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Assessing the Ecological Impacts of Bioenergy Projects

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Abstract One of the major objectives of the current expansion in bioenergy cropping is to reduce global greenhouse gas emissions for environmental benefit. The cultivation of bioenergy and biofuel crops also affects biodiversity more directly, both positively and negatively. Ecological impact assessment methods for bioenergy projects (including changes to policy and land use) should address not simply changes to species abundance at field level, but include larger scale issues, including changes to landscape diversity, potential impacts to primary and secondary habitats and potential impacts on climate change. Such assessments require a correspondingly broad range of scientific methods, including modelling of climate and land use as well as the observation of biodiversity and landscape indicators. It is also possible to adopt evidence-based guidelines for good practice for situations where comprehensive assessments are not available. These might include favouring projects and policies that avoid gene flow to wild relatives of crops in centres of diversity, that do not result in invasion by the crop into other habitats, that enhance field-scale biodiversity, that increase landscape diversity, that do not threaten valued habitats within the local landscape, that promote the sustainable management of biodiverse habitats, that do not increase the risk of loss of primary habitats and that result in a proportionately large reduction in greenhouse gas emissions.

Keywords Biofuel · Biodiversity · Environmental risk assessment · Land use change · Land use conflict

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Introduction

One of the factors driving the current interest in bioenergy cropping is the potential environmental benefit through the reduction in greenhouse gas emissions [57]. However, any major changes in land use have the potential to impact other aspects of the environment. It is clear that intensive agriculture and forestry have undermined the delivery of ecosystem services in many parts of the world as a result of impacts on biodiversity [43]. It is also clear that biodiversity is also under threat from global environmental change [63]. Bioenergy cropping therefore has the potential to benefit biodiversity by mitigating against climate change. However, it is important to consider the potential impacts on biodiversity as a result of changes in land use and management [38]. The purpose of this paper is to consider the issues that need to be addressed when assessing the impacts of bioenergy crops on biodiversity, and the methodologies that are available. The paper also considers potential guidelines for good practice for bioenergy cropping in the absence of a complete assessment.

For an ecological impact assessment, the processes that relate the proposed changes to effects on biodiversity need to be each understood as a function of some form of hazard or potential benefit and the probability of its occurrence. The hazard or benefit arises from a change in a pressure (using terminology from the OECD driver–pressure–state–impact–response model for managing environmental change [44]) that directly impacts one or more components of the environment. Such impacts are observed through changes to measurable indicators.

An important precedent for assessing potential impacts of new cropping patterns on biodiversity is the process of environmental risk assessment of genetically modified (GM) crops. Early risk assessments considered the potential

for environmental harm arising from the crop plants themselves. The introduction of the new varieties constituted the pressure that could cause ecological impacts by being toxic to non-target organisms and by affecting the gene pools of wild relatives. While these potential hazards could be explored in the laboratory, the probability of the hazard materializing required field work of considerable scale [56, 71]. These assessments did not address the indirect effects arising from how the crop plants are managed, notably the pressures of new combinations of pesticides and herbicides associated with the crops and their impacts on arable plants, invertebrates and birds [39]. New experiments were devised to estimate these effects through comparison of biodiversity indicators for GM and non-GM cropping systems [18]. While it proved possible to establish the extent of differences between these two systems at field level [5, 17, 29, 31], these differences were not constant; they could be mitigated by changes to crop management [11] and were sensitive to the scale of cropping at the landscape level [15]. Moreover, because the differences observed between GM and non-GM cropping were smaller than those found between crop species [5, 17, 29, 31], it was not clear that the effects of GM cropping were any greater than those involved with other changes in agricultural land management [15].

There are important aspects of the design of risk assessments of GM crops that are inappropriate for those of most introductions of bioenergy crops. The risk assessments assumed that GM crops might replace conventional varieties of the same species, rather than change cropping patterns substantially. This assumption might have been reasonable for the case of GM crops, and may be valid for varieties of existing arable crops being planted for biofuel. But it does not hold for plantings of bioenergy crops such as willow (*Salix* spp.), poplar (*Populus* spp.) and Miscanthus (*Miscanthus* spp.), especially if they replace very different land covers such as grassland or annual row crops. Ecological risk assessments of GM crops are triggered by how the crop has been bred, rather than how it will be used, while for bioenergy crops the effects of cultivation practices, choice of areas and crop species are likely to have bigger environmental impacts than the methods of plant breeding [15]. Risk assessments for GM crops in Europe adopt the position that effects on biodiversity should be no less than the comparable conventional crop [14], but this position is more complex to evaluate for bioenergy crops as they are expected to have a broader environmental benefit as well as local impacts.

A broader understanding is required that addresses potential impacts on biodiversity of bioenergy (and, by implication, biorefinery) projects that impact on land use and land management. These projects might be new varieties, new policies or new commercial opportunities.

They could be at a very local scale, such as a proposal to plan bioenergy crops near a nature reserve, or to manage a local forest for harvesting biomass. They could be technological, for example the development of genetically modified varieties of bioenergy crop plants, or they could be policy related, whether aimed at national energy security or the global control of greenhouse gas emissions. A framework is needed that addresses potential positive and negative impacts on different taxa at differing spatial and temporal scales, recognising that there might be acceptable trade-offs between localised risks and benefits to biodiversity compared to larger scale, longer-term impacts. It is helpful to separate impacts at the global, regional, landscape and crop scale, not because they are independent [19], but at least this distinction helps isolate particular processes and how they might be assessed.

This paper discusses the ecological impacts that should be considered when constructing risk assessments for bioenergy projects that involve changes in land use and management, noting the key questions to be addressed and the methodologies available.

Field Scale

Pressures

The lowest level change at field level in a bioenergy project is that the use of the crop is changed, but not the crop itself, e.g. using grass for bioenergy production instead of grazing [66]. The next level is that of swapping varieties of the same species, as may happen with arable biofuel crops and tree plantations. It is also likely that the new varieties will involve different levels of fertiliser and pesticide inputs, analogous to changes in pesticide regimes associated with GM crops.

It is also likely that the crop species itself is changed. This can be more than swapping one arable species to another, and may involve substantial changes to the growth form, phenology and disturbance regime, as happens by the replacement of grassland, conservation reserve or annual row crops with biomass crops.

Impacts

The impacts on biodiversity at the field level include the potential for gene transfer to wild relatives. This potential is considered an important risk to biodiversity should the new crop be genetically modified [37, 49], and especially if the crops are located in an area of genetic diversity [15]. There is the potential for direct effects on those taxa that rely on the crop plant, directly or indirectly.

A simple switch between varieties of the same species can influence the species in and around the crop [12],

especially if the switch is also associated with changes to crop management [15]. The effects tend to be of a similar order to other changes in agricultural practice [15].

Changes to the gross growth form and phenology of the crop are likely to result in much greater effects on more species. Their cultivation is likely to eliminate niches for some species, but open up other niches for others; not simply modifying the existing ecology, but introducing a new suite of species. This would happen, for example, when grassland is transformed into forestry. The issue then is not simply the loss of the grassland habitat and the biodiversity associated with it, but also the gain of a new forest habitat, and its *potential* quality compared with other secondary woodlands.

The key questions to be asked as part of an assessment are, therefore,

- What is the potential for gene flow to wild relatives?
- If the new crop does not involve a major change in growth form from existing land use, what is the potential for direct and indirect impacts on the species associated with it?
- If the new crop involves a major change in growth form, what is the potential biodiversity compared to (a) the existing land use and (b) existing habitats of similar structure to the new crop?

Methodologies

The methods used to answer these questions all involve the choice of indicators, selected by considering the process by which the pressure may have an effect. While methods of assessing gene flow are well established, the question of how much gene flow is acceptable in ecological terms is more contentious [3, 49]. Likewise, methods of establishing both hazard of toxicity effects on non-target organisms and the likelihood of such hazards being realised are well understood [56].

The UK Farm Scale Evaluations of GM crops established a robust method for assessing risks to biodiversity resulting from changing one cropping system to another [18]. It involved establishing a set of indicator species that were monitored in a randomised block experiment in which the two treatments corresponded to GM and non GM cropping systems of the same crop species—i.e. GM maize was compared with conventional maize. The experiment was designed to test the null hypothesis of no difference between indicator levels between treatments [46]. The observed effects were extrapolated to longer time scales [30] and to other taxa [23].

This null hypothesis is appropriate for designing experiments when the differences between the two systems are small, but is not appropriate when the change involves the

transformation of habitats. This is because most biodiversity indicators will be associated with one or the other habitat (e.g. grassland vs forest). Moreover, the species composition during the early years of such a transformation may not reflect that to be found once the habitats are mature. A more appropriate approach would be to consider the ecological quality of the present and proposed land uses compared with similar habitats. Thus the loss of a species-poor, intensive grassland would be more acceptable than that of a species-rich meadow, especially if the new habitat is to be managed in ways that enhance its biodiversity potential. The quality of existing habitats can be tested on the ground [58] or using existing conservation databases and designations. While the potential for biodiversity of new habitats is best determined on the basis of experimental evidence, models are appearing that forecast the potential species occupancy on the basis of the niches that will become available [9, 48].

Landscape Scale

Pressure

Transitions between annual crops, grazing land, biomass grasses, coppice and forest involve the creation and destruction of habitats. The implications of such changes are not simply restricted to the land parcels themselves, but to the biodiversity of the whole landscape. This is due to the importance on the spatial structure and turnover of habitats within a landscape to many species [19].

The first pressure is that of changing the use of different parcels of land. The issues involved from changing from one crop type to another are noted above, but it is also possible that land is brought into cropping from other uses, including semi-natural or even primary habitats. Such changes will affect the diversity of land use within a landscape, making it more uniform in the case of large scale plantings or more diverse in the case of small parcels of biomass crops. A second pressure is to change the structure of the landscape itself, for example by dividing or aggregating existing land parcels into smaller or larger units, and by creating or destroying non-cropped features in the landscape such as hedgerows or buffer areas. Bioenergy cropping may impose a third pressure, by changing the rate of turnover of habitats, for example as new rotations are introduced to coppice or arable cropping.

Impacts

The biodiversity of a landscape is closely related to the quality of individual habitats, the diversity of habitats, their turnover and the spatial relationships among them. In agricultural

landscapes, habitat quality is often a function of the history of land management, with the most biodiverse habitats being those that have had continuity of less intensive practices [35]. At the landscape scale, it is generally true that the greater the diversity of habitats, the greater the diversity of species [4, 19], though habitats managed traditionally at large scales, such as steppe, have their own assemblages of high conservation value. This diversity is increased when the spatial structure of the landscape facilitates dispersal of organisms between habitat patches [28], which is why the biodiversity of farming systems is dependent upon the landscape character as well as on the management of the individual parcels of land [22, 34, 70].

A major negative potential impact on biodiversity is the loss of a high-quality habitat, either by its replacement by a bioenergy crop or by large changes in its management (e.g. increased extraction of woodfuel from woodland). A second negative impact would arise should the introduced crop species prove invasive, especially likely in the cases of grasses including giant reed (*Arundo donax*) and, potentially, *Miscanthus* [50]. The risk of invasiveness needs to be addressed when considering the location of the crops in the landscape. For example, there are potential benefits in planting bioenergy crops adjacent to high quality habitats, so that they act as buffers for control of water quality and/or microclimate. However, this would be inappropriate for the giant reed, as it is known to invade riparian habitats [50].

The greatest potential benefit at the landscape scale is from the creation of new habitats by planting bioenergy crops, especially woodland and short rotation coppice. While the new crop will gain a new suite of species, there are time lags as the crops themselves grow and mature, and as species immigrate into the new habitats or become locally extinct. These time lags vary among species, and depend on their presence in the vicinity [59], which in turn depends upon the landscape structure and its past management [59]. They may be surprisingly long. For example the distribution of a carabid beetle in an agricultural landscape in 1993 was actually better correlated with the distribution of its hedgerow habitat in 1952 than the contemporary pattern [47], while the plant species diversity in a Swedish agricultural landscape is best explained by land use patterns 200 years ago [27].

Another potential impact is through the removal or addition of linear habitat features and small areas of semi-natural habitats, such as lines of trees, hedgerows, water-edge and ponds, with consequent losses of habitat and potential corridors for species dispersion [8, 13]. Again, there is the potential to use bioenergy crops as buffer zones to reduce soil losses or diffuse pollution into watercourses [1], whilst creating habitat for some species.

While habitat turnover can reduce the abundance of many species that have poor dispersal abilities, it is required

for the persistence of some early-succession plant and animal assemblages. This is particularly true for the forest floor flora that became associated with woodland coppice in north-west Europe. Willow and poplar coppice for bioenergy can be beneficial for these species, but only if the new rotations are in phase with the dispersal, life cycle and dormancy patterns of the species involved [10].

The key questions to be asked as part of an assessment are, therefore,

- Does the proposal threaten, or buffer, existing high quality habitats in the landscape?
- Does the proposal affect landscape diversity, structure and turnover?
- Is the crop likely to prove invasive in its new environment?
- Is there potential for species losses or gains through landscape modification?

Methodology

Any change at the landscape will affect some species positively, and others negatively. It is therefore important to identify the priorities for biodiversity conservation, and how their needs may be met should the landscape change. These priorities are likely to focus on either individual species or habitats, or a more generalised desire to increase diversity. The issue of individual species or habitats arises when their presence in the landscape is already known, their conservation importance already established, and any management criteria understood. Potential proposals should be challenged against these criteria, and methods sought that improve the viability of the species of habitats by, for example, acting as buffer zones for microclimate or water quality control, or by creating potential networks for species dispersal.

The ideal methodologies for assessing potential impacts of new developments for a broader range of taxa involve the use of baseline data on both landscape and biodiversity, as well as the means for assessing the potential impacts of changing the landscape. There are many approaches to landscape and biodiversity inventory and monitoring [16, 25, 36, 51]: in general, landscapes can be monitored using remote sensing, but species assessments need to be made on the ground. Models are becoming available to help forecast impacts of changes on higher plants, invertebrates, birds and mammals. It is possible to evaluate the viability of landscapes for multiple taxa according to the area and configuration of habitats they require [6, 62]; it is also possible to model the biodiversity of a potential landscape through the niches that are available to different species [9] or by using agent-based simulations of the dynamics of different species in a landscape [67]. These are all promising

techniques, but some are data intensive and none have been validated for bioenergy cropping. Fortunately, the general principles of what makes a biodiverse agricultural or forest landscape are well understood, and evidence-based strategies for managing landscape change are available [20]. These include maintaining large patches of native/uncropped vegetation with corridors and stepping stones between them, and buffers around them; maintaining appropriate disturbance regimes, maintaining species of particular concern and key species interactions, and controlling aggressive and invasive species [21].

Regional Scale

One of the concerns about changes to bioenergy policy is the potential to disrupt distant ecosystems by driving production elsewhere at the expense of primary forests and the species within them [45]. Bioenergy cropping is already competing with food production [7], and will in turn influencing global patterns of agriculture and pressures on biodiversity [65]. There may be changes to the intensity of land management. While these may have negative impacts locally on biodiversity at the landscape scale, they may be offset by reducing pressure on further habitat loss [26]; but see [40].

Impacts

The major potential negative impact of bioenergy policies and large scale programmes is that they will have the effect of increasing pressure on the degradation and loss of more remote habitats and landscapes. Yet this need not happen, especially if they are designed to use land that is no longer biodiverse, but is marginal, recently abandoned or degraded. Indeed, there is the potential for large scale land restoration using bioenergy crops.

The key questions to be asked as part of an assessment are, therefore,

- What is the risk of loss of primary habitat, direct or indirect?
- What is the risk of loss of secondary (non-agricultural) habitat, and potential consequences of that loss?
- Will new habitats be created, and what might be the local and regional benefits to biodiversity?

Methodology

Analysis at this scale is perhaps most appropriate for the analyses of policy changes. Formal methods involve modelling land use change in response to different economic/policy scenarios, often by allocating pixels of land to different uses.

Such scenarios can have a short-term focus [68] or can be more forward looking and sensitive to higher-order political processes [43, 52]. They are useful for showing broad patterns of potential land use change, rather than for identifying particular threats to particular habitats.

Global Scale

At the global scale, the major impact of bioenergy programmes is to reduce net greenhouse gas emissions, with consequently better control of global climate change and benefits to biodiversity [42, 61, 63]. Therefore the potential global benefits depend upon a whole life cycle assessment of carbon balance and implications for other greenhouse gases, and how they differ between crop type, production and distribution systems. The key question is, therefore,

- To what extent will the project reduce the net production of greenhouse gases, and what impact will this reduction have on scenarios for future climate change?

Bioenergy projects are being evaluated for their potential to mitigate climate change at a range of scales [2, 24, 32]. It is beyond the scope of this paper to explore the issues involved in estimating the potential impact of new developments on greenhouse gas emissions and hence on climate-related risks to biodiversity, but it is worth noting the large uncertainties involved, not least in terms of specifying the system to be included. It is also worth noting that the global emissions of greenhouse gases from the loss of natural forests exceeds that of the transport sector, and that curbing deforestation is a “highly cost-effective way to reduce emissions” [61], implying that direct and indirect effects of bioenergy projects on rates of habitat loss need to be taken into account in greenhouse gas budgeting. The potential release of carbon from soils disturbed for the planting of bioenergy crops also needs to be considered.

Towards Good Ecological Practice for Bioenergy Projects

The ecological implications of any bioenergy development are indeed complex. This is because the impacts vary between scales, in that the conversion of large areas of land to monocultures of bioenergy crops may have locally damaging consequences, but could contribute to the global reduction of greenhouse gas production. The impacts vary among taxa, so, for example, the conversion of grassland to woodland coppice would favour species associated with open woodland habitats at the expense of those that favour more open habitats. There are substantial uncertainties in

these potential impacts, and strong dependencies on the management of the bioenergy projects across their whole life cycle. And, finally, there are other goals for bioenergy production than the conservation of biodiversity, including energy security and rural development.

A complete assessment therefore involves the balancing of goals across a wide variety of stakeholders, to an even greater extent than has been the case for GM crops. Some of the engagement processes used in the GM crop debate [33, 53] offer useful models, but many others are available [69, 72]. Clearly, complete assessments will prove complex and time consuming. Given that these will be most needed when there are clear conflicts of interest to be resolved, it is better to avoid these conflicts in the first place. This can be done by adopting simple guidelines, drawing upon the existing rich evidence base of interactions between land use and biodiversity. Projects could be favoured that:

- *Avoid gene flow to wild relatives in centres of diversity*

The greatest ecological risk of gene flow from crops to wild relatives is that it may reduce the genetic diversity at centres of origin and diversity [15].

- *Do not result in invasion by the crop into other habitats*

The risk of invasiveness results from a combination of the characteristics of the plant itself, that can be increased or decreased a result of breeding programmes [50], and of its receiving environment.

- *Are biodiversity in their own right*

Many biomass cropping programmes can be developed using local varieties of a wide range of species, and so maintaining genetic diversity. It may prove viable to create and manage biodiverse grasslands and woodlands for bioenergy [66].

- *Enhance field-scale biodiversity compared with local habitats of equivalent growth forms, taking establishment time into account*

It is possible to create habitats and food resources for biodiversity within bioenergy crops. Arable crops can be managed with areas in and around them to provide habitats and food [41, 60, 64], while perennial crops can be managed with varieties, rotations and planting densities that create niches for ground flora and fauna and nesting birds [12, 54, 55].

- *Increase landscape diversity*

In the majority of agricultural landscapes, increasing the diversity of land cover types and the levels of connecting features increases biodiversity through availability of multiple habitats and the facilitation of dispersion among them [20].

- *Do not threaten valued habitats and species within the local landscape*

Conservation concerns are often focused on individual species or habitats at the landscape scale. New projects

should not replace these habitats, nor threaten them indirectly (e.g. by changing the local hydrology).

- *Promote the sustainable management of biodiverse habitats*

It may prove possible to manage some habitats for biomass removal, increasing their long term economic value and hence sustainability, or to use bioenergy crops to provide buffers around existing nature reserves.

- *Do not increase risk of loss of primary habitats*

This risk is most relevant to changes in policies and trading regimes, and includes indirect risks, such as through changes to food markets.

- *Result in a proportionately large reduction in greenhouse gas emissions*

A whole life cycle approach is needed that takes into account not simply the carbon balance for the crop itself but also potential carbon losses due to land clearance and soil disturbance.

In general, the best way to integrate bioenergy requirements with the conservation of biodiversity is to minimise the conflicts over land use. This will prove easiest for bioenergy projects that take advantage of land that has been used for agriculture, but is currently degraded or recently abandoned. Such land is unlikely to be rich in biodiversity, and its conversion is unlikely to increase pressure for habitat loss elsewhere.

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