertical structure of SRC crops allows growth of an understory below (Rowe et al., 2009; Cunningham et al., 2004). Rowe et al. (2009) reports that the understory floral community can comprise agricultural weeds or can resemble woodland-scrub communities depending on the land use of surrounding areas.

Bird diversity in particular tends to be higher in perennial energy crop plantations compared to annual crops. In a US study in southern Michigan, Robertson et al. (2011) found bird species richness and species density were greater in mixed-grass prairie and switchgrass than in contemporary feedstock such as maize. This paper also notes that grassland species of conservation concern (e.g. Henslow's Sparrow) were found to occur primarily in switchgrass and prairie fields. Similar results were found in British studies; Bellamy et al. (2009) report a greater abundance and diversity of birds in Miscanthus fields than in conventional croplands such as wheat fields. A few of the species recorded in these Miscanthus fields belong to the Red and Amber List of Species of High

3 The exception is that certain types of beetles in some studies were found to have higher species richness in food crops compared to energy crops.

Conservation Concern, including the skylark and reed bunting. SRC plantations such as willow or poplar also tend to have higher bird diversity compared to annual crops (Sage et al. 2006; Sage et al. 1994; Berg 2002). These studies recorded a majority of scrub and woodland habitat birds such as blackbirds, chaffinch, and reed bunting, as well as seven UK Amber-Listed species and six Red-Listed species. Other studies have found that bird species in SRC crops resembled open farmland or transitional scrubland communities rather than woodland ones, but with time they will transform to be more similar to forest communities (reviewed in Dauber et al., 2010).

Perennial grasses compared with uncultivated landscapes

Few studies compare perennial crops with uncultivated landscapes, and results depend strongly on the type of uncultivated land and what grows on it. In their review, Dauber et al. (2010) report results from a study by Clapham & Slater (2008) that compares biodiversity in perennial grass crops to that in unimproved grasslands. They found that the abundance of individual birds was higher in *Miscanthus x giganteus*[4] than in grasslands, but the number of bird species did not change. They also report results from a German study by Loeffel & Nentwig (1997) stating that more ground beetle species were found in *Miscanthus sinensis* than in managed grasslands. Another study found higher bird, spider, and ground invertebrate species richness in Miscanthus fields than in uncultivated stands of common reed (Jodl et al., 2004). A review paper argues that converting marginal land to biofuel production maintains the same grassy composition as the original land and therefore supports wildlife by keeping a similar habitat to the original one, including several ecological niches for birds, insects, reptiles and mammals (Hartman et al., 2011).

Meehan et al. (2010) created an empirical model to predict biodiversity in annual crops (maize and soybeans) and a native perennial grass mix grown on marginal land, using data from fields across the US Midwest and assuming that annual crops require fertilizer and pesticide application but perennial grasses do not. Their analysis predicts that growing annual crops on marginal land will decrease avian richness by 7% to 65% compared with an uncultivated state, whereas the perennial grasses will increase avian richness by 12% to over 200%, and in particular may aid the recovery of species of conservation concern. These results support the findings of Dauber et al. (2010) mentioned above that energy crops generally have higher biodiversity than annual row crops.

Some perennial grasses pose an invasive risk if cultivated outside their native areas, and could potentially have strong negative impacts on biodiversity if they escape plantations and spread over natural areas. Switchgrass, Miscanthus, and *Arundo donax* have all been classified as invasive species (Low and Booth, 2007). Great care must be taken when cultivating these species for biomass to prevent unintended spread. Control measures may include establishing wide, regularly mown buffer strips along the edges of cultivated fields and regular monitoring.

Woody energy crops compared with uncultivated landscapes

SRC plantations may support greater biodiversity than perennial grasses. SRC crops have a vertical structure that provides heterogeneous habitat for many breeding birds

4 The Miscanthus hybrid most commonly grown for biomass. *Miscanthus* x giganteus is a cross between *M. sinensis* and *M. sacchariflorous.*

(Baum et al. 2012), as well as an understory of perennial plant species creating habitat for intvertebrates (Rowe et al., 2010; Dauber et al., 2010). In addition, ground cover under SRC crops provides other benefits, such as reducing erosion risk and preserving soil moisture (Rowe et al., 2010).

Similarly to perennial grasses, the biodiversity impacts of SRC plantations vary according to the type of land with which they are compared. Higher bird species richness was reported in SRC plantations when compared to set aside land, but no differences was found when compared to uncultivated fens (Reddersen; Reddersen & Petersen 2004). Some studies reviewed in Dauber et al. (2010) find greater biodiversity of some species groups in some types of energy crops than in uncultivated grasslands, and others report higher diversity of other taxa in grasslands; yet other comparisons showed no significant differences. These comparisons also changed over time: For example, plant species richness was found to be higher in recently planted SRC willow fields in one study, but declined with increasing age of the plantations (Dauber et al. 2010). Dauber et al. (2010) found that most studies comparing woody crops to woodland habitats reported lower species richness in the biomass crops or no significant difference. In particular, the bird species composition of SRC crops resembled that of open farmland or transitional scrubland communities rather than that of woodlands. A meta-analysis conducted by Fletcher et al. (2011) found pine and poplar plantations to consistently have lower vertebrate diversity than nearby undisturbed habitats.

It should be noted that the grassy and woody perennial energy crops discussed here require two to three years for establishment and to reach maximum yields, and during the initial establishment phase the crops may be more closely managed to limit floral diversity.

Biodiversity in annual energy crop systems

Very little information is available on biodiversity in annual energy cropping systems such as biomass sorghum. It seems likely that much of the biodiversity benefit of perennial crops compared with that of annual food crops as discussed above is due to the far lower frequency of soil and ground cover disturbance. Because biomass sorghum must be harvested and re-sown similarly to annual food crops, in the absence of other information we would not assume any biodiversity benefits compared to other annual crops.

Harvesting

For perennial grasses to benefit biodiversity, certain management practices should be adopted, especially regarding nesting periods of birds. Joly et al. (2015) suggests avoiding harvest during nesting periods and promoting streamside buffers. Another concept put forward by several papers is to harvest in rotations, creating a mix between harvested and non-harvested fields in order to consistently provide suitable habitats for different types of grassland birds (Hartman et al. 2011; Roth et al. 2005).

It is not clear whether spring or fall harvests best support biodiversity. Fall harvests generally maximize yield but leave no vegetation in the field for animal habitat over winter. On the other hand, harvesting in the spring may interfere with the breeding times of many animals, for example when birds may be nesting on the ground or in branches of SRC crops (Riffell et al., 2012).

Energy crops on contaminated land

Some energy crops can be used for phytoremediation of contaminated lands. They have the potential to enhance biodiversity as well as to decontaminate the soil and groundwater. For example, Miscanthus and SRC poplar were found to have positive effects on invertebrate biodiversity when planted on land polluted by metals and dissolved salts (Hedde et al. 2013). So cultivating energy crops on contaminated land that would otherwise not be used may have co-benefits in supporting biodiversity.

Guidelines to improve biodiversity in energy crop plantations

Perennial energy crop systems have a number of ecological advantages over annual row crops, as outlined above by Dauber et al. (2010). Some of these traits, such as heterogeneity of spatial structures, could be encouraged through certain management practices. General guidelines to supporting higher biodiversity in biomass crops following Dauber et al. (2010), Hartman et al. (2011), and Riffell et al. (2012) include:

- Stagger planting and harvesting of fields, creating a patchwork of young, mature, and cut grasses or woody crops.
- Grow multiple crop species together in a field ("polyculture," "multicropping," or "intercropping"), for example growing bluestem grasses together with switchgrass.[5]
- Design fields with more edge area (e.g., long, narrow fields).

Overall, the diversity of birds, plants, and other animal groups has been found to be greater along the edges of plantations than in the center (Dauber et al., 2010; Sage et al., 2006). This finding suggests that commercial-scale bioenergy plantations may have lower diversity than experimental-sized plots, and thus the impact of energy cropping on biodiversity could potentially be more negative than reflected in these review papers—but more research on commercial-scale fields would be needed before drawing conclusions.

It is also important to note that perennial grasses should be cautiously introduced because of their invasive potential. Barney (2014) notes that they are poorly studied in this context, and that the characteristics that make them good energy crops are also those that could make them dangerous: They are competitive, establish rapidly, and are tolerant to poor conditions.

BIOMASS STOCKS AND PRODUCTIVITY

Biomass productivity

Almost by definition, energy crops can generally be expected to increase productivity over virtually any system they are replacing, because the main characteristic of energy crops is high yields. In Searle and Malins (2014b), we provided yield ranges for two perennial grasses (switchgrass, Miscanthus) and three SRC crops (willow, poplar, eucalyptus) grown on marginal agricultural land without irrigation or fertilizer (Table 2). These yield estimates take into account biomass drying and harvesting losses, as well as other effects that may inflate reported results from experimental studies compared with what can be expected at commercial production (for example, edge effects). Commercially harvestable biomass is on the order of 30% lower than what may be

5 Biomass yields may be lower in multicropping systems.

measured in a small, carefully managed experimental trial (reviewed in Searle and Malins, 2014b). Higher yields may be expected for warm temperate countries (e.g., Spain) than colder temperate regions (e.g., Scandinavia). It should also be noted that yields for any particular crop will vary widely depending on the exact location, climate, and management regime.

Table 2. Yields of energy crops that can be expected at commercial scale on land that is marginal for agriculture, by climatic zone; all values in dry t ha^{-1} yr^{-1}

	Cold temperate	Temperate	Warm temperate	Tropical/ subtropical
Miscanthus	3-5	7-15		
Switchgrass		2-7	5-10	
Willow SRC	0-10	4-13		
Poplar SRC	3-8	4-10	4-10	4-10
Eucalyptus		5-15	5-15	5-15

Natural systems such as natural grasslands or forests generally do not achieve such levels of productivity (except when the natural system essentially is an energy crop, such as switchgrass, which is abundant in the United States; DOE, 2011). For a broad example of natural vegetation growth rates, we can look to the Woods Hole emission factors for foregone sequestration (biomass production that would occur in the absence of land disturbance) in various ecosystem types, as presented in Searchinger et al. (2008, Supporting Online Material). These emission factors are based on literature and data review for vegetation in different regions. For Europe, this study estimates biomass growth rates of approximately 2.8-3.8 dry t ha^{-1} yr^{-1} for mature temperate forests and around 2.4 t ha^{-1} yr^{-1} for mature boreal forests. Biomass growth in re-growing temperate forest is estimated at around 3.8-4.2 t ha^{-1} yr^{-1}, and in re-growing boreal forests at 2.4 t ha^{-1} yr^{-1}. These latter estimates may best represent the level of biomass growth that can be expected on abandoned agricultural land that was historically forested and is in the process of returning to forest. It should be noted that these are absolute growth rates, and so in order to make them more directly comparable to the estimates for harvestable biomass in Table 2 we should subtract approximately 30%. If we compare a "harvestable" range of natural forest growth of 1.5-2.9 t ha^{-1} yr^{-1} for Europe, it is clear that natural biomass growth falls below the range that can be expected for energy crops in most cases. That said, it should be understood that variation in growth rates among specific locations vary widely, and so energy crop yields as well as natural biomass growth rates could be much higher or much lower than the generalizations presented here under specific circumstances.

Standing biomass stocks

Another important issue is how the standing biomass stocks of energy crops compare to existing vegetation. According to IPCC's default biomass stock factors, European grasslands generally hold around 6-14 t ha^{-1} yr^{-1} in dry biomass[6] (IPCC, 2007a). If European grassland is cleared in order to cultivate a relatively high-yielding energy crop, then the amount of carbon released from the biomass from the land conversion can reasonably be expected to be offset by higher annual productivity within a few years.

6 Including belowground biomass, which generally accounts for the majority of total grassland biomass.

On the other hand, European temperate forests generally hold in the range of 50-130 dry t ha^{-1} yr^{-1} in aboveground biomass (IPCC, 2007b)—it could take 10 to 25 years to regain the carbon lost from this type of land clearing.[7] In the long run, replacing unmanaged forest with energy crops could deliver carbon savings, but it would be difficult to justify from a climate perspective, even without considering the potentially negative impacts to biodiversity discussed above.

This illustration confirms what may be considered common sense—that replacing a low-productivity unused grassland with energy crops is likely to deliver carbon savings, whereas cutting down a forest for bioenergy production would drive an increase in emissions in the short run.

SOIL CARBON

Introduction to soil carbon changes

More carbon is stored in the world's soils than in the world's vegetation, and changes in soil carbon can have a dramatic effect on the global carbon balance (Anderson-Teixeira et al. 2009; Guo & Guifford 2002). Land disturbance usually releases some amount of soil carbon, and, depending on the land use history, the introduction of different vegetation systems can either increase soil carbon stocks or decrease them further.

It is almost undisputable that conversion of uncultivated land to annual food crops causes a net release of carbon, both immediately upon land conversion and over time (Anderson-Teixera et al., 2009; Guo and Gifford, 2002; Murty et al., 2002; Don et al., 2011a). Reverting arable land to pasture, grassland, or forest, or simply letting the land go fallow slowly, returns that soil carbon (Guo and Gifford, 2002; Don et al., 2011a). The soil carbon stocks on abandoned agricultural land may thus approximate those of natural grassland after a number of years.

Establishment of perennial energy crops may cause an initial release of carbon that is regained over time. In their meta-analysis, Anderson and Teixeira (2009) found that switchgrass and Miscanthus establishment may cause a small but statistically insignificant release of carbon that is regained within a three-year period.

Soil carbon changes with perennial grass cultivation

Soil carbon may generally be expected to increase with perennial grass cultivation compared to annual food crops because (a) grasses allocate a majority of biomass growth below ground, (b) the soil is not tilled every year, and (c) the ground surface is almost never completely bare. The latter two effects reduce erosion.

A number of studies have confirmed this. A review paper found that perennial crops in general were found to sequester carbon when planted on former cropland, with accumulation rates of 0.66 tC ha^{-1} yr^{-1} for Miscanthus (Don et al. 2011b). In a single field experiment, another study found that Miscanthus would sequester 0.4 tC ha^{-1} yr^{-1} and giant reed would sequester 0.9 tC ha^{-1} yr^{-1} when established on land previously used for arable crops (Ceotto and Di Candilo, 2011). Switchgrass has also been found to increase soil carbon compared with cultivated croplands (Liebig et al., 2005; Bransby et al., 1998). In particular, this study found that switchgrass increases soil carbon at

7 Assuming an energy crop yield of 8 t ha^{-1} yr^{-1} compared to annual growth of 3 t ha^{-1} yr^{-1} for natural forest, resulting in a net annual gain of 5 t ha^{-1} yr^{-1} dry biomass from the energy cropping system.

greater depths, where it is more stable. Post and Kwon (2000) reported that perennial grasses in general would increase soil carbon by up to 1.1 tC ha^{-1} yr^{-1} when grown on cultivated land. *Arundo donax* fields have been found to have similar soil carbon stocks as switchgrass and Miscanthus (Monti & Zatta, 2009).

However, it is not clear whether perennial energy grasses will increase or decrease soil carbon when compared with unused marginal or abandoned agricultural land or grassland. Two studies that found perennial grasses to increase carbon over arable crops reported that pastures and meadows sequestered carbon faster, suggesting that grassy energy crops may have a negative effect on soil carbon if established on grasslands (Bransby et al., 1998; Ceotto and Di Candilo, 2011). No change in SOC was reported for Miscanthus established on former grassland in a review paper (Don et al., 2011b). In contrast, another review paper found that Miscanthus and switchgrass would in general accumulate soil carbon on previously uncultivated land (Anderson-Texiera et al., 2009).

While in theory soil carbon stocks on abandoned agricultural land should eventually resemble those on undisturbed land, several studies have found that soil carbon increases following land abandonment are very slow, at 0.03-0.19 tC ha^{-1} yr^{-1} (Gebhart et al. 1994; Burke et al. 1995; Knops and Tilman, 2000). Inferring from the soil carbon accumulation rates for perennial grasses on cultivated land above (ranging from 0.4-1.1 tC ha^{-1} yr^{-1}), one may conclude that perennial energy grasses are likely to increase soil carbon on former agricultural land faster than simple abandonment.

Soil carbon changes with woody crop cultivation

Similarly to Miscanthus, poplar and willow SRC increase soil carbon when planted on former cropland. Reviewing a number of studies, Don et al. (2011b) estimated that cultivating SRC on land previously used for row crops results in soil carbon accumulation rates of 0.44 tC ha^{-1} yr^{-1}. Two other review papers similarly concluded that SRC crops would increase soil carbon on agricultural land (Rowe et al., 2009; Baum et al., 2009). In an individual study, Dimitriou et al. (2012) found considerably higher soil organic carbon concentrations under willow SRC (9% in the topsoil and 27% in the subsoil) than fields with row crops. Similarly, Guinina et al. (2015) found that poplar and willow SRC had higher soil carbon than nearby agricultural fields, and they state that this could be due to higher input of plant litter and root exudates.

In contrast, planting SRC on grassland likely has a negative impact on soil carbon. The review by Don et al. (2011b) concluded that poplar and willow SRC decrease soil carbon by 1.3 t ha^{-1} yr^{-1} when planted on grassland—a relatively high rate of soil carbon loss. Similarly, an individual study measured a soil carbon loss of 15% when SRC was planted on grassland (Jug et al., 1999).

We did not find any studies on soil carbon changes when growing SRC on abandoned or marginal agricultural land, but there may be reason to believe it would be beneficial to do so. The rate of soil carbon increase when planting SRC on agricultural land (0.44 tC ha^{-1} yr^{-1}) is higher than natural soil carbon sequestration on abandoned agricultural land (0.03-0.19 tC ha^{-1} yr^{-1}, discussed above), suggesting that cultivating SRC on abandoned agricultural land would improve soil carbon faster than not using the land. Another finding supports this idea: Ceotto and Di Candilo (2011) found that woody crops including poplar, willow, and black locust sequester soil carbon on arable land faster than conversion to meadow or perennial energy grasses (1.2-1.6 tC ha^{-1} yr^{-1} for woody crops compared to 0.8 tC ha^{-1} yr^{-1} for meadow and 0.4-0.9 tC ha^{-1} yr^{-1} as discussed above).

However it should be noted that some studies (e.g. Post and Kwon, 2000) have measured higher rates of soil carbon increase under perennial grasses than Ceotto and Di Candilo (2011), and so it is not clear that planting SRC on agricultural or abandoned agricultural land would necessarily deliver higher soil carbon benefits than cultivating perennial grasses. In contrast, some authors believe there is a theoretical basis for believing that SRC would provide a smaller soil carbon benefit than would perennial grasses because woody crops allocate a smaller fraction of biomass below ground, and rotting roots are a major source of soil carbon (Guo and Guifford, 2002).

Annual energy crops

Annual energy crops such as biomass sorghum would generally not be expected to have the same beneficial impact on soil carbon on agricultural land as the perennial energy crops discussed above, because the annual harvesting and sowing will lead to the same soil disturbance as annual food crops (Ranney & Mann, 1994). One study's model predicted no soil carbon loss when biomass sorghum is planted on agricultural land if best management practices including no till are implemented (Meki et al., 2013) but it is not clear if biomass sorghum would deliver a benefit above what could be achieved with implementing the same best practices for annual food crops. Another study modeled SOC changes under biomass sorghum based on empirical data and reported a soil carbon increase on agricultural land (Dou et al., 2014). This could be because sorghum tends to have very extensive root systems that contribute to the buildup of soil carbon (Wilhelm et al. 2004). More research is needed before conclusions can be drawn on the likely impact of biomass sorghum cultivation on soil carbon under different settings.

In addition, there is a theoretical reason to believe that biomass sorghum may require more fertilizer than the perennial energy crops discussed above, because it typically must be harvested green, according to agricultural experts surveyed in a DOE workshop (DOE, 2011). The primary mechanism that enables biomass sorghum to grow larger than sweet sorghum or grain sorghum is that this cultivar is photoperiod-insensitive. Decreasing daylight in late summer triggers sweet and grain sorghum varieties to flower and thereafter senesce, but biomass sorghum does not respond to the daylight signal until far later in the season. While this allows these plants to continue growing larger, it also means that biomass sorghum typically does not fully translocate nutrients to the roots (and to the soil after the roots rot) during the senescence process before it must be harvested (DOE, 2011). However, in EPA's Notice of Opportunity To Comment on the Lifecycle Greenhouse Gas Emissions for Renewable Fuels Produced From Biomass Sorghum (EPA, 2014), the agency reports that biomass sorghum requires less fertilizer than switchgrass.

Contaminated soils

Energy crops may have the added benefit of remediating polluted water and land. Willow can be used to remove nutrients from municipal wastewater, farmland drainage water, and sewage sludge, and has also been found to remove cadmium from contaminated soils (reviewed in Rowe et al., 2009). Indeed, lower levels of cadmium and zinc were found in willow and poplar SRC fields than in arable fields (Dimitriou et al. 2012; Baum et al. 2009).

The potential of *Arundo donax* to treat soil contaminated with heavy metals has been widely researched in the literature. For example, Papazoglou et al. (2005) found that *A. donax* can tolerate high concentrations of cadmium and nickel without affecting growth rates. Mirza et al. (2011) reported that *A. donax* accumulates arsenic in its roots, shoots, and leaves, and therefore could potentially be used to rehabilitate soils contaminated with arsenic. However, using energy crops for soil remediation may pose challenges when processing the metal-contaminated biomass for fuel or combusting it for power.

WATER REQUIREMENTS

The water requirement of energy crops is an important concern because much of the marginal agricultural land that may be available to grow energy crops without significant environmental impacts is too dry to be used for food production. Identifying energy crops that can produce viable yields without high water needs is thus a priority. However, it should be noted that energy crops could potentially utilize wastewater or moderately salty water that is unsuitable for food crops or other uses (Schnoor et al., 2008).

Arundo donax **(giant reed)**

Although *Arundo donax* typically grows in riparian habitats and readily consumes water when available, it has been found to produce high yields on marginal land when grown without irrigation. One study achieved fairly high yields (17 t ha^{-1} yr^{-1})[8] for *A. donax* grown on sandy, marginal soils with low water retention capacity, without irrigation, and with annual precipitation of 876 mm (Nassi Di Nasso et al., 2013). This total amount of precipitation is not particularly low, but in this study it exhibited an uneven pattern across the study period. Similarly, Consentino et al. (2014) measured yields of 13 t ha^{-1} yr^{-1} for *A. donax* grown in Italy with irrigation only in the establishment year, and with no nitrogen fertilizer. Another study measured higher yields (38 t ha^{-1} yr^{-1}) of *A. donax* without irrigation on land receiving only 379 mm of annual precipitation (Angelini et al., 2009).

In their review paper, Lewandowski et al. (2003) conclude that *Arundo donax* has strong potential for growth on degraded soils where water and nutrient availability would be a problem for conventional crops. Arundo donax is commonly considered a drought resistant species because it can survive through long periods of severe drought—a finding supported by the uneven rainfall patterns in Nassi Di Nasso et al., (2013). Lewandowski et al. theorize that this is because of the crop's "coarse drought-resistant rhizomes and their deeply penetrating roots that reach deep-seated sources of water."

Switchgrass

There are many different ecotypes of switchgrass, some of which are better suited to dry upland soils and others to wet soils. Some reviews have reported that lowland ecotypes of switchgrass can grow better on wetter soils and produce higher yields (Lewandowski et al. 2003; Sanderson et al. 1996), although we did not find this difference in our more recent review (Searle and Malins, 2014b). As may be expected, one review reported that upland switchgrass ecotypes are generally more drought-resistant and recover more quickly following drought than lowland ecotypes (Parrish and Fike, 2005). In contrast to these results, Barney et al. (2009) reported no difference in outcome for lowland vs. upland ecotypes exposed to drought conditions.

In our previous review, none of the studies we included on switchgrass stated that the crop was irrigated (Searle and Malins, 2014b). While switchgrass yields under natural

8 All yields presented in this report are dry unless otherwise specified.

conditions were highly variable among studies and locations, these results suggest that switchgrass can be fairly drought-tolerant, and can sometimes produce good yields with moderate water availability. However, there is evidence that switchgrass does not produce high yields under very low water conditions. In Searle and Malins (2014b), we reported that switchgrass yields are sometimes as low as 1-2 t ha^{-1} yr^{-1} with inadequate precipitation. For example, one study found that under arid conditions with only 151 mm precipitation over the growing season, irrigated switchgrass yields were more than six times higher than non-irrigated (Mann et al., 2013). As a point of reference, annual precipitation is typically around 600 mm in London and Berlin and around 400 mm in Madrid and Athens.

Miscanthus

There is evidence that Miscanthus can produce very high yields with high water availability, but does not always grow well without irrigation under arid or semi-arid conditions (Heaton et al., 2004, Stephens et al., 2001). Mann et al. (2013) found that under arid conditions, Miscanthus yields were 82 times greater with irrigation than without, and exhibited greater drought intolerance than switchgrass grown in the same study (discussed above). However, Consentino et al. (2007) found that Miscanthus yields were only modestly lower without irrigation (20 t ha^{-1} yr^{-1}, fall harvest) than with irrigation (25 t ha^{-1} yr^{-1}) in extremely arid conditions with only 11–19 mm annual precipitation. One possible reason for drought tolerance may be that Miscanthus is able to extract water from the soil up to two meters deep, as suggested by Stephens et al. (2001).

SRC poplar and willow

These woody crops may not be as drought-tolerant as the perennial grasses discussed above, which is not very surprising as willow in particular is a riparian species. SRC poplar and willow have been reported in the literature to have slightly higher water use than agricultural crops including barley and wheat (Dimitriou et al. 2009; Oliver et al. 2009). SRC poplar is said to be more sensitive to water deficit than other woody crops, but certain hybrids have been found to be better suited to semi-arid Mediterranean environments. Navarro et al. (2014) reported that one poplar genotype delivered reasonable but not high yields (4 t ha^{-1}) under semi-arid conditions. Kauter et al. (2003) reviewed the characteristics of poplar SRC and report a minimum of 350 mm of rainfall during the growing season as a basic requirement, as well as favorable climatic conditions, nutrient supplies, and deep soils.

Biomass sorghum

Relatively few studies have examined the water requirements and drought tolerance of biomass sorghum, but those that have report the crop to tolerate semi-arid conditions without irrigation reasonably well. One study found modestly lower yields (~10-20%) for biomass sorghum grown without irrigation than with irrigation when annual precipitation was 337 mm in the first year and 573 mm in the second year (Rocateli et al., 2012), but it should be noted that this amount of precipitation in the second year is fairly generous. Another study similarly measured modestly lower yields (20-29 t ha^{-1}) under rain-fed conditions compared with irrigated (33-51 t ha^{-1}) in southern and eastern Italy. Tadesse Yimam et al. (2015) report that in one trial, biomass sorghum was found to have greater water use efficiency than switchgrass.

CONCLUSIONS

While there is variability among studies and relatively little research on marginal agricultural land in general, some conclusions can be drawn about the likely environmental impacts of growing energy crops on marginal land, shown in Table 3. Both perennial grasses and SRC woody crops support similar and sometimes greater levels of bird and insect diversity compared with marginal lands and grasslands, and allow growth of understory vegetation, especially after the initial establishment phase. Energy crops in general have a strongly positive effect on carbon storage in biomass stocks and annual biomass carbon sequestration in most cases. The scant evidence base on soil carbon impacts provides mixed results, and it is likely that energy crop cultivation will increase soil carbon in some cases but not in others. Perennial grasses, including switchgrass, Miscanthus, and giant reed, are generally moderately drought-tolerant, but woody crops are less so; however, it should be noted that these crops generally will produce lower yields under low water conditions, which may not be commercially viable depending on the producer. There is less evidence on the environmental impacts of annual energy crops such as biomass sorghum than the perennial candidates, but the evidence that does exist suggests that biomass sorghum should at least not be expected to have markedly negative environmental effects when grown on marginal land. Overall, it is clear that there should be opportunities for biomass production to deliver direct environmental benefits under certain circumstances as well as displacing fossil fuel use, but it is important to remember that environmental benefits and risks of energy cropping are highly dependent on local circumstances.

Table 3. Summary of environmental effects of energy crops

Environmental effect on marginal land	Perennial grasses	Woody crops	Annual energy crops
Biodiversity	Potentially higher	Potentially higher	No evidence
Biomass productivity	Likely higher	Likely higher	Likely higher
Biomass stocks	Potentially higher	Likely higher	Not clear
Soil carbon	Not clear	Not clear	Not clear
Water requirements (are crops viable in dry regions)	Potentially yes	Likely no	Maybe

Although we did not specifically review the issues of fertilizer and pesticide use with energy crop cultivation, these crops are generally considered to require much less of these inputs than food crops (reviewed in Searle and Malins, 2014b), so the associated environmental damage is likely relatively low for all the crops considered here.

SARDINIA CASE STUDY

SUMMARY OF SARDINIA CASE STUDY

This chapter describes a project led by Biochemtex, growing *Arundo donax* (giant reed) on unutilized and underutilized agricultural land in the Carbonia-Iglesias Province of Sardinia, Italy. The arid Carbonia region is characterized by agricultural land on poor soils, much of which is fallow or abandoned, and areas contaminated by mining activity in the 20th century. Biochemtex is currently in its second year of *A. donax* trials at three sites in the Carbonia region. If implemented, project plans would expand *A. donax* cultivation to 5,500 hectares on agricultural land and 500 hectares on contaminated land.

For this study, we conducted site visits to compare the *A. donax* trials with the surrounding agricultural land in terms of key environmental parameters. In a cursory assessment, biodiversity appeared to be very low in both the *A. donax* plots and adjacent fields that were either fallow or used to grow hay, although additional surveys would be necessary to determine whether threatened bird or other animal species may sometimes be present. The number of plant species present tended to be higher in *A. donax* plots than in the surrounding areas, but as expected the energy crop dominated plant communities where it was grown. There was high variability in soil carbon and nitrogen among the sites with no clear trend: at two sites, soil carbon and nitrogen were somewhat lower in the *A. donax* plots than the adjacent fields, but at the third site these parameters were much higher in the *A. donax* plot than elsewhere. *A. donax* produced far higher standing biomass stocks, up to 44 tonnes per hectare, than the surrounding fields, where biomass stocks were near zero, and therefore sequestered carbon in biomass at a much faster rate. At one site, an irrigation experiment was performed, providing *A. donax* with either 0%, 50%, or 100% of its irrigation needs. *A. donax* yields were relatively low when grown at less than the plant's irrigation requirements. At full scale, this project would consume 2–4% of available water resources in the Carbonia region, and the plan involves ceasing irrigation in times of water shortage. Like some other types of energy crops, *A. donax* requires water availability to thrive, and should only be grown where and when it would not divert water resources from other needs such as food production.

This project is believed to pose low sustainability risk. While there is always a risk that *A. donax* could potentially displace some food production, it is unlikely given current low prices for biomass. Biochemtex expects that farmers will utilize the least productive, abandoned agricultural land to grow *A. donax* as a diversification measure while maintaining production of food crops on the best land. The project must also be vigilant to ensure that protective measures are properly implemented to prevent cultivated *A. donax* from spreading into the few areas it is not yet introduced in Sardinia. Potential biodiversity impact is believed to be low but requires further assessment.

PROJECT BACKGROUND

Land use history of Carbonia region

The Carbonia region in the south of Sardinia (Figure 1) was a center of coal mining in the early to middle part of the 20th century.[9] After World War II, competitive imports

9 The name "Carbonia" literally means "the place of coal mining."

of lower sulfur coal forced the closure of Carbonia's mines (Sardinia.net, 2015). The last coal mine was closed in 2012 (Bianchi, 2012). As a result of decades of coal mining, large areas of the province of Carbonia-Iglesias have been contaminated with heavy metals (Cidu et al., 2009).

Much of the land of Carbonia-Iglesias that has not seen industrial use is agricultural land, but the agricultural sector in this region has also suffered from decline. Sardinia was a major producer of sugar beet in the 20th century, harvesting 12% of Italy's total sugar beet production in 1996 (Tugnoli, 1998). However, Italy experienced a rapid drop-off in sugar beet production after 2000 (Figure 2), likely due to reforms to sugar policy in Europe's Common Agricultural Policy (CAP) in 2006 (European Commission, 2015). Since 2003, the Italian National Institute of Statistics does not report any sown or harvested area of sugar beet in the Carbonia-Iglesias province.

Figure 1. Map of Italy, showing Sardinia in orange and the province of Carbonia-Iglesias in red.

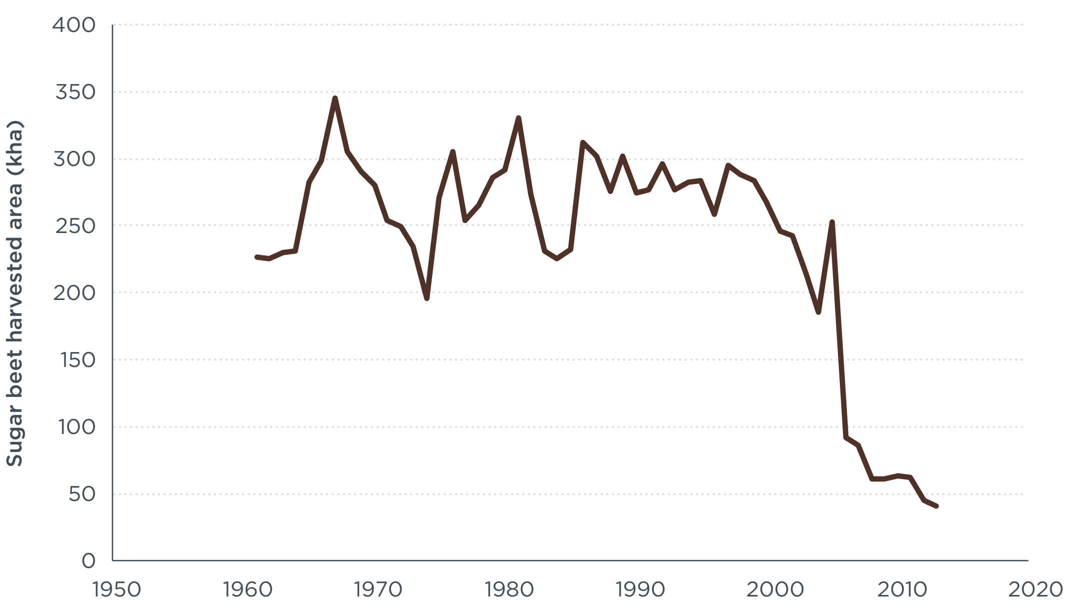

Figure 2. National total area harvested for sugar beet in Italy over time, thousand hectares. Data from FAOSTAT.[10]

10 http://faostat.fao.org/

At present, around one-third of Carbonia-Iglesias's land is under active agricultural production at any given time (Figure 3). Cereals, grapes, and vegetables in greenhouses are the main categories of food crops produced, but in total food crops only occupy 10% of the land area of the province. Fodder crops, mostly hay and other grasses, occupy another 5% of total land area, and grazing land for livestock (primarily sheep and goats) represents another 21%. It should be noted that these statistics represent a snapshot in time, and the proportion of total land area in Carbonia-Iglesias that is actively used for agriculture could change due to a myriad of factors. Some of the land area that is not currently used for agriculture, as shown in Figure 3, is fallow land in rotation that will be cultivated or used for pasture within the next few years; our observations suggest that such land usage does not constitute a large fraction of land not currently used for agriculture. Land in the Carbonia area is generally underutilized (personal communication, Prof. Pier Paulo Roggero) and characterized by low productivity due to poor soils and the arid climate, apart from a few fertile spots where grapes or horticultural crops are grown (Figure 4). Based on our observations and interviews with farmers and experts, the ecological habitat of the province appears to be dominated by extensive agricultural systems. The majority of the land area in Carbonia has been classified as of "low ecological importance" (Camarda et. al., 2015).

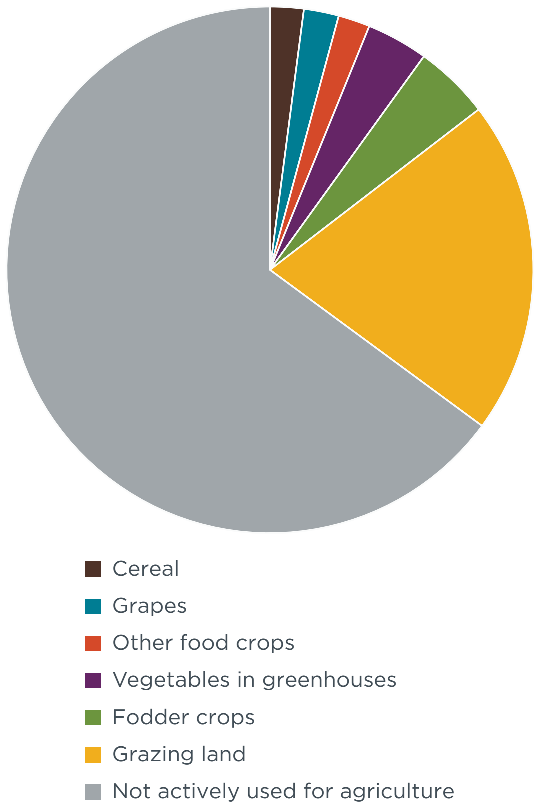

Figure 3. Land use in the province of Carbonia-Iglesias in 2009. Agricultural area data from the Italian National Institute of Statistics.[12]

Note that "not actively used for agriculture" is the remainder of total land area in Carbonia-Iglesias. Some of this land is likely fallow or semi-abandoned, in addition to fully abandoned land.

11 Data from http://www.istat.it/en/.

Figure 4. (a) Landscape characteristic of the Carbonia region; and (b) poor soils at Serramanna (photographs by C. Petrenko).

Biochemtex project

The proposed energy cropping project in the Carbonia region is led by Biochemtex, part of Mossi Ghisolfi Group (M&G).[12] Biochemtex, headquartered in Tortona, Italy, built the world's first cellulosic ethanol demonstration plant in Crescentino in partnership with Beta Renewables, Texas Pacific Group, and Novozymes.[13] This plant produces ethanol from wheat straw harvested in the Piedmont region of Italy. Increased cellulosic ethanol production could help Italy reach its blending target for advanced biofuels of 0.6% by 2018 and 1% by 2022.

Biochemtex is now seeking to expand cellulosic ethanol production into Sardinia. This plan could potentially involve the construction of one or multiple biorefineries. Biomass would be sourced from a 75 km radius of each plant and would likely include a mix of agricultural residues and cellulosic crops, primarily *Arundo donax*. The project plan is to create purchase contracts with farmers for feedstock that is grown on privately owned land. Biochemtex expects that farmers would utilize abandoned agricultural land that is prevalent throughout the region, and that they would grow *A. donax* as a diversification measure rather than displacing existing production of food crops, because of the relatively lower value of biomass.

12 http://www.biochemtex.com/
13 http://www.biochemtex.com/company-profile/biochemtex

This project could involve biomass harvests from 5,500 hectares of agricultural land as well as 500 hectares of the contaminated industrial land described above. Biochemtex expects that *A. donax* would primarily be grown on abandoned agricultural land. The planned project would occupy around 6% of the total land area not actively used for agriculture, as shown in Figure 3, and so is not expected to pressure other land uses from the perspective of land availability alone, even considering that some of the land not actively used for agriculture is semi-active fallow. In order to reduce the risk of energy crops displacing food production, Biochemtex plans to propose to farmers that *A. donax* not occupy more than 10% of their total land holdings, and that it be produced in small parcels of one to five hectares each. Biochemtex has been funded by the FAO for a study on using biofuel crops to decontaminate soils, and this study will take place over the next several years. Plans are being explored to use *A. donax* not only as a biofuel crop, but also for phytoremediation.

A. donax was chosen as the primary energy crop because it already grows extensively across the island of Sardinia. The plant is thought to be native to eastern Asia and is invasive in Europe (Pilu et al., 2013). It was introduced to Sardinia hundreds, or possibly even thousands, of years ago and has since been naturalized (i.e., naturally reproducing) across the island. It propagates readily from rhizomes and grows in dense thickets, outcompeting other species. It requires at least moderate water to grow, and so generally occurs only in clumps along rivers and wetlands. There are still some ecologically sensitive areas in Sardinia not yet invaded by *A. donax*. The Biochemtex plan involves limited future harvests of naturalized *A. donax* along waterways, which could aid in management of this invasive species. Permission has been given for a trial harvest of *A. donax* along several kilometers of a stream in the Carbonia-Iglesias province. Biochemtex plans to comply with regional environmental legislation that prohibits practices that cause erosion or disturb bird reproduction. The plan is to harvest biomass either manually or using small equipment, and to harvest *A. donax* selectively to avoid disturbing other vegetation, especially trees and shrubs. Harvests would be conducted during specific time windows of the year to avoid the breeding season for birds.

Where *A. donax* is grown on abandoned agricultural land, the plan is to mow buffer strips of 3.5 meters along the edges of the fields to prevent unintended spread of the crop. This is already common practice in this region to prevent fires during the summer. Because *A. donax* propagates by rhizomes[14] and not by seed, this is typically considered an effective measure.

Because this region is arid and water availability is sometimes limited, Biochemtex plans to halt irrigation during years of drought. There is a system of water reservoirs and irrigation pipes through the region, and water service is centrally controlled by the water holding companies. Each farm has water gauges in every field, approximately one per hectare, and the water companies will shut off water service to gauges in *A. donax* fields during drought periods. Biochemtex will be able to conduct monitoring and verification of the plan using the irrigation records at the water holding companies.

14 Underground tubers

Figure 5. *Arundo donax* growing along riverbanks in the Carbonia region (photographs by C. Petrenko).

The project is now in a trial phase in collaboration with the University of Sassari's Desertification Research Centre[15] to test growth of *A. donax* at different sites in the Carbonia region. This case study investigates how these energy crop trial plots are affecting biodiversity, soil carbon stocks, and biomass stocks in this area.

15 http://nrd.uniss.it

METHODOLOGY FOR ENVIRONMENTAL MEASUREMENTS

Study sites

Ecological surveys were conducted in early September 2015 at all three of the *A. donax* cultivation trial areas, in Tratalias, Masainas, and Serramanna, Sardinia (shown in Figure 6). *A. donax* was planted at the Masainas and Serramanna sites in October 2014, and at Tratalias in spring 2015. At present, 5 hectares of *A. donax* trials are planted across the three sites. At the Serramanna trial, an irrigation experiment was being performed, with 0%, 50%, and 100% of *A. donax* irrigation requirements being applied as treatment, and all three of the irrigation treatments were sampled in addition to the adjacent field. At each site, environmental measurements were taken within the *A. donax* trial areas and in control plots adjacent to the trials. At the Masainas plot, measurements were made in two control plots, fields that had been fallow for one and five years. Since riverbeds and abandoned, contaminated land may also be used to contribute feedstock, parameters such as soil properties were measured there. In the case of the riverbeds, where *A. donax* was already growing, biomass estimates were made.

Figure 6. The three *A. donax* trial sites and surrounding area (photographs by C. Petrenko).

The ecological surveys made at the three trial sites were designed taking into account information kindly provided by Biochemtex and University of Sassari research teams about the experimental design and the management history of the experimental plots.

Species richness and evenness

Brief wildlife surveys were held for 60 minutes at each trial site. Binoculars and cameras were used to identify and document birds. We determined the number of bird species in a trial area and when possible estimated the number of individuals. The same individuals revisited areas repeatedly.

At each of the three *A. donax* trial sites, vegetation surveys were conducted inside and adjacent to the *A. donax* trial plot. A 20 m transect was laid parallel to the longest side of the cultivated field. We identified all plants within 1 m of each side of the transect. Plants were identified to the species level in most cases, though some plants were identified to the genus, and in two cases only to the family level. Percent coverage by present species was estimated for each transect.

Species richness and evenness were calculated using the Shannon-Wiener Index. Species richness is a basic diversity index and simply represents the number of species in a given area, while species evenness takes into account the relative abundance of the groups present.

Biomass stocks

In *A. donax* plots, 1 m x 1 m subplots were delineated at the beginning, middle, and end of the transect, for three total subplots. We counted the number of *A. donax* stems per plot and recorded the heights of three randomly selected stems per plot. Dry mass of individual stems was calculated based on plant height, according to the methods of Spencer et al. (2006). Biomass of *A. donax* was calculated per square meter, as follows:

Biomass $m^{-2} = s\,[14.265\,h^2]$

where s represents the number of stems per square meter and h represents the mean height of stems from that plot. Biomass measurements were scaled to metric tons per hectare. Carbon pools were calculated based on biomass, using the commonly accepted conversion of biomass being 45% C.

Fields adjacent to *A. donax* trial plots were either recently fallowed or hayed fields. As such, the standing biomass was extremely low by comparison. The height of shrubby vegetation was measured in cases where the fields were not hayed, but destructive sampling that is required to make biomass measurements in uncommon species was not feasible.

Soil characteristics

Soil samples were collected from the beginning, middle, and end points of each transect. The three samples from each transect were bulked/mixed together, resulting in one larger sample per transect. Samples were air-dried and then stored in sterile whirl-pak bags. The samples (13 total from five study sites) were analyzed by the Forestry Commission England, Center for Ecosystems, Society and Biosecurity, United Kingdom.

The laboratory analysis included sieving soils to 2 mm, oven drying, and measurement of percent C and N. In the case of the contaminated industrial site, aluminum (Al), lead (Pb), and mercury (Hg), along with a suite of other elements, were measured. Soil nutrient pools were calculated by multiplying the soil bulk density by the concentration of that element. Measurements were scaled to tons per hectare. Soil bulk density measurements were provided by researchers from the University of Sassari, who have been co-designing and co-conducting with Biochemtex the three field experiments on the *A. donax* study sites.

RESULTS OF ENVIRONMENTAL MEASUREMENTS

Species richness and evenness

Based on this short survey, animal diversity at the trial sites appeared to be low. The only mammals observed in the vicinity of the trial sites were domesticated animals such as dogs and goats. While birds flew over the study site areas, few of them stopped in the fields or interacted with the *A. donax* plants. Across the three study areas, between four and six different bird species were seen at each site during the hour-long surveys. The birds flew overhead, with some stopping in vegetation at the edges of open fields. Only sparrows interacted with *A. donax*, sitting on the tops of stems. One sparrow was seen at each of the three trial areas sitting on *A. donax*. Birds observed included swallows, sparrows, black kites, finches, one cattle egret, seagulls, and crows. Rare or threatened animals were not observed, and no animals were observed inside the *A. donax* monoculture plots. It is likely that other animals move through these areas throughout the year, and additional surveys at other times of the year would be necessary to determine whether threatened or endangered animals are sometimes present, and establish the overall level of risk to biodiversity from *A. donax* establishment.

Figure 7. Sparrow in flight over *Arundo donax* (photograph by C. Petrenko).

Across all three trial sites, plant species diversity was extremely low (Table 4). The Shannon-Wiener diversity index (H), a measure that takes into account both species richness (number of species present) and species evenness (how well balanced the community is) fell below 1 in all but one transect. In typical ecosystems, values of H fall between 1.5 and 3.5. The highest value in our study was 1.11, which would not be considered to be diverse or even. The values for species evenness (E) alone were also quite low, with the highest value being 0.49. A value of 1 for E would indicate that all species are equally represented. Since most of the values in this study were closer to zero, we may conclude that one or two species, including *A. donax*, dominated the community.

Table 4. Plant diversity measures at the three *Arundo donax* trial sites and adjacent control plots.

Site	Plot	Species richness (S)	Evenness (E)	SHANNON-WEINER INDEX (H)
Masainas	1-year fallow	7	0.49	0.95
	5-year fallow	7	0.35	0.69
	A. donax	8	0.04	0.08
Serramanna	Grass field	5	0.02	0.04
	A. donax (0% irrigation)	6	0.23	0.48
	A. donax (50% irrigation)	8	0.46	0.82
	A. donax (100% irrigation)	10	0.03	0.08
Tratalias	Grass field	11	0.46	1.11
	A. donax	11	0.33	0.78

In Serramanna, where irrigation treatments were applied, H and E were highest in the 50% irrigation treatment. This is likely due to the fact that there is more water available for plant growth compared to the surrounding, arid environment, which allows plant species to establish and thrive in the understory of *A. donax*. Because *A. donax* is only receiving half of its water requirements in that treatment, the overstory has not filled in, and there is still space and light for other species. When *A. donax* is irrigated at 100%, however, it easily outcompetes all other plants. Water may be available for other species, but there is no light or space in the understory of *A. donax*. The competition of other plants with *A. donax* could be seen at the Tratalias site as well, where the trials were planted recently, in spring 2015. Diversity was higher inside the trial plots because *A. donax* was not yet fully established and was growing in relatively sparse patches. It should be noted that when the project is scaled, *A. donax* will be grown with 100% irrigation needs and will effectively outcompete all other plants after the first growing season. The Masainas site and the Serramanna 100% irrigation treatment are representative of likely diversity scenarios when the project scales up. In both cases, species diversity and evenness were very low. No pesticides or herbicides were used in any of the trials.

In all cases, the land adjacent to the *A. donax* fields was either recently abandoned agricultural fields or hayed fields, which commonly offer little native diversity. All plants identified outside of the *A. donax* trial plots could be broadly classified as agricultural weeds. While none of the species outside of the trial plots were rare or important plants, it can be noted that *A. donax* monoculture cropping leads to species evenness of nearly zero. Although agricultural weeds were present in low numbers in the crop's understory, the abundance of *A. donax* greatly outweighs contributions of other species.

Sardinia has a high degree of endemism and is considered to be relatively ecologically diverse, but endemic species were not found in the agricultural areas in this study, although endemic birds and other animals may sometimes move through these areas and additional surveys would be necessary to verify this. Based on this cursory assessment, we identified no evidence that the proposed project would interfere with native species or negatively affect local biodiversity. Additional survey work would be necessary to confirm this result. This preliminary finding is consistent with the Italian government's classification of this region as agricultural habitat of low ecological importance, and by our literature review finding that perennial energy crop cultivation typically does not have a negative impact on biodiversity when replacing abandoned farmland (see: "Biodiversity impacts").

Biomass stocks

Aboveground biomass stocks at the trial sites can broadly be interpreted as annual yields, as *A. donax* at the two-year old sites had been harvested in 2014 and measurements were made near the end of the growing season in 2015. *A. donax* biomass stocks were also measured at a site where it had been established on a riverbank—it should be noted that here, the plants had been growing, unharvested, for years and so the measured standing biomass stocks at this site are much greater than can be expected for annual yields.

At the trial sites, biomass stocks were highest at the two-year old sites (Masainas and Serramanna) at 100% irrigation (Figure 8). At Tratalias, *A. donax* was patchy, and yields were lower than at the other sites. This is likely because the Tratalias trial was in its first growing season at the time of measurement. According to information provided by project partners, the yields at Tratalias estimated here are similar to those achieved at the Masainas and Serramanna sites in 2014, during their first year of growth. At Serramanna, yields increased with increasing irrigation.

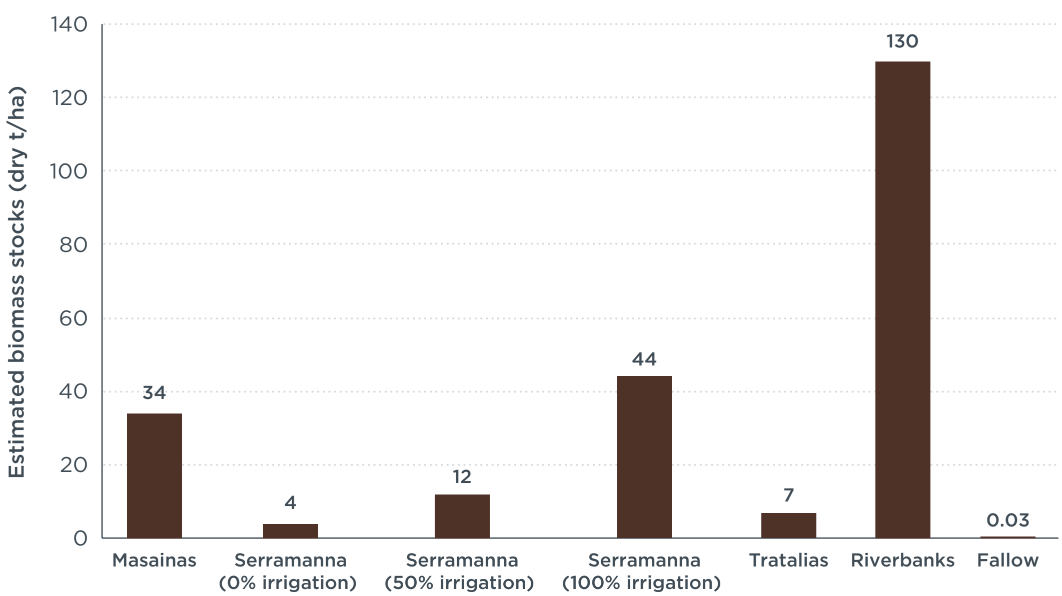

Figure 8. Estimated standing biomass stocks (dry tonnes per hectare) at each *Arundo donax* trial site, at a site where *A. donax* grows naturally along a riverbank, and at fallow land adjacent to the Masainas site.

The riverbank site had extremely high biomass relative to other sites (Figure 8). This is likely due to the fact that the *A. donax* has been growing there for years and was much taller (Figure 5), and it should be understood that the standing biomass stocks observed here are much higher than would be expected for annual yields. Riverbank biomass may be underestimated due to the branching morphology of older plants, which was not accounted for in the allometric equation used for biomass estimations.

We were not able to measure biomass stocks on the land adjacent to the *A. donax* trials. At Serramanna and Tratalias, the surrounding fields had just been hayed, so the standing biomass stocks were effectively zero. It is unknown what the hay yields were. At Masainas, the surrounding area had been fallow for one year, and vegetation was sparse (Figure 6). It was not feasible to measure biomass stocks for this study. For the fallow land at the Masainas site, we assume values of up to 0.03 t ha^{-1} from another study on native Sardinian shrubs growing on arid land (De Dato et al., 2009). Given that it is extremely unlikely that the farmland will be afforested in the near future, estimates of aboveground biomass in open fields are likely to continue to be near zero for the foreseeable future.

Belowground biomass stocks (i.e. roots) were not measured or estimated in this study, but it is reasonable to assume that belowground biomass scales roughly with aboveground biomass; i.e. belowground biomass is likely higher at any of the *A. donax* sites than adjacent fallow land.

These findings that *A. donax* cultivation greatly increases biomass stocks is a strong example of how energy crops will generally have higher productivity than any type of natural land cover they replace, as discussed in our literature review (see: “Biomass stocks and productivity”).

Soil characteristics

Soil carbon (C) and nitrogen (N) stocks were generally low at all the sites measured, confirming a visual impression that the soils are not highly productive. C and N pools were relatively similar between *A. donax* trial plots and control areas adjacent to the trial plots (Table 5). At Serramanna and Masainas, C and N content of the soil was lower in the trial plots than in the control, but this was not the case in Tratalias. In Tratalias, both C and N content of the soil was considerably higher in the trial area. Since Tratalias was planted in spring 2015, it is unlikely that the higher nutrient content of the soil was due to only a few months of *A. donax* growth. Masainas and Serramanna have been in cultivation since fall 2014, and so there is a greater possibility that the lower C and N stocks at these sites compared with the surrounding land is due to *A. donax* cultivation. However, given the variation in the results we cannot draw any firm conclusions about the effects of *A. donax* cultivation on soil C and N stocks in this study. Findings in the literature also produce mixed results, making it difficult to conclude whether energy crops in general increase or decrease soil carbon on abandoned agricultural land (see: “Soil carbon”).

Table 5. Concentrations and stocks of carbon (C) and nitrogen (N) in the top 10 cm of soil at each site.

Site	Plot	Fraction organic carbon	Organic carbon stocks (tonnes per hectare)	Fraction nitrogen	Nitrogen stocks (tonnes per hectare)
Masainas	1-year fallow	0.010	22.2	0.001	1.6
	5-year fallow	0.012	25.9	0.001	1.9
	A. donax	0.009	18.8	0.001	1.3
Serramanna	Grass field	0.009	25.4	0.001	2.0
	A. donax (0% irrigation)	0.008	23.8	0.001	2.0
	A. donax (50% irrigation)	0.009	24.5	0.001	2.0
	A. donax (100% irrigation)	0.008	21.3	0.001	1.6
Tratalias	Grass field	0.014	17.6	0.001	1.6
	A. donax	0.025	31.3	0.002	2.4
Riverbank		0.025	N/A	0.001	N/A
Contaminated industrial land		0.015	N/A	0.002	N/A

Heavy metal concentrations in the soils of the contaminated industrial site are presented in Table 6. Mercury and arsenic limits are for sludge, while lead, copper, cadmium, chromium and selenium limits are for agricultural soils. For two metals, mercury and arsenic, a comparison is made to legal limits of the metals in sludge applications in the United States (NRCS, 2000). Maximum allowable values for agricultural soils were not readily available. For all other metals, a comparison is made with maximum allowable values in agricultural soils (Grubinger and Ross, 2011), as mandated by the US EPA. Most of the heavy metals tested were below EPA limits for agricultural soils, but there was high variation in the results. In two cases, lead and chromium, the mean was above the maximum allowable value, but the standard deviation overlapped with the limit. Since soil samples were collected within a 200 meter radius of the proposed plant, we may conclude that metal concentrations vary greatly within a relatively small spatial area. Overall, the area seems to have contaminated hot spots, which would make cultivation of food crops or grazing there dangerous.

Table 6. Mean heavy metal concentrations (standard deviation) in soils from the contaminated industrial site of Portovesme.

	Mercury	Arsenic	Lead	Copper	Cadmium	Chromium	Selenium
Mean metal concentration (ppm)	0.70 (0.75)	7.9 (4.1)	288 (271)	16.6 (15.3)	8.1 (5.7)	12 (4.2)	0.73 (0.42)
US regulatory limit (ppm)	840	75	200	270	0.43	11	1

Water use and availability

Irrigation water is sourced from a network of reservoirs, and infrastructure is present across the region, with water access available in most agricultural fields. *A. donax* was drip irrigated at all trial sites. Irrigation levels for *A. donax* at these trial plots were estimated according to the plant's coefficient of evapotranspiration. One hundred percent irrigation reflects 100% of the estimated water requirements for the plant.

Although *A. donax* is typically thought of as a wetland plant, and indeed grows naturally along waterways in Sardinia, our findings in this case study confirm those of the literature review that this energy crop can produce high yields with lower water availability (Figure 8; also see: "Water requirements").

We estimate the total amount of water that would be consumed in irrigating *A. donax* at the full scale of the planned project if all the cultivated areas are provided with 100% of their water requirements. At the contaminated industrial site, an estimated 2.5 million m^3 of water would be used to irrigate 500 hectares of *A. donax* annually. This amount is approximately 5-8% of the available resource in the designated reservoir, which is 30–50 million m^3 according to the Directorate-General of the Sardinia River Basin Agency (2015). Currently, the reservoir that would serve the contaminated land is not connected to the network of reservoirs in southern Sardinia, making this site most sensitive to shortages of water.

For the remaining 5,500 hectares of cultivated *A. donax* that is planned on agricultural land, we estimate irrigation needs at 25 million m^3 annually, and the reservoir network from which this water will be drawn holds 700-1100 million m^3 H_2O (Directorate-General of the Sardinia River Basin Agency, 2015). The water needs of *A. donax* cultivation on agricultural land would thus be 2–4% of available resources.

Under Biochemtex's project plan, irrigation would be halted during times of drought by shutting off water service to *A. donax* fields through centralized irrigation control by the water holding companies. It is now clear from the trials that *A. donax* yields would not be economically viable without irrigation (Figure 8). Biochemtex would therefore not plan to harvest *A. donax* on nonirrigated areas in drought years. The plants do survive in the absence of irrigation, and so the expectation is that they would produce viable yields in subsequent years when sufficient water is available, and harvests would recommence. It should be noted that reservoirs are drained before winter and much of the unused water is discharged into the ocean, so water consumption for *A. donax* would not affect year-to-year supplies in the reservoirs.

INTERPRETATION AND CONCLUSIONS

Based on the information gathered in this study, it appears reasonably clear that Biochemtex's project plan for large-scale cultivation of *A. donax* in the Carbonia region of Sardinia is not likely to result in significant negative environmental impacts as long as the sustainability controls the company is planning are robustly implemented.

Carbonia-Iglesias consists primarily of agricultural land categorized as having low ecological importance, but only about one-third of the total land area of the province is actively used in any given year. Over half of the land that is currently under agricultural production is used for low-density grazing (for example, see the Serramanna site, Figure 6). Large areas of land are left fallow for one or multiple years, perhaps because it is not economical to produce crops on the poor, arid soils of this region (Figure 4). For example, a field adjacent to one of the *A. donax* sites had been left fallow after a poor melon harvest the previous year failed to deliver profit (personal communication with farmer).

It is clear that large areas of land are unused and available, and Biochemtex expects that farmers will only use abandoned agricultural land to grow *A. donax*. This appears to be a reasonable assumption, as the value of *A. donax* per hectare is much lower than that of food crops, even with high yields. For example, we estimate the value of one hectare of land currently used to grow artichoke (one of the most common food crops in Sardinia) at approximately €13,000.[16] Even if we assume high yields for *A. donax* in the Carbonia region at 44 tonnes per hectare, the highest estimate of biomass stocks measured in this study, and assume that 100% of this biomass can be harvested,[17] the *A. donax* would need to sell for €340 per tonne[18] in order to achieve the same value per hectare as artichokes. This is much higher than current prices for biomass such as agricultural residues and is very likely much higher than can be supported by biofuel production (e.g., see Peters et al., 2015). Thus, it is very unlikely that the value of *A. donax* will rise high enough to displace food crops based on its value per hectare alone. However, there is always a risk that *A. donax* could displace food production on the most productive land, for example if farmers value the lower management requirements of *A. donax* compared with food crops. It is also possible that *A. donax* will replace grazing land, as this land is generally of lower value and productivity than that used for food production. Land in the contaminated industrial area cannot be used for food production and could be utilized for *A. donax* cultivation without any land use impacts.

The agricultural landscape of Carbonia-Iglesias is categorized as having low ecological importance. The areas surrounding the *A. donax* trials supported grass common plants that can be broadly classified as agricultural weeds. In a short survey, the only wildlife observed in any of these areas was a number of birds flying overhead, most of which are very common species and none of which are threatened or endangered. Where *A. donax* was planted and irrigated, as expected it dominated vegetation communities, but the number of plant species actually increased in the *A. donax* plots, likely a result of water availability (Table 4). These findings are in line with those reported in the literature review (Section: Biodiversity impacts), that energy crop plantations typically support greater biodiversity than annual crops, and generally do not negatively affect biodiversity compared to fallow or abandoned land.

However, it is likely that other animals, especially birds, sometimes pass through the areas around the trial sites. Due to limited resources, we were only able to conduct very brief, cursory assessments of animal diversity, and additional surveys, preferably at various times throughout the year, would be needed to determine if endemic or threatened wildlife are ever present in these areas. One bird species in particular that may pass through these areas is the little bustard (*Tetrax tetrax*), a medium-sized bird that tends to inhabit open grasslands and relatively undisturbed agricultural landscapes, including the type of fallow and hay field mosaic observed near the *A. donax* sites in Sardinia (Morales et al., 2013). The little bustard is native to Sardinia and is classified as "near threatened" (Birdlife International, 2016a). These birds tend to live a solitary life during much of the year, but starting in late summer they congregate in flocks and wander (mostly walking) together seeking food (Garcia de la Moreina et al., 2015; Suarez-Seaone, 2008), this means the birds were likely in groups at the time of our assessment. While a flock of walking little bustards would be highly conspicuous during

16 Using data on yields, export price and export quantity in Italy from 2008-2011 from FAOSTAT data. Using this method, the value of land for other exported fruits and vegetables was generally higher (€16,000–€35,000 per hectare), while that for tomatoes was very high (€119,000) and for cereals was lower (around €1,000 per hectare). Current conversion rate of 1.09 US dollars to Euros was used.

17 It is very likely that a significant amount of biomass would be lost in the drying process, and that not all of the remaining biomass could be harvested given realistic constraints with harvesting equipment; e.g., most harvesters cut the biomass at 6-12 inches above the ground surface (Searle and Malins, 2014b).

18 At 15% moisture, which is a typical moisture content for commercially traded biomass.

a wildlife survey, this behavior would make it statistically less likely to see a little bustard at any one place at any particular point in time, and so it is not surprising that these birds were not observed in our survey, even if they are present at other times. Little bustards sometimes migrate between breeding grounds and summer or winter grounds, but not at great distances and the movement patterns are not consistent (Silva, 2010).

It is not known how *A. donax* cultivation would affect little bustards, and whether these fields could be suitable habitat. Males tend to prefer shorter vegetation (less than 30 cm) during breeding season, but females prefer denser vegetation that offers more cover (Morales, 2008). The project plan is to limit *A. donax* to small fields of 1–5 hectares, which would continue to provide the type of agricultural mosaic preferred by little bustards and other birds. Whether little bustards would frequent *A. donax* stands may depend on the availability of foods such as arthropods, a staple in the little bustard diet (Jiguet, 2002). While *A. donax* has been found to have lower arthropod diversity and abundance than other riparian habitats (Herrera and Dudley, 2003), it is not clear how arthropod availability in *A. donax* stands would compare to the hayfields and fallow land of Carbonia. The Biochemtex project does not use herbicides or pesticides on *A. donax*, which would otherwise negatively impact arthropods. Some studies have found arthropod diversity and abundance to increase with increasing plant productivity, regardless of plant diversity (Siemann, 1998; Perner et al., 2005); based on this finding, it may be possible that *A. donax* cultivation could actually encourage the production of the little bustard's key food source compared to the surrounding landscape. How these factors play out in terms of overall habitat suitability is unclear.

Other near threatened or endangered bird species that could plausibly inhabit or move through the trial areas include: great bustard (*Otix tarda*), Eurasian curlew (*Numenius arquata*), red kite (*Milvus milvus*), and saker falcon (*Falco cherrug*) (Lepage, 2016; Birdlife International, 2016b,c,d). A few types of threatened or endangered reptiles could also potentially be found in pastoral landscapes of Sardinia, including Bedriaga's rock lizard (*Archaeolacerta bedriagae*, vulnerable) (Bombi and Vignoli, 2004), Hermann's tortoise (*Testudo hermanni*, near threatened) (van Dijk et al., 2004a), and the spur-thighed tortoise (*Testudo graeca*, vulnerable) (van Dijk et al., 2004b). Sardinia has an endemic tarantula species, the Nuragic spider (*Amblyocarenum nuragicus*), that could plausibly be found in the agricultural areas of the *A. donax* trials; it has previously been found in gardens (Decae et al., 2014). This spider has only recently been discovered and has not been classified by the IUCN as endangered or not.

Additional, longer surveys would be necessary to determine whether the little bustard or any other near threatened or endangered species are ever present near the trial areas. Ideally, these surveys would be conducted during multiple seasons. While some birds are likely present year-round, migratory birds or birds that are more active in certain seasons may only be observable at some points during the year. For example, one study on bird diversity in a roughly similar environment in arid cereal steppes of Portugal surveyed birds at multiple points during the year, and observed 27 species year round, 20 species only during the breeding season, eight species only during the winter, and five species only occasionally (Delgado, 2000). Little bustards in particular may be somewhat easier to find during the breeding season compared with other times of the year, but previous studies appear to have had no problem finding flocks in the autumn (e.g. Santangeli and Cardillo, 2012; Garcia de la Moreina et al., 2015; Suarez-Seaone, 2008; Delgado, 2000). Nuragic spider males wander in late summer and can be found at dusk or during the night (Decae et al., 2014).

A. donax very clearly increases carbon storage compared with the surrounding landscape in Sardinia. Especially when irrigated, standing aboveground biomass stocks of *A. donax* were very high, up to 44 tonnes per hectare at one site, compared with very low biomass stocks in the adjacent fallow and grass fields (Figure 8). This difference would likely be accentuated were belowground biomass (roots) taken into account. There was no clear effect of *A. donax* cultivation on soil carbon stocks due to high variability among sites (Table 5).

A. donax responds very strongly to water availability, and it is clear from these trials that yields are not viable without irrigation. The trial areas and the proposed project expansion have access to irrigation infrastructure tapping into a network of water reservoirs from which there is typically excess water available that is discharged into the ocean before winter each year. If the project is expanded to the full 6,000 hectares, it would only utilize around 3% of water available in the agricultural region of Carbonia-Iglesias and around 7% of available water in the contaminated industrial area. The project plans to cease irrigation during times of water shortage to avoid negative impacts on food production.

If *A. donax* cultivation is expanded onto the contaminated industrial area of the Carbonia region, it could potentially remediate soils that currently have high concentrations of some heavy metals (Table 6). As discussed in the literature review, *A. donax* has been found to be tolerant of contaminated soils and to bio-accumulate some heavy metals, removing them from the soil.

In summary, the proposed project to cultivate *A. donax* has the potential to avoid significant negative effects on biodiversity or water availability, would almost certainly substantially improve terrestrial carbon storage where it is grown, and could improve the quality of contaminated soils. Vigilance will be needed to ensure that protective measures against unintended spread of this invasive species are properly put into practice.

MACEDONIA CASE STUDY

SUMMARY OF MACEDONIA CASE STUDY

There appear to be large areas of unused abandoned agricultural land in Macedonia that could be available for energy crop cultivation without significant negative environmental impacts. Ethanol Europe, in partnership with DuPont and NexSteppe, are planning a large project in Pelagonia, Macedonia, that would grow biomass sorghum and switchgrass on abandoned land to supply a biorefinery.

The project is currently in a very early phase, having begun energy crop trials in summer 2015. Trial plots are being conducted in two general areas: on actively used agricultural land outside the city of Bitola and on unused abandoned land in the arid region of Mariovo. Near Bitola, where land is heavily used for production of cereals, livestock fodder, tobacco, and fruits and vegetables, we observed small plots of biomass sorghum intermixed with maize and other crops; it was thus not clear that biomass sorghum in the trials was being grown on land that otherwise would have remained unused. At these plots, the biomass sorghum was irrigated liberally and achieved high yields. It is possible that as the project develops it will implement safeguards against displacement of other crops.

Land in the Mariovo region is greatly underutilized, so energy crop cultivation in this area would not likely affect other uses. However, irrigation was not available at the test site in Mariovo, and as a result the biomass sorghum and switchgrass grown here were stunted.

The project will not likely have negative impacts on biodiversity, as diversity of plants and animals was very low and consisted of common species at all sites.

PROJECT BACKGROUND

Land use history of Pelagonia

Land use for agriculture has on the whole declined in Macedonia over the past few decades. Figure 9 shows a 20% decrease in total harvested area from 1992 to 2012, the time period over which data was available. The percentage of the whole country's land area that is under agriculture has declined from around 17% to 14% over this period. While data prior to 1992 is not available, this pattern of abandonment could have begun before that point. In neighboring Bulgaria, widescale agricultural abandonment was already in full swing in the 1960s, but it did not begin until 1990 in Albania, and there is no clear time trend for Greece (also neighboring countries).[19] In any case, it is clear that there must be large areas of abandoned agricultural land in Macedonia.

19 Data from FAOSTAT.

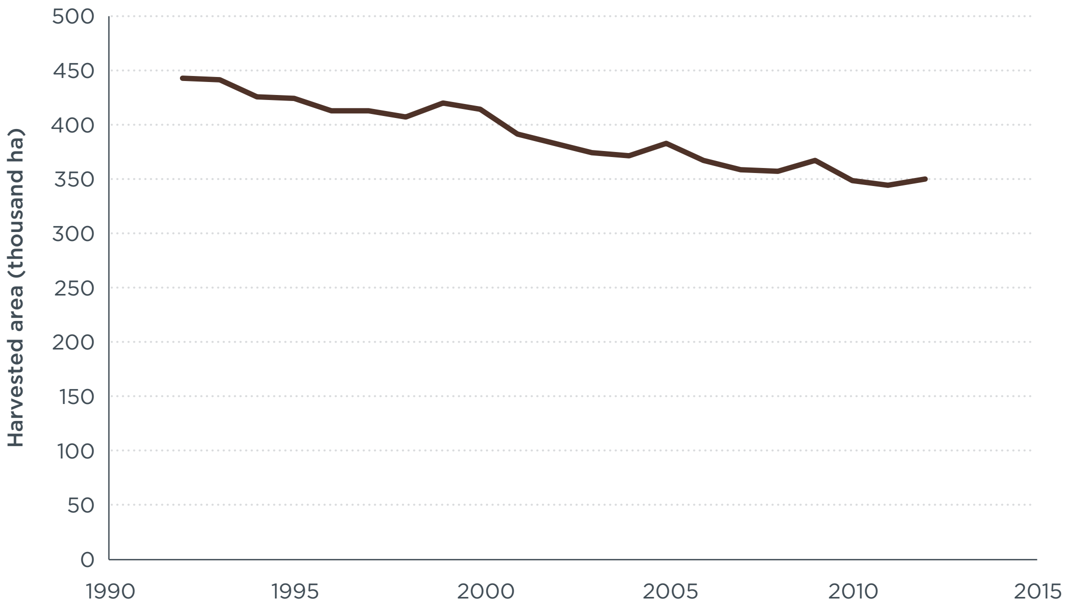

Figure 9. Total harvested area in Macedonia from 1992 to 2012 (thousand hectares). Data from FAOSTAT.[20]

Around 11% of the Pelagonia Statistical Region was actively utilized for agriculture in 2007,[21] suggesting that large areas of this region are currently unused. The main crops grown in Pelagonia are cereals (largely wheat, maize, and barley), fodder crops for livestock, industrial crops, and fruits and vegetables (Figure 10, Figure 11). Industrial crops are largely (94%) tobacco, which represents around 14% of Pelagonia's agricultural production overall. In 2007, about 4% of total agricultural land area was fallowed but still actively in rotation (this statistic likely does not count land that was fallowed for only part of the year). The available data is not detailed enough to analyze time trends for Pelagonia, but if land use in Pelagonia has followed the same trend as Macedonia as a whole, it may be inferred that there are at present around 13,000 hectares of agricultural land that have been abandoned since 1992, and the total amount may be greater if widescale abandonment began before 1992.

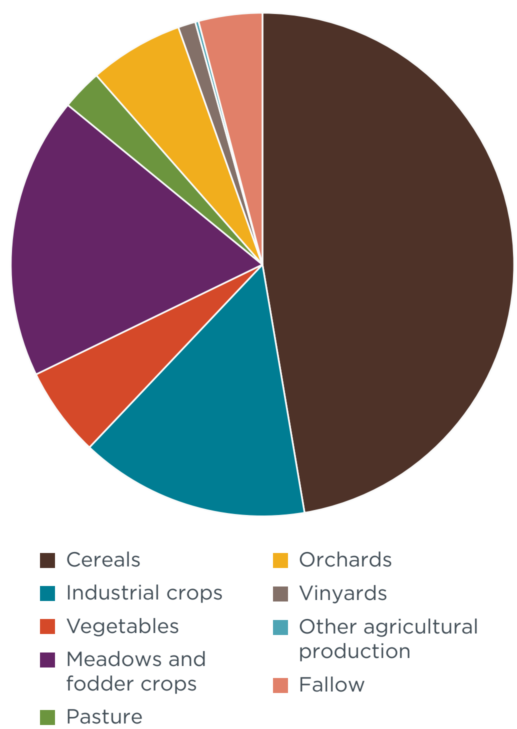

Figure 10. Agricultural land area in Pelagonia by land use type. Data source: Republic of Macedonia State Statistical Office (2007).[23]

20 Note that this data may count double cropped area twice (e.g., if one hectare is used to produce wheat in the winter and maize in the summer, it may be counted as 2 hectares in the data).

21 Calculated from an area of 51,384.5 hectares of "total utilized agricultural land" from the Republic of Macedonia State Statistical Office (2007) and a total land area of 4,719 km^2 for Pelagonia (Wikipedia, 2015).

22 Where multiple crops are produced on the same area of land within one year, this data shows only the main crop as the land use for that area. Multi-cropped areas are not double counted.

Ethanol Europe project plan

Ethanol Europe, in partnership with DuPont and NexSteppe, is proposing a project to grow 20,000 hectares of biomass sorghum and switchgrass in Pelagonia to supply production of cellulosic ethanol and/or potentially bioplastics. The plan involves cultivating 5,000 hectares of biomass sorghum on agricultural land outside the cities of Prilep and Bitola, perhaps in rotation with wheat (a winter crop in Macedonia), and 10,000–15,000 hectares of energy crops, including switchgrass, in the mountainous Mariovo region to the east of Bitola (Figure 12). A biorefinery would be constructed near Prilep and would process biomass crops grown within a 50 km radius.

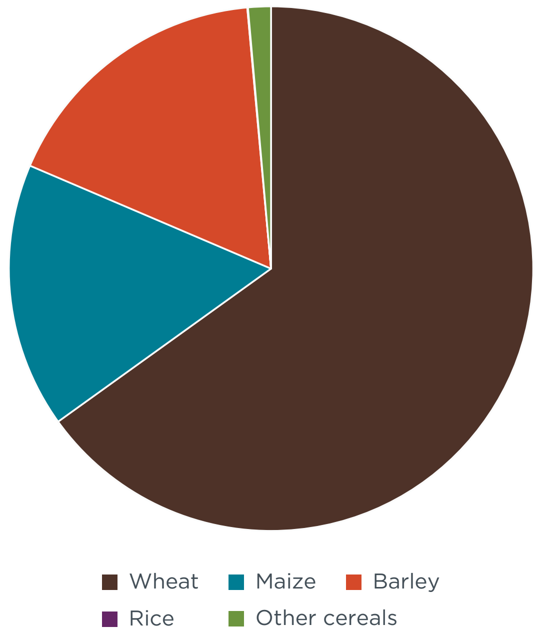

Figure 11. Agricultural land use for cereals by type. Data source: Republic of Macedonia State Statistical Office (2007).

Figure 12. Location of Pelagonia Statistical Region and major towns within Macedonia.

Pelagonia is an arid region, and Mariovo is especially dry. The project plans include cultivating drought-tolerant cultivars of switchgrass in Mariovo, although at this point it is unclear from the plans and trials whether irrigation would be needed to achieve viable yields. Biomass sorghum, which has higher water needs, would mainly be grown near the cities where there is irrigation infrastructure and water availability, although some may be grown in Mariovo if irrigation is made available.

This project is currently in a trial phase to observe yields at different sites. Nineteen hectares were planted with biomass sorghum and switchgrass in summer 2015. In this trial, biomass sorghum was grown outside Bitola and both biomass sorghum and switchgrass were grown in the Mariovo region.

SITE VISIT FINDINGS

The information presented in this case study was gathered in early September 2015 from site visits to five trial plots, interviews with farmers and town council members, and translated conversations with a farmer who is running the trial plantings. It was noted that there were some inconsistencies in the understanding of the project plan between different parties with whom we consulted. For example, some parties expected that biomass sorghum in the actively used areas near the cities would only be grown in rotation with wheat and thus not cause crop displacement, while others reported that they understood the project plan could include single-cropping biomass sorghum in these areas. This confusion may have reflected a distinction between trials in the short term and the wider scale plan for the long term, but this was unclear. There were also inconsistencies about whether biomass sorghum should be grown in Mariovo, and whether irrigation is needed in this region. It seems that some of these issues are still in flux as the project gets started in this early phase.

The site visits supported many of the statistics presented above about land use in Pelagonia. There are large areas of unused land (as mentioned above, only 11% of the land area of Pelagonia is under active agricultural use), and observed crops include tobacco, maize, wheat, vegetables and fruits, and sunflowers. Wheat is mostly grown as a winter crop in Macedonia, from October to June, and so was not prevalent at the time of the site visits. Farmers reported that several of the crops currently being grown are exported.

The land around Bitola appeared to have good soils and was heavily used for agriculture (Figure 13). It was not clear whether the land that is used to grow wheat in the winter was actively in use during the summer. Clover was observed growing over a significant amount of land, so it is possible that the wheat fields are left fallow in the summer (this would very likely be counted as "wheat" and not "fallow" in the statistics given for Pelagonia agriculture above). If this is true, these hectares could potentially be considered available for biomass sorghum production during the three to four months of summer season without displacing other crops, although reduction of fallow time could cause reduced yields in both wheat and biomass sorghum over several years. Fallowing fields tends to reduce erosion and return organic matter, nutrients, and water retention capacity to the soil and thus maintain fertility over time as well as providing other benefits such as weed control and disease suppression (IEEP, 2008; Silcock and Lovegrove, 2007; Oliver and Sands, 2013), although it should be noted that crop rotations would also likely reduce pest and disease pressure compared with continuous cultivation of one crop.

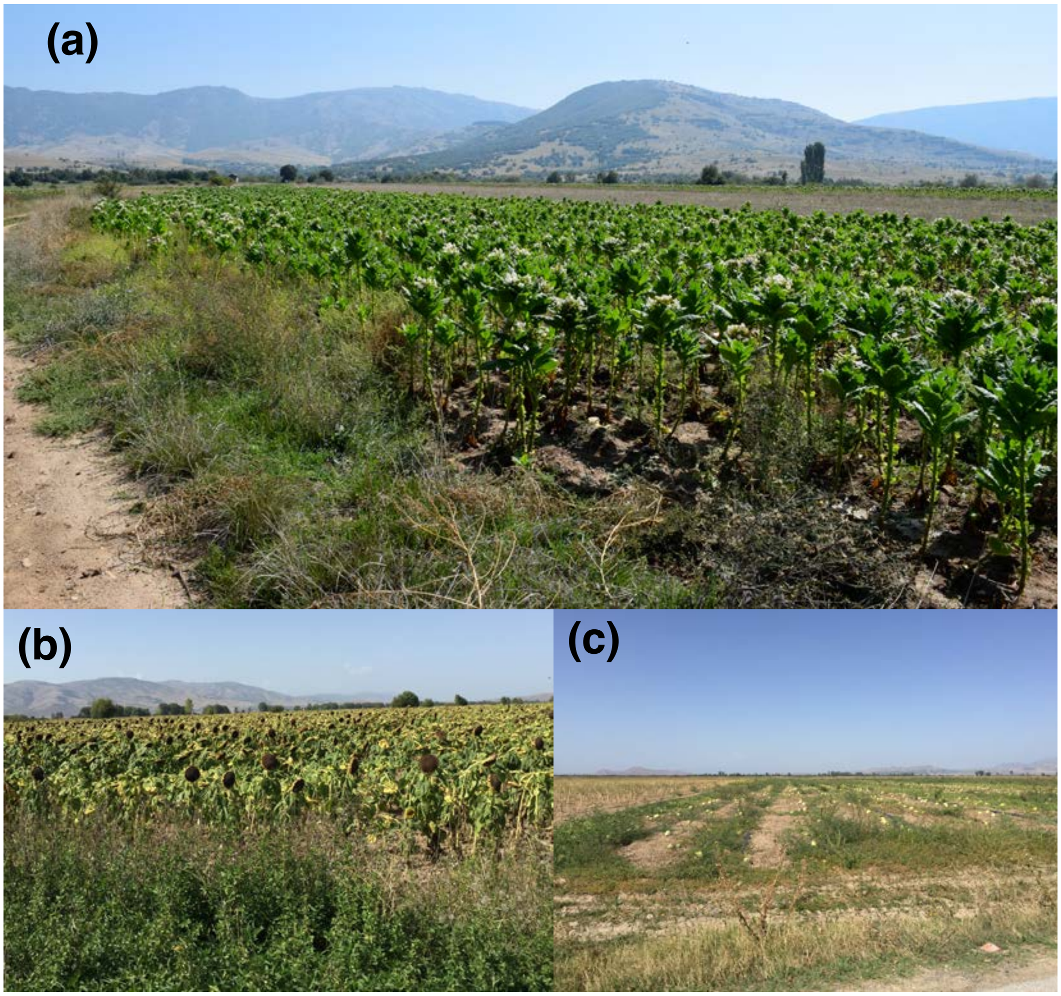

Figure 13. Crops growing near Bitola: (a) tobacco, (b) sunflowers, and (c) melons (photographs by C. Petrenko).

However, it appeared that some biomass sorghum trials were grown on land that would otherwise have been actively used for other summer crops. Figure 14 shows a small plot of biomass sorghum in between two plots of maize, suggesting that this area would normally be used for maize. At each of the four sites we visited near Bitola, biomass sorghum was grown in heavily used areas. In an interview, city council members reported that biomass crops should only be grown on poor soils, but this did not appear to be the case in some of the trial areas. Farmers reported that they prefer to grow biomass sorghum than other crops because it grows quickly and requires much less management than food crops or tobacco.

Figure 14. Biomass sorghum growing between two plots of maize (photograph by C. Petrenko).

We visited one trial site in the dry Mariovo region where biomass sorghum and, to a lesser extent, switchgrass was grown. The energy crops at this site were stunted compared with those at the sites near Bitola (Figure 15). The land in this region appeared to be mostly unused, although one pine plantation was observed in the vicinity of the trial plot. Crumbling buildings scattered throughout Mariovo suggest this area was abandoned several decades ago.

We were told by project partners that one reason yields were lower than anticipated in both Mariovo and near the cities is that this year, the crops were planted much later than planned because the seeds were held for six weeks in customs. The delay in planting meant that crop establishment occurred during the drier month of June, rather than May when there is more precipitation. Establishment and competition with weeds at the non-irrigated sites were more challenging than would be expected had planting occurred on schedule. It should be noted that according to the project plan, biomass sorghum that is double cropped with wheat will be planted in the irrigated areas in July, after the wheat harvest—so even though planting in these areas will occur in the dry summer, irrigation should aid crop establishment. Switchgrass yields were low because 2015 was the first growing season of this crop, and switchgrass typically does not reach maturity until the second or third year. Yield data over the next two years will be needed before conclusions can be drawn about the viability of switchgrass in Mariovo.

Figure 15. Biomass sorghum grown in the arid Mariovo region (photograph by C. Petrenko).

Vegetation and biodiversity

Biodiversity was low at all sites. At the trial sites near Bitola, all of the surrounding area was under agricultural use. Common agricultural weeds were observed, including purslain (*Portulaca oleracea*), wild lettuce (*Lactuca* spp.), thistle (*Asteraceae* family), and lamb's quarter (*Chenopodium album*). No birds or other animals were seen at these plots.

Vegetation in the Mariovo region outside of the energy crop plots was sparse and consisted mainly of dead grass and occasional shrubs and short trees, including birch, acacia, and oak. Kites, which are common birds, were observed flying overhead.

These observations, as well as our literature review (see: "Biodiversity impacts"), indicate that there would not be significant biodiversity impacts of expanding energy crop cultivation in Pelagonia. We were unable to measure biomass stocks at any of the sites due to loss of instrumentation in transit. While it seems unlikely that energy crop cultivation would decrease biomass stocks, it was not clear that it would substantially increase them either: plant height was roughly similar between biomass sorghum and the surrounding maizefields at sites near Bitola (Figure 14), and growth was patchy at the Mariovo site, likely not much greater than the natural patchwork of shrubs and grass (Figure 15).

Soil quality

Soil samples were taken from the top 10 cm at each site and analyzed at the Institute of Tobacco in Prilep, Macdeonia. The organic matter content of the soils ranged from 1.2–6.0%. Soil organic matter is roughly half carbon, so these measurements indicate soil carbon concentrations ranging from approximately 0.6–3.0%. For comparison, soil carbon concentrations at most of the sites in Sardinia were around 1.0%. However, we cannot calculate total soil carbon pools as we were not able to measure soil bulk density in Pelagonia. The soils in Sardinia were very rocky and the Macedonian soils were not—because rocks are sieved out of the soils before analysis, examining only the soil carbon concentration of the sieved soils from Sardinia would tend to overstate the actual amount of soil carbon per hectare. Thus, it is likely that soil carbon stocks in Macedonia were greater overall. This inference is in line with visual inspection that the soils in Pelagonia appeared to be of higher quality.

Observed soil carbon concentrations were slightly lower in biomass sorghum plots than in adjacent plots. However, it is unlikely that this difference is a result of sorghum cultivation as the sorghum had only been growing for a few months at the time of measurement.

Water availability

Water availability is a potential problem with this project. Biomass sorghum clearly requires irrigation in this arid region to achieve high yields. The sorghum plots near Bitola received regular irrigation (around 200,000 liters per hectare over the course of the growing season) and were approximately 3.8 meters tall at the time of observation in early September. In contrast, the sorghum grown in the Mariovo region with little irrigation was around 1 meter tall and exhibited patchy growth (Figure 15).

There was evidence of political issues around water permitting. A Sorghum trial plot in the Mariovo region was watered several times without explicit permission, after which farmers who used water from the reservoir prohibited further use. By September the reservoir had dried up, indicating that water resources were indeed scarce and in high demand. At another remote site, the government did not grant the needed permits, despite proper applications being filed. It is possible that lack of water availability will be a significant hurdle in this project.

Irrigation was conducted with hoses and spray equipment, which is less water-efficient than using drip irrigation (which was used in the Sardinia project). It would have been impractical to establish drip irrigation in this early trial phase.

CONCLUSIONS

The energy cropping trials in Macedonia are at a very early stage, making it difficult to draw firm conclusions. While there are large areas of abandoned agricultural land available in Macedonia, it is not clear that the proposed project has safeguards in place to direct energy crop cultivation onto currently unused land, in preference to higher quality land where yields could be better. At the sites near the city of Bitola, we observed plots of biomass sorghum intermixed with food crops—this context suggests that sorghum may have been grown on land that otherwise would have been used for maize and other crops. Farmers reported that they preferred growing biomass sorghum because of its rapid growth and low maintenance requirements. Without safeguards, it appears that increasing demand for biomass sorghum in this region carries a risk of displacing other crops. This project is in its first year of trials, which are being performed on a small scale, and there appears to be inconsistency in understanding among project partners and stakeholders about the long-term plan. It is possible that as the project is further developed, the project partners will implement stronger controls to prevent biomass sorghum from displacing existing crops, but it is unclear whether this result would be achieved through economic factors alone. Such controls would be necessary for the project to ensure that cultivation could proceed with no net displacement of other crop production.

There are large areas of unused land in the Mariovo region that could be available for energy crop cultivation without affecting food production or other uses. However, it is not clear that energy crop yields would be viable in this area. The project does not have permission to use irrigation in Mariovo at the present, and likely as a result, yields of biomass sorghum and switchgrass appeared to be low.

This project would not likely have negative impacts on biodiversity. At all the sites we visited, biodiversity appeared to be low, and non-agricultural vegetation was sparse. It was not clear whether energy crop cultivation would have a positive or negative impact on standing biomass stocks, but any impact either way would likely be low.

OPPORTUNITIES FOR ENERGY CROPS IN PALUDICULTURE

SUMMARY OF PALUDICULTURE

There is a large opportunity to reduce greenhouse gas emissions in Europe through the practice of "paludiculture," the wet cultivation and harvest of biomass in peatlands. Six percent of the EU's land area is on carbon-rich peat soils, and much of this has been drained and degraded for agriculture, releasing vast amounts of CO_2 to the atmosphere. Much of this land has been abandoned over the past few decades and remains unused. Rewetting these peatlands can stop the carbon loss and restore these areas to net carbon sinks, although for a period of time following rewetting, high methane emissions will reduce the overall GHG benefit. Harvesting biomass for energy or material uses can provide an economic incentive to rewetting and restoring degraded, unused peatlands. Paludiculture can provide the additional environmental benefit of supporting increased biodiversity of animals and plants compared to the abandoned state.

In this chapter we highlight two paludiculture projects, one in Poland and one in Belarus. A project in Poland led by the Polish Society for the Protection of Birds (OTOP) has restored large areas of a fen in the Biebrza Valley, an important site for breeding of the threatened aquatic warbler. Since abandonment, these areas had become overgrown with reeds and shrubs, making them less suitable for the warbler. The OTOP project has restored the fen to the short vegetation heights preferred for warbler nests by mowing the natural growing biomass and delivering it to a pelleting facility for use in energy or as animal bedding. The Wetland Energy Project in Belarus, led by an international consortium of environmental organizations, is rewetting and restoring degraded sites where peat extraction has taken place for energy. Over some of this restored area, biomass harvesting of the natural growing plants is being piloted, with the biomass delivered to a mobile briquetting module. The goal of the project is to displace peat briquetting in Belarus, and to reduce GHG emissions from peat combustion and peatland drainage.

Paludiculture is in the early stages of adoption, and several challenges remain. Mechanical harvesting of biomass is difficult on wet peatlands without damaging the fragile peat surface. The two projects described above use special harvesters that exert less pressure on the ground surface than conventional equipment, but still have limitations. A major challenge for paludiculture is economic viability. In the OTOP project, net revenues from biomass harvest slightly exceed costs, but this project does not pay for the use of land. Paludiculture is a strong complement to conservation and GHG reduction projects, but will not likely replace active uses of peatlands such as agriculture without additional policy interventions.

INTRODUCTION

Context: peatlands in Europe

Europe has extensive peatlands. These soils have high levels of organic matter formed by centuries or millennia of decaying plant matter, typically in wetlands. The EU is on average 6% peatlands, with the distribution of these soils skewed towards northern countries, particularly Finland, Germany, Poland, Sweden, and the UK (Figure 16).

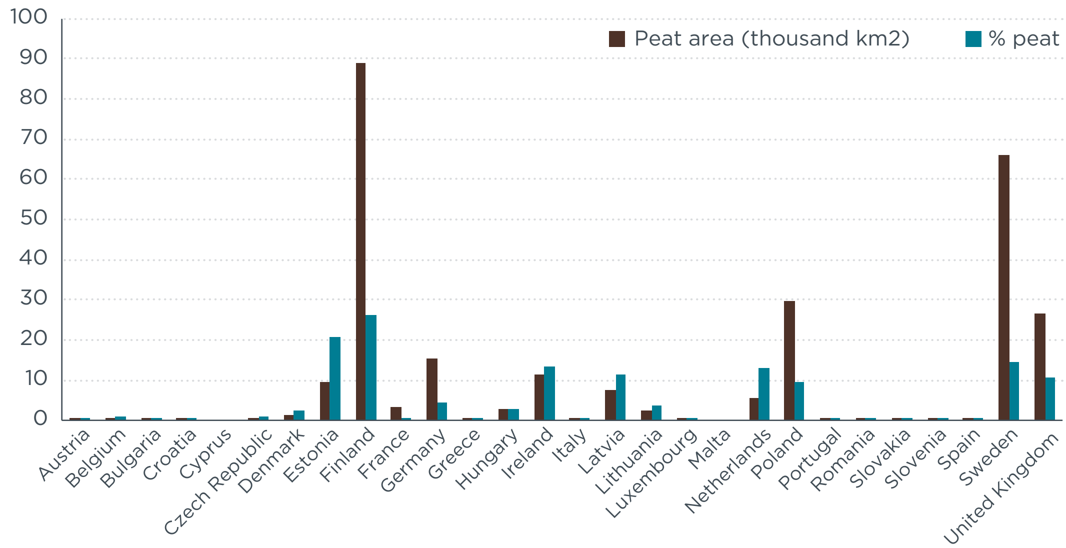

Figure 16. Total area and percent area with peat soils by EU country. Data from the European Soil Database, as reported in Montanarella et al. (2006).

When in a pristine state, these peatlands store vast amounts of organic carbon that does not rot due to the anoxic conditions of flooded soils. But as large areas of peatlands have been drained to support agriculture, air has entered the soils, and the resulting oxygen has allowed the organic material to decompose into CO_2. Separately from agriculture, some peatlands in Europe have been drained in order to harvest the peat as a fuel. Globally, CO_2 emissions from drained peatlands and peat fires contribute almost 25% of the CO_2 emissions from the entire land use, land use change and forestry (LULUCF) sector (Joosten, 2013). In Europe, drained peatlands are used mainly for meadows and pasture, although some are used for the cultivation of annual crops. In Germany (85%), Poland (70%), the Netherlands (85%), Hungary (98%) and Greece (90%), most peatlands have been degraded for use in agriculture (Strack, 2008).

The only way to reverse CO_2 loss from drained peatlands is to re-flood them, stopping the decomposition of organic matter and allowing peat to rebuild from new plant matter. It is important to keep flooded peatlands wet and prevent their degradation. Flooded peatlands can support biomass production as well as providing habitat for sensitive wildlife.

What is paludiculture?

It is possible to rewet peatlands and keep them wet while using them for productive purposes. Paludiculture is the wet cultivation of peatlands. Using these wetlands to produce bioenergy feedstocks and building materials can give them economic value and prevent them from being drained for other uses, while at the same time continuing to build peat and provide wildlife habitat.

Any type of plant that grows naturally in wetlands could potentially be harvested and used for bioenergy. Native peatland plants in Europe typically include a variety of sedge species, sphagnum moss, cattails, grasses, and many other plants, sometimes including trees and bushes. Abel et al. (2012) present a database of potential useful paludiculture plants, and a few examples are shown in Figure 17.

Species that are particularly attractive for paludiculture include common reed (*Phragmites australis)*, reed canary grass (*Phalaris arundinacea*), and alder trees (*Alnus* spp.). Common reed can have very high yields and is resistant to rot under moist conditions, which means it can be stored uncovered outside after harvest. However, it colonizes new areas aggressively and can dramatically and irreversibly alter ecosystems (Brix et al., 2013). Sphagnum moss farming is of interest for supplying a growing medium for horticulture, but is an unlikely energy crop candidate due to its relatively low yields.

Figure 17. Potential paludiculture plants: (a) alder (photograph by Quadell) (b) sedges (photograph by S. Searle) and (c) common reed (photograph by Janke).[23]

ENVIRONMENTAL COSTS AND BENEFITS OF PALUDICULTURE

One of the main environmental benefits of paludiculture is carbon savings—protecting wet peatlands maintains their function in net CO_2 sequestration and rewetting drained peatlands reverses their status as net carbon emitters to net carbon sinks. Management of wetlands through paludiculture can also maintain wildlife habitat, improve biodiversity, and protect endangered species.

Greenhouse gas savings

Paludiculture affects the GHG balance in peatlands in both the soil and in biomass.

Cultivating wet peatlands can increase or decrease the amount of carbon sequestered by biomass depending on how the productivity of the biomass crops compares with

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that of the pre-existing vegetation. Common reed can have high yields, from 8-19 t ha^{-1} yr^{-1} for natural stands or cultivation without fertilizer and higher with fertilizer addition (Kulhman et al., 2013). Cattails and reed canary grass yields may be somewhat lower, and mosses and sedges may produce only a few tons biomass per hectare per year (Timmermann, 2003, as cited in Wichtmann and Joosten, 2007). If, for example, a degraded peatland that has been used as pasture is reflooded and planted with common reed, this project would likely increase biomass productivity. In contrast, sphagnum moss farming may not change productivity, or could even decrease it compared with the degraded state.

The main GHG benefit seen in paludiculture is in preventing high CO_2 release from oxidized peat soils. Drained peatlands are a major contributor to total anthropogenic GHG emissions worldwide. Globally, drained peatlands and peat fires emit around 2 billion tonnes CO_2e per year (Joosten, 2009), on the order of 5% of total anthropogenic GHG emissions worldwide.[24] In Europe, drained peat soils have been estimated to emit around 20 tCO_2 ha^{-1} yr^{1} (Couwenberg et al., 2011; Danevčič et al., 2010; Alm et al., 2007); this is roughly equivalent to growing an additional 12 tonnes of biomass on a hectare of land and burning it without any productive use. Stopping the oxidation process by rewetting drained peatlands can thus dramatically reduce CO_2 emissions.

Functional wet peatlands, on the other hand, are a mild carbon sink. Over time, decaying plant matter creates new peat that remains in flooded soils. Sphagnum moss typically builds peat in raised bogs, but common reed has been found to build peat as well and could potentially drive carbon storage in paludiculture systems (Brix et al., 2013). These peatlands emit some methane from the anoxic decomposition of dead plant material, but not enough to offset GHG reduction through the increase in soil carbon.

Rewetted peatlands do not immediately switch from a net GHG source to a net GHG sink. For some period of time after initial re-flooding, peat soils emit high levels of methane, much higher than pristine peatlands, when a large influx of dead plant material is suddenly introduced to an anoxic flooded environment. Methane emissions subside over time and eventually resemble the lower levels of emissions from pristine peatlands. Over the long run, the increase in methane emissions is not enough to completely offset the GHG benefit of halting peat oxidation (Couwenberg, 2009).

Exactly how much methane is emitted and for how long significant amounts of methane are emitted varies greatly among locations. For example, one study found that methane emissions at a rewetted fen in northern Germany had returned to levels in pristine peatlands after 15 years. Overall, GHG emissions were 17 tCO_2e ha^{-1} yr^{-1} lower compared to a drained state (Günther et al. 2014). In contrast, methane emissions remained high (22-51 tCO_2e ha^{-1} yr^{-1}) at another German wetland after 30 years (Vanselow-Algan et al., 2015). Even this high-emitting wetland probably delivers a climate benefit over a longer timeframe. Augustin and Joosten (2007) have estimated that even if the high methane phase of a rewetted peatland lasted 50 years, it would still reduce GHG emissions over a 100-year timescale when compared with a drained peatland. Although rewetting peatlands will deliver carbon benefits over the long run, it is clear that methane emissions in the first stage of rewetting are significant and must be accounted for.

24 Estimated based on ~32 billion tonnes CO_2e yr^{-1} global anthropogenic emissions (IEA, 2015).

Interestingly, a high rate of methane emissions from reflooded peatlands is a phenomenon seen only in the higher latitudes. Couwenberg (2010) writes: "In contrast to temperate and boreal peatlands, the risk of substantial increase in methane emissions is low." Reflooding of drained tropical peatlands, for example those used for palm oil production in Malaysia and Indonesia, may deliver much higher and more immediate GHG benefits compared to European peatlands.

Biodiversity

Similarly to energy crop production on dry soils, paludiculture may have mixed effects on biodiversity. Monoculture almost always reduces plant diversity, especially in the case of common reed, which aggressively colonizes new areas to form dense, single species stands (Brix et al., 2013). Common reed has been known to have a negative impact on butterflies in particular (Skorka et al., 2007), and likely other insects and birds that depend on nectar. Harvesting native plant species in a wet or rewet peatland would not likely negatively affect plant diversity. However, there is a tradeoff between supporting plant diversity and attaining high biomass yields. Native mixed communities of sedges and other plants have much lower yields than monoculture stands of common reed, for example.

Rewetting degraded peatland, at least with native plants, tends to increase animal diversity. One research group found higher bird and insect diversity on rewetted peatlands compared to drained, intensively managed grasslands or partially drained moist meadows (Görn et al., 2014; Görn et al., 2015). Harvesting of biomass from the rewetted sites generally did not negatively affect insect diversity and may even help support it as some insects thrive in short vegetation (Görn et al., 2014). Mowing existing plants on abandoned peatland that has never been drained may improve animal biodiversity compared to allowing succession (transition to forest communities) to take place. As discussed in the case studies below, harvesting biomass in a wet fen maintains the ideal habitat for an endangered bird species. However, one study found that plant diversity increased in peatlands with succession to forest cover compared to those that had been cut over (Woziwoda and Kopec, 2014).

It should be noted that repurposing a pristine peatland for biomass cultivation, especially as a monoculture, would likely have a negative impact on biodiversity because it would displace native plant communities that support wildlife.

Similarly to biomass cultivation on dry soils, certain management techniques may encourage biodiversity. These best practices include rotational harvests, leaving an area of older crops when mowing, and avoiding the breeding season for harvesting. For paludiculture systems in particular, late summer harvesting of biomass may support much more bird diversity than winter harvesting (Görn et al., 2015).

PALUDICULTURE CASE STUDIES

Efforts are underway to research and establish paludiculture projects across Europe, with several projects ongoing in Poland and Belarus. Paludiculture is at the intersection of biomass production, habitat conservation, and climate mitigation; interests from all these sides have come together to support challenging projects. Here, we discuss two case studies: one in Poland that began as a conservation program, and an effort in Belarus to harvest biomass from rewetted peatland.

Aquatic warbler habitat in Poland

The OTOP project in Poland is part of a large initiative led by the group, with the primary aim of improving and maintaining habitat for the threatened aquatic warbler (Figure 18). This initiative is supported by the European Commission's LIFE programme, which funds environmental and climate projects.

Figure 18. Aquatic warbler. *Photograph by S. Seyfert.*

The OTOP project covers several wetland sites in Poland. Here, we describe an effort to restore 900 hectares of a large abandoned fen in the Biebrza National Park in northeastern Poland. The Biebrza Valley is the largest site in the EU and the second most important site in the world for aquatic warbler breeding, which requires wet, low-lying vegetation like sedges (OTOP, 2011). Over much of the past 300 years, this fen was used as a hay meadow, harvesting grasses with hand scything, which kept the vegetation at an appropriate height for aquatic warblers. When this type of land use stopped in the 1970s, the fen started to become overgrown with dense reeds and trees due to a combination of anthropogenic changes to its hydrology, eutrophication, and slow natural succession[25] (Lachmann et al., 2010). The overgrowth of this fen threatened its suitability for the aquatic warbler and other wildlife (OTOP, n.d.; Kloskowski and Krogulec, 1999).

The OTOP project seeks to restore an area of the Biebrza Valley to its pre-abandonment state as an open fen through bush removal and annual mowing. The project is piloting a complementary biomass production effort, harvesting the mown sedges, grasses, and other plants that naturally grow in the fen. Mowing began in 2005 and biomass collection has taken place in each year from 2012–2014 (Lachmann et al., 2010; Mucha and Gaszewski, 2014). Harvesting is done using "ratraks," second-hand machines previously used to groom snow on ski slopes, which spread the weight of the equipment over a large surface area; this reduces pressure and damage on the delicate peat surface and vegetation (OTOP, n.d.). The biomass is then transported to a nearby pelleting facility in Trzcianne (OTOP, 2011).

Biomass yields from this project have been variable over the three years of harvesting, largely due to a drought in 2013. In 2014, 674 tonnes biomass (at 15% moisture) were collected and delivered to the pelleting facility, averaging 2 tonnes per harvested hectare (Mucha and Gaszewski, 2014). An economic analysis was conducted to determine if harvesting the entire 900 ha project area for biomass pellets would be

25 Note: In a pre-industrial world, it is likely that fens like the Biebrza Valley did grow up into forest, and that wildlife such as the aquatic warbler that require open wetlands colonized new areas that were cleared as a result of natural forest fires. Today, land use change (largely for agriculture) and fire suppression have reduced the availability of new, suitable habitat areas for these wildlife. This is why it is important to conserve open fens by preventing natural succession.

feasible. Net revenue from the project, after accounting for harvesting and transporting costs, would amount to €10,000 per year, or about €11 per hectare per year. If retail profit from selling the pellets for fuel and pet bedding (for which the price is twice that as for fuel[26]) is taken into account, net revenue would be €13,000 per year, or €15 per hectare per year (OTOP, 2014). It should be noted that this land is a national park owned by the government and OTOP does not pay any rent or fees for use of the land. While this conservation project can pay its operational costs through biomass harvest, it would not likely be economically viable if it also had to pay land rent.

The OTOP project represents a win-win for low-carbon biomass production and environmental conservation. In this case, harvesting biomass for energy or other uses actively improves sustainability of a fragile ecosystem for a threatened species. Utilizing the land for paludiculture could potentially protect the peatland from being drained for other uses, although as this area is part of a national park there may not be much of a risk of intentional degradation.

This case study brings attention to one of the main challenges in paludiculture: economic viability. A bioenergy company would not make a profit conducting a similar project on private land that could be used for something else. Net revenues of this project would be much greater if a higher-yielding crop such as common reed were grown, but this would reduce the conservation value of the project because dense reeds do not provide suitable habitat for the aquatic warbler or other wildlife species that require low vegetation or specific plants.

Belarus

The Belarus Project was a large effort restoring 10 sites across Belarus from 2008–2011 that largely had previously been drained for agricultural use and were abandoned. The effort was led by an international consortium of environmental organizations from the UK, Belarus, and Germany and includes the Royal Society for the Protection of Birds (RSPB), Akhova Ptushak Batskaushchyny (APB), BirdLife Belarus, and The Michael Succow Foundation (MSF) (Anzaldua and Gerdes, 2011).

The main motivation of the project was reduction in greenhouse gas emissions. The project aimed to rewet 14,000 hectares of degraded peatland, and as of mid-2011, 9,000 hectares had been successfully restored. The project estimated a GHG sequestration benefit of 2.9 tonnes CO_2e ha^{-1} yr^{-1}.[27] Other environmental benefits include habitat restoration, micro-climate regulation, soil degradation prevention, water regulation and retention, and peat fire prevention. Some bird species appeared post-restoration that had not been seen at these sites before, including the blue throat, water rail and spotted crake (Anzaldua and Gerdes, 2011).

The project was connected with an effort to create a methodology for rewarding peat reduction projects with carbon credits. Overall, the project expended €433,000 in one-off administrative and ecosystem restoration costs, with recurrent costs of €235,000. On a GHG basis, costs were estimated at €7.11 per tonne CO_2e but were expected to decline over time. Economic benefits to the region included food production in the restored

26 It is likely that pellets used for pet bedding would need to be of higher quality than pellets used for energy.

27 It was not clear from the documentation whether the -2.9 $tCO_2e/ha/yr$ is the net carbon balance of the rewetted peatland or the net GHG benefit compared to the baseline of drained peat emissions, or whether it accounts for the spike in post-wetting methane emissions.

ecosystem (cranberries, blueberries, mushrooms and fish) and peat fire prevention (Anzaldua and Gerdes, 2011).

At one of these Belarus Project sites in Sporavia in Southern Belarus, a pilot project (the Wetland Energy Project) was started on 500 hectares in 2012 to harvest biomass for energy. The aim of this project is to replace peat briquettes, commonly burned for energy in Belarus, with biomass briquettes. The pilot has harvested plants growing naturally at the site, including common reed, reed canary grass, and sedges (Wichtmann et al., 2012). Some of the sites in this pilot were rewetted in 2007 (Wetland Energy Project Newsletter, 2013). A spring harvest in 2014 yielded 3.7-11.4 dry tonnes of biomass per hectare per year, and the material was found to have good composition for combustion (Wichtmann et al., 2014). In 2015, biomass was harvested using a lightweight harvester with low-pressure balloon tires (Wetland Energy Project Newsletter, 2015a), and was then processed in a mobile briquetting module of a briquetting factory, built specifically to process fen biomass (Wetland Energy Project Newsletter, 2015b). One analysis showed that combusting briquettes that are 50% fen biomass and 50% peat through this project can generate a GHG reduction benefit worth €814,500 per year in the EU ETS compared with combusting 100% peat briquettes (Bogodiash, 2015, as cited in Wetland Energy Project Newsletter, 2015b). Eventually, the project is expected to harvest 2,500 tonnes of biomass annually (UNDP, 2013). An additional benefit of the biomass project, similarly to the OTOP project in Poland, was to maintain low, open vegetation for wildlife, including the aquatic warbler and greater spotted eagle (Wichtmann et al., 2012).

CHALLENGES FOR PALUDICULTURE

While paludiculture can deliver high environmental benefits, it may be less economically viable than other types of energy crops due to lower yields and difficulty managing and harvesting biomass in wet soils.

Harvesting

Traditionally, wet hayfields were harvested by hand using scythes. This technique is now too expensive due to the high labor costs. Conventional harvesting equipment cannot be operated on peat without creating ruts and damaging the soil surface and vegetation.

The harvester used by the Wetland Energy Project in Belarus (described above) is a lightweight conventional harvester with low-pressure balloon tires that reduces damage to the ground surface. However, use of this machinery is limited: the centers of rewetted plots were not accessible, and only the edges of the plots with firmer ground could be harvested (Wetland Energy Project Newsletter, 2015a).

Another solution is to use the “ratraks” deployed by the OTOP Poland project, repurposed snow grooming machines that run on caterpillar tracks (Figure 19; Dubowski et al. 2014). Harvesting blades can be attached to the front to cut biomass.[28] Similarly to the balloon tires in the Wetland Energy Project, the weight of the machine is spread over a high surface area, reducing the pressure on the ground compared to wheeled vehicles.

28 A video of a ratrak harvesting biomass can be seen at: https://www.youtube.com/watch?v=qxEvkOjpAdE

Figure 19. A "ratrak," which is a snow grooming machine that can be used to harvest biomass in paludiculture with less damage to the soil than conventional harvesters. Photograph by Picswiss.

While ratraks are a major improvement over wheeled harvesters for paludiculture, they still cause some damage to vegetation and the peat surface, especially when turning. Their use is also somewhat limited in summer months. Because they are designed for use in cold temperatures, they can overheat in summer weather. They cannot tolerate more than a little water on the ground, and so some paludiculture areas may be inaccessible (Dubowski et al. 2014). Ratraks operate best on a frozen surface and so can be used on peatlands in the winter, but at these times the biomass may be mostly buried under the snow surface and not harvestable. Because these are secondhand machines that may be starting to deteriorate, there is an increased risk of spilling oil from broken hoses (Dubowski et al. 2014).

Dubowski et al. (2014) have piloted other harvesting solutions, the most promising of which may be hovercraft. This research group's second prototype exerts one-third the pressure as a ratrak, and so results in much less damage to the ground surface. Another advantage of hovercraft is that they can very easily travel over lakes and peatlands with high standing water levels. Dubowski et al. are working on a third prototype with more power to achieve greater clearance in order to avoid damaging tussocks that rise above the ground. One issue that is not addressed in this paper is whether hovercraft can be cost-effective for commercial paludiculture.

Economic viability

Even without using hovercraft, there are still questions about the economic viability of paludiculture projects. As discussed above, an analysis of the aquatic warbler project in Poland showed that revenues barely exceeded costs when there was no rent or opportunity cost of the land. In this specific case, because the project was prioritizing conservation value it was harvesting low-growing vegetation with low yields—the project could potentially be more profitable if a high yielding crop such as common reed were grown.

Another study (Kuhlman et al., 2013) investigated the economic viability of growing common reed in the Netherlands for use in combustion, ethanol, or biogas production. All three pathways were determined to lead to a net financial loss, with the smallest lost for combustion. For combustion, the value of energy production was estimated at €475 ha^{-1} yr^{-1} in 2010 and €772 ha^{-1} yr^{-1} in 2030, assuming increasing energy prices over time, compared to costs of €1285 ha^{-1} yr^{-1}. If value is given for environmental services including GHG reduction, water buffering, and water purification, there could be a positive net value to reed production. It is not clear whether land rents are taken into account in this analysis. This study shows that, at least in the Netherlands, paludiculture may require strong policy support to be viable.

It is clear that in some cases, such as the aquatic warbler project in Poland, paludiculture can be economically viable on unused land that does not carry an opportunity cost. This could potentially be true for privately held unused peatlands as well as those that are government-owned; a private landowner may potentially find it more profitable to harvest biomass on an unused wet peatland rather than not. However, where active restoration is needed for drained and degraded peatlands, biomass harvesting may not cover these up-front costs. When drained peatland is used for productive purposes such as growing food crops, rewetting for biomass production will almost certainly not be financially preferable. In all of these cases, policy support for GHG reduction and other environmental services would make paludiculture much more viable.

CONCLUSIONS

This study investigated the environmental impacts of energy cropping through case studies on pilot projects in Sardinia and Macedonia and through literature review, both on the topic in general and specifically on paludiculture.

There is reason to believe that energy crops could potentially deliver environmental benefits when grown on previously disturbed, abandoned agricultural land. While there are few studies in the literature comparing biodiversity and carbon stocks in energy crop plantations to marginal land (land that was previously disturbed for agriculture or industry but has now been abandoned due to low productivity and that has low biodiversity and low carbon stocks), it is clear that perennial energy crops can improve agricultural land previously used for annual row crops and may offer similar environmental benefits when compared to some existing unmanaged grassland. The literature suggests that growing perennial energy crops may rehabilitate agricultural land faster than simple abandonment. Perennial grasses, including switchgrass, giant reed, and Miscanthus, may be successfully grown on semi-arid marginal land without irrigation, while poplar and willow likely require wetter environments. Data on annual energy crops such as biomass sorghum is scarcer, but they may be sustainably cultivable in many areas. The typical environmental effects of these different categories of energy crops grown on marginal land are summarized in Table 1.

Table 7. Summary of environmental effects of energy crops from literature review

Environmental effect on marginal land	Perennial grasses	Woody crops	Annual energy crops
Biodiversity	Potentially higher	Potentially higher	No evidence
Biomass productivity	Likely higher	Likely higher	Likely higher
Biomass stocks	Potentially higher	Likely higher	Not clear
Soil carbon	Not clear	Not clear	Not clear
Water requirements (are crops viable in dry regions)	Potentially yes	Likely no	Maybe

To investigate how energy crops grown on marginal land affect the environment in practice, we conducted on the ground observations and environmental measurements at two energy crop projects currently under development by the European biofuels industry.

We visited three sites in the Carbonia region of Sardinia, Italy, where Biochemtex is conducting trials of *Arundo donax* (giant reed) on underutilized agricultural land. Following the collapse of the sugar beet industry in Italy a decade ago, this region has large areas of semi-arid, low-productivity abandoned agricultural land with very little biomass stock and biodiversity. *A. donax* is invasive in Sardinia, but has already colonized most waterways on the island. There are still some sensitive areas of the island where *A. donax* has not yet been introduced, and it will be important for the project to prevent spread to these areas. The project plans to implement mown buffer strips along fields to prevent spread. In addition to planting fields with *A. donax*, the project would harvest existing stands from riversides. If done appropriately, this harvesting could aid management of the invasive species. The project developers are committed to follow environmental laws and guidelines to minimize erosion and disturbance to natural vegetation and wildlife while harvesting. The region is largely classified as having low ecological importance, and in a cursory biodiversity assessment we saw only common birds and agricultural weeds in the areas surrounding the energy crop fields. Based on this assessment we did not identify any major biodiversity concerns related to cultivation of *A. donax* in this area, but additional surveys would be necessary to confirm this result. It was clear that *A. donax* produced far higher biomass stocks than the surrounding landscape. It was not possible to clearly identify the impact of *A. donax* cultivation on soil carbon stocks. Observed soil carbon levels were mixed across sites, sometimes higher in the samples planted with *A. donax* than in comparison samples, but sometimes lower, echoing findings in the literature. It is considered unlikely that soil carbon change associated with *A. donax* establishment would be a major contributor to the lifecycle carbon footprint of *A. donax* cultivation on this type of site, either positively or negatively. These trials grew *A. donax* at different levels of irrigation and found that yields were only commercially viable when well irrigated. Because agricultural production has declined so much in this region, it appears that in most years, ample water is available to irrigate the planned 5,500 hectares of *A. donax* if this project reaches full scale, without impacting other uses. The project plans to halt irrigation to *A. donax* fields in years of water shortage through centralized irrigation control through water holding companies. 500 hectares of the planned project would remediate industrial land contaminated with heavy metals that is currently unfit for other crops. While there is some risk that *A. donax* could displace food crops in Sardinia, it is unlikely to happen on a large scale because the biomass would not be worth as much as most of the food crops currently grown on the best land. Overall, we conclude that the Biochemtex project has the potential to deliver some environmental benefits including increased biomass stocks, invasive species management and soil remediation, while posing little risk to soil carbon stocks, water use, or displacement of other crops, and with no major risk to biodiversity identified at this time. The extent to which these benefits will be realized in practice will depend on how a full-scale project is implemented.

The second case study we examined is in the Pelagonia region of Macedonia. Here, Ethanol Europe is collaborating with DuPont and NexSteppe to test biomass sorghum and switchgrass on two types of land: (1) agricultural land near the cities of Bitola and Prilep that is actively used to produce cereals, tobacco, and a variety of fruits and vegetables, and (2) arid, abandoned agricultural land in the dry Mariovo region to the east of the cities. The project plan includes replacing the short summer fallow period of winter wheat with biomass sorghum on 5,000 hectares in the active agricultural areas supported by available irrigation infrastructure, and to grow more drought-tolerant switchgrass on 10,000–15,000 hectares in Mariovo. During our site visit, we witnessed challenges in project implementation in this first year of trials. It was not clear that biomass sorghum was planted on land that would otherwise be fallow on the agricultural land near the cities, and the situation of some plots suggested the energy crop may be displacing food. It should be noted, however, that this year represented a small-scale initial trial, and it is not clear whether the type of food displacement potentially observed this year would be avoided for the project in the longer-term. The project leaders have stated their commitment to avoiding displacement of food production if the associated facility becomes operational, which could be possible if energy crop production is constrained to the dry Mariovo region and to land that had been fallow in prior summers. Both sorghum and switchgrass were grown in Mariovo, and the sorghum in particular did not appear to produce viable yields. Delays in spring planting of the crops in both areas may have contributed to poor yields in this first year. Biodiversity and biomass stocks appeared to be very low in the Mariovo region based on a cursory assessment, and so it is possible that switchgrass grown here could deliver environmental benefits or at least pose low risk of environmental harm, and would not likely affect other uses of the land. The Macedonian trials are at an earlier stage of development than the Sardinian case, and it was apparent that the project has experienced challenges in coordination and planning in its first year. There seem to be real opportunities for both the use of abandoned land and for the introduction of double cropping, but it is not yet possible to be confident that commercial yields can be achieved without environmental impact or displacing food production.

Through literature review we also investigated a rather different type of energy crop system that could potentially deliver high environmental benefits. "Paludiculture," the wet cultivation of peatlands, could be used to produce biomass for energy while actively rehabilitating degraded peatlands in Europe, sequestering soil carbon and supporting native plant and animal species. In particular, if paludiculture encourages rewetting of degraded soils that had previously been drained for agriculture, it can reverse ongoing carbon loss from the soils and return the land over time to being to a net carbon sink. We describe two projects where paludiculture is being actively pursued as an environmental conservation strategy. In the Biebrza Valley of Poland, the Polish Society for the Protection of Birds (OTOP) has restored large areas of an abandoned fen. The project mows the natural vegetation annually to prevent overgrowth of shrubs and trees in order to preserve the area as suitable habitat for the threatened aquatic warbler. The biomass is delivered to a pelleting facility, after which it may be used for energy purposes. Another project in Belarus organized by an international consortium of environmental organizations is rewetting and restoring degraded sites formerly used for peat extraction. The natural growing plants are harvested and processed into briquettes, which can be used to displace mined peat for energy. Paludiculture is still in the early stages of adoption, and challenges remain for more sustainable harvesting technologies and economic viability of project—but in cases where there is an economic case for biomass production, paludiculture could deliver a win-win-win for climate mitigation, wildlife conservation, and renewable energy.

Through on-the-ground verification, this report supports much of what is shown in the literature—that there is a real potential to cultivate energy crops sustainably with little environmental risk, and in some cases while delivering substantial direct environmental benefits other than renewable energy production. At the same time, we highlight challenges in the implementation of energy crop projects and hurdles that must be overcome before sustainability can be assured, particularly the difficulty in managing impacts from energy crop production on other agricultural output, and in preventing overuse of water resources.

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