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NOTICE: This is the accepted version of the following article: Journal of Applied Ecology, 2016, 53, 1422–1429. doi:10.1111/1365-2664.12683, which has been published in final form at http://dx.doi.org/10.1111/1365-2664.12683

What does Life Cycle Assessment of agricultural products need for more meaningful inclusion of biodiversity?

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Short running title: Towards a meaningful biodiversity inclusion in LCA

Word count. Manuscript as a whole: 5710. Abstract: 150. Main text: 3165. References: 1446. Tables and Figure legends: 159.

Number of cited references: 49

Number of Figures and Tables: 2 figures and 1 table

Abstract

1. Decision makers increasingly use Life Cycle Assessment (LCA) as a tool to measure the environmental sustainability of products. LCA is of particular importance in globalized agricultural supply chains, which have environmental effects in multiple and spatially dispersed locations.
2. Incorporation of impacts on biodiversity that arise from agricultural production systems is an emerging area of work in LCA, and current approaches have limitations, including the need for: (i) improved assessment of impacts to biodiversity associated with agricultural production; (ii) inclusion of new biodiversity indicators (e.g. conservation value, functional diversity, ecosystem services); (iii) inclusion of previously unaccounted modelling variables that go beyond land use impacts (e.g. climate change, water and soil quality).
3. *Synthesis and applications.* Ecological models and understanding can contribute to address these limitations and to develop more ecologically-relevant LCA approaches. This will be necessary to ensure that biodiversity is not neglected in decision-making that relies on LCA.

Keywords: environmental impact, sustainable agriculture, livestock, food products, policy, supply chain, off-farm impact

1. Introduction

Agricultural production is one of the most pervasive drivers behind a number of global pressures on the environment. For instance, it contributes to about a quarter of global greenhouse gas emissions (IPCC 2013) and has directly modified natural habitats in approximately 38% of the Earth's terrestrial surface (Foley *et al.* 2011). The conversion of natural ecosystems into crops and pastures has been accompanied by an increased rate of species extinction, drops in genetic and species diversity and degradation of ecosystem services (MEA 2005, Steffen *et al.* 2015). Unless agricultural production methods change, environmental impacts will most likely worsen due to increasing global food demand resulting from a growing human population and changing patterns of food consumption (Alexandratos & Bruinsma 2012). As a consequence, agriculture currently occupies centre stage in the debate on sustainable production and consumption.

Among the range of environmental assessment methods, Life Cycle Assessment (LCA) is increasingly used for decision making by food companies and policymakers (Guinée & Heijungs 2011). LCA is an approach to quantify multiple potential environmental impacts (e.g. climate change, eutrophication) along the supply and consumption chain. It originates from the manufacturing industry where it initially (in the 1950s-1960s) responded to the need for budget management over increasingly complex and globalized production processes (Curran 2012). When environmental impacts became major social and policy concerns, LCA was first applied to the accounting of resource and energy efficiency, pollution or waste disposal and today it has developed into a standardized method providing sound scientific information on environmental sustainability. LCA occupies a central role in the current development of the European Union policy on product environmental footprint that is likely to have an important influence on eco-labelling, trade and consumer's choice of products including those from agriculture (EU 2013).

Food production now faces similar complexity and globalization issues as industrial production; for instance, in 2011 over 35% (vs. 9% in 1961) of the global production of soybean cakes was exported by 86 countries and imported by 114 countries as livestock feed (FAOSTAT, 2014). An important share of internationally traded soybean cakes is produced in cultivation areas that are expanding into Amazonian rainforests and other globally important ecosystems. LCA is an essential tool to quantify environmental impacts distributed over globalized agricultural supply and consumption chains. Its application to livestock production has revealed to the scientific community, food processors and the public the major contribution of this sector to human-related greenhouse gas (GHG) emissions (Steinfeld *et al.* 2006). Only 48.5% of emissions are directly associated with animals (enteric fermentation, manure storage and processing) while 45% come from feed production, a different, often spatially distinct step, of the supply chain (Gerber *et al.* 2013).

Notwithstanding the acknowledged consequences of agricultural production on biodiversity, impacts on biodiversity are not fully considered in current LCAs (Souza *et al.* 2015, Teixeira *et al.* 2016). Behind this lacuna lies the difficulty in reconciling the need for simplification inherent to LCA – only one final indicator is generally used, in order to ease interpretation of results – with the complex nature of biodiversity that cannot be captured in a single metric. In LCA, GHG emissions along the supply chain are easily aggregated as they all contribute to the increase in GHG air concentration. A more difficult question is how to combine impacts on biodiversity occurring at different steps of the supply chain and geographical locations? Taking the modification or conversion of one hectare of habitat, the biodiversity impact strongly depends on the species composition and habitat type, as well as human-derived value systems that afford higher conservation values to some species and habitats (e.g. LEAP 2016). How do we generalise and transcend the potential to require overwhelming data and detail, while at the same time provide well-founded models that retain sufficient information for useful differentiation and guide decision-making?

Overcoming these challenges is required for a more comprehensive assessment of multiple agri-environmental criteria including biodiversity. To achieve this goal, LCA methodology development would strongly benefit from increased engagement of ecologists and their capacity to analyse and model complex ecological systems. Feedback from ecologists is important in the process of defining scientifically robust descriptive models, indicators and measures, in order to integrate ecological knowledge into decision-making, as LCA. Conversely, in the absence of relevant LCA methodologies that incorporate agricultural impacts on biodiversity, there is a risk of biodiversity being excluded from environmental assessments, and thus from decision-making processes (Souza *et al.* 2015).

Here, our aim is to outline some of the knowledge gaps and constraints in the life cycle assessment of agricultural production impacts on biodiversity, and to raise awareness and interest among the ecology scientific community to address these challenges. Although we address and outline different types of agricultural impacts on biodiversity, we put more focus on impacts from land use because they have a higher level of methodological development and scientific consensus in LCA. First, we describe the main features of LCA methodology and how it relates to ecological approaches. Second, we describe current challenges faced by LCA models in characterizing the impacts of agricultural production on biodiversity and discuss how ecologists could contribute to the solution of these challenges. Finally, we discuss barriers to collaboration between LCA practitioners and ecologists, and argue that they must be overcome for biodiversity dimensions of agricultural systems to be better considered in decision making processes.

2. The LCA approach

LCA is mainly used in decision support and intends to be a holistic assessment identifying the transfer of environmental burden among stages of the supply chain or among types of environmental impact. LCA application is ruled by a set of international standards (ISO 2006a; b) and it is used by a wide variety of stakeholders, such as governments (e.g., for regulations or eco-labelling), companies (e.g., to adopt environmentally sound practices and to assess/increase eco-efficiency of products), and NGOs (e.g., to promote transparency and inform consumers). The first steps of an LCA include the identification of the product system boundaries (which processes are to be included in the assessment) and the functional unit (unit that quantifies the functions or services delivered by the product system, to which all impacts will be scaled). In Box 1, for example, system boundaries span from feed production to the dairy farm gate, and the impacts are expressed per kg of milk, which is the functional unit. For each unit processes (activity) within the system boundaries, data on inputs and outputs is compiled and associated with the functional unit.

LCA quantitatively models cumulative impacts along environmental cause-effect chains using characterisation models and factors (e.g. those translating land use into impact on biodiversity as in

Box 1). These aggregate life-cycle inventory inputs and outputs (material flows and emissions) into selected midpoint impacts, and, finally, to endpoint impacts which represent damages to defined areas of protection (Fig. 2, Finnveden *et al.* 2009). The development of characterisation models and factors represent key challenges for empirical research to define mechanisms by which different interventions and midpoint impacts are quantitatively related to changes in biodiversity.

Box 1. Off-farm impacts on biodiversity (*via* land use) can be as great as the farm-scale impacts.

Agricultural supply chains are increasingly globalized, with production sites connected by complex international trade routes. Habitat degradation can occur in locations far from the place of consumption, causing significant impacts on local and regional biodiversity (Lenzen et al. 2012).

Fig. 1a illustrates the relative importance of on-farm and off-farm land use (related to internationally-traded feed) in an example of intensive European dairy farms. We estimated the impacts on biodiversity associated with on-farm vs. off-farm land use, using the global characterisation factors proposed by Alkemade *et al.* (2009; 2012) (Fig. 1b). These factors quantify the impact on biodiversity for different land use categories – 0.9 for conventional crops, 0.7 for organic crops, 0.6 for conventional grassland, 0.5 for organic grassland. Undisturbed habitats have an impact value of 0 while a value of 1 means that all biodiversity is lost.

[Figure 1 placeholder]

Differences between ecological and LCA approaches

The goal of LCA is to quantify environmental impacts of material and energy flow in often globally integrated supply chains as an accounting and decision-oriented tool. To fulfil this goal, LCA requires standardization and simplification in order to (i) aggregate various environmental impacts along the different steps of the supply chains and (ii) provide information relevant to decision and usable for comparison/benchmarking purposes. In contrast, ecological science aims to understand the full complexity of biodiversity and ecosystems. This contrast has consequences in how the environmental cause-effect chain is described in LCA and ecology (Table 1). Ecology often uses a variety of indicators to describe biodiversity's intrinsically complex relation to human activity. The different elements of the chain are assessed separately (*i.e.*, pressure, state and response indicators), or models are used to characterize a variety of links between these elements. In LCA, the focus is on developing characterisation models to estimate the effects of interventions through the environmental cause-effect chain, expressing impacts in a limited number of midpoint and endpoint impact categories.

Ecology and LCA have orthogonal perspectives on the relationship between agriculture and environment (Table 1). Many agri-ecological studies tend to adopt a 'horizontal' perspective of the agricultural system, and assess ecological interactions and their alteration by human activities on a spatial unit (e.g. farm, landscape, watershed) that represents a limited part of the supply chain. In contrast, LCA adopts a 'vertical' perspective, and assesses potential environmental impacts associated with a product along its supply and consumption chain, based on a comprehensive quantification of inputs (raw materials, energy and intermediate products) and outputs (emissions, residues, products and by-products).

Local ecological assessments can comprehensively capture impacts on biodiversity only in agricultural production systems where the whole supply chain is local. In other words, the value of ecological assessments for agricultural products is limited by the application of biodiversity indicators focused on a bounded area (e.g. a farm or watershed) when impacts may occur outside of that boundary. We know that supply chains are global in many systems (Box 1) and the impact of imported products, such as livestock feed, may represent a significant share of the farm's land use (Fig. 1a) and associated impacts on biodiversity (Fig. 1b). Accounting for off-farm land use can certainly change the magnitude of the impact, and depending on the location and practices can even change the comparative evaluation of different production systems. Thus, a full understanding the ecological effects of agricultural products requires a supply chain perspective with attention to not only on-farm, local-scale impacts but also to off-farm impacts that may be globally distributed.

3. The characterisation of impacts on biodiversity in LCA: current practice and challenges

LCA characterisation models need to better link land use to biodiversity

Land use is one of the main drivers of the impact of agriculture on biodiversity and it is also dominant in terms of methodological development and implementation (Fig. 2). A challenge for LCA characterisation models that link land use to biodiversity is to incorporate more complex ecological knowledge and overcome the trade-offs that exist between the models' geographical coverage (e.g. local, regional or global), their degree of spatial differentiation (e.g. ecoregions or biomes) and their definition of land use classes.

Characterisation models covering a large geographical scale often lack precision in terms of spatial differentiation or land use classes definition. For instance, the characterisation factors mentioned in Box 1 are applied at global scale without spatial differentiation, *i.e.* the species abundance is assumed to be the same in European and Latin American forests, despite considerable evidence of greater species richness and abundance in the latter (Dirzo & Raven 2003). More recent global characteriztaion factors consider spatial differentiation between biomes (de Baan *et al.* 2013) or ecoregions (Chaudhary *et al.* 2015). However another important trade-off exists between geographical coverage and definition of land use classes. For instance, the model proposed by Jeanneret *et al.* (2014) defines characterisation factors for precise land use classes differentiating between agricultural land uses and practices (intensive and extensive grassland) but it has a low geographical coverage (central Europe). On the other hand, models with global coverage have a coarse definition of agricultural land use classes (e.g., *grassland* and *cropland*, in de Baan *et al.* 2013 and Chaudhary *et al.* 2015). A better distinction among land use intensity and management practices – including those with a positive impact on biodiversity (e.g. extensive grazing, Watkinson & Ormerod 2001) – is a priority for increasing the capability of LCA as an analytical and decision support tool for agricultural products.

LCA characterisation models need to include a wider range of categories of biodiversity impacts

While land use and land use change are key drivers of biodiversity change, a priority need is to consider other interventions and midpoint impacts (Fig. 2). For instance, very few LCA models include the impacts of climate change on biodiversity (De Schryver *et al.* 2009; Alkemade *et al.* 2009), despite it being an important driver of biodiversity loss that also receives a contribution from agriculture (IPCC 2013). Nutrient pollution (acidification and eutrophication) from agriculture also poses significant impacts on species and their ecosystems but only a limited number of LCA models can assess these impacts (Struijs *et al.* 2011; Azevedo, *et al.* 2013a;b). There is a need to develop characterisation models that capture a more comprehensive range of impacts on biodiversity, and to be relevant to a variety of agricultural production systems for which the main categories of impact on biodiversity may differ.

LCA requires more ecologically relevant descriptions of biodiversity

Future LCA methods will not only need to better model the links between a wide range of midpoint impact categories and biodiversity, but also to assess biodiversity in a more ecologically relevant manner.

First, LCA characterisation models largely neglect the impact of landscape-scale processes on species' populations. In the main LCA framework, impacts of land use on biodiversity are expressed as a local biodiversity impact*area combined with an assumed linear scaling (Koellner *et al.* 2013). This will underestimate the total impact because habitat fragmentation often accompanies habitat conversion and worsens the effect of habitat loss in a non-linear manner. More generally, the impacts of land use change on biodiversity are not only local and the surrounding land uses in a landscape mosaic can also have an effect (e.g. because they provide complementary resources or because they hamper migration, Donald et al. 2006).

Second, most characterisation models use species richness as an indicator and (vascular) plants as a proxy taxon. Although many models assume that plant diversity is reasonably well correlated with other terrestrial taxa (Weidema & Lindeijer 2001), ecological studies show that the correlation of the response of different taxa to disturbance can be low and context-dependent (Wolters *et al.* 2006). One strong limitation of the use of species richness is that it does not reflect differences in the relative conservation values of species (e.g. endemism, specialisation, rarity). A few LCA characterisation models differentiate between species conservation values (Michelsen, 2008; de Baan *et al*., 2015) and use ecological data such as the IUCN red list of species. Moreover, the use of species richness does not adequately capture species functional traits (Souza et al. 2013) and ecosystem services. Current LCA characterisation models assessing biodiversity do not integrate ecosystem services. Because the relationship between biodiversity and ecosystem services is complex (Mace *et al.* 2012), assessments of biodiversity and ecosystem services could be correlated more or less closely, or even negatively if biodiversity competes with other services (e.g., highly productive monocultures). Including ecosystem services in LCA would improve ecological relevance but also raise new challenges.

4. Future research directions: what does LCA need from ecology?

We advocate the use of an interdisciplinary approach to involve LCA and ecology in the development of LCA methods to assess the impact of agriculture on biodiversity. Several experiences (e.g. LEAP 2016; Teixeira *et al*. 2016) show that dialogue and collaboration is possible but takes time and requires funding for interdisciplinary research as experts of the two communities have to understand each other's concepts and achieve a common understanding of the challenges and objectives. Specific domains of collaboration are listed below.

Concepts. Landscape ecology concepts have been largely ignored by the LCA community. Including some of these concepts (such as the effect of habitat fragmentation or landscape heterogeneity on populations) will be essential to increase the ecological relevance of LCA models linking land use to biodiversity. In order to improve on the current taxonomic measures of biodiversity, LCA should rely more on concepts from functional ecology such as species' functional traits, and the characterisation of ecosystem services and their link to biodiversity. Zhang *et al.* (2010) critically reviewed how ecosystem services are quantified by LCA models, and suggested that LCA experts should seek help from ecologists to address a number of challenges related to ecosystem services e.g. broadening the current focus from only provisioning services and finding common units to aggregate different ecosystem services.

Local designation frameworks and information. There is a crucial need to improve the spatial differentiation of LCA models, by reflecting how biodiversity and the impact of the same pressure (e.g. land use) vary with locality. Ecological data and designation frameworks (e.g. IUCN red list of species and ecosystems, protected species and habitats) should be used to indicate that conservation value and priorities can differ between locations. As shown in Box 1, important contributions to the impacts on biodiversity can take place off-farm and better spatial differentiation would improve the ecological relevance of the assessment of on-farm and off-farm impacts and the way they are combined. A difficulty is that better spatial differentiation is only useful if the location of off-farm activities is known which is often not the case. To begin addressing the knowledge gap of the provenance of imported feed, research linking ecology and agriculture focusing on providing national average estimates reflecting the state and value of biodiversity of national production will be valuable. Global trade data could then be a proxy for direct knowledge of the feed origin and the new national averages used as default values. This would provide new evidence to raise awareness among decision-makers, and foster collaboration between actors of the agricultural supply chain on the importance of tracking the exact location of activities.

Data. Many available regional-scale ecological and agricultural datasets are not used by LCA methods' developers and could lead to three main types of improvements. First, they could be used as local information to increase the spatial differenciation of LCA models from global to regional or sub-regional scale. Second, ecological data such as the Pan-European Common Bird Monitoring Scheme or the Mapping and Assessment of Ecosystem Services could address new taxa and new biodiversity dimensions in LCA. Third, ecological and agricultural datasets could be useful to include new land use classes and drivers of biodiversity changes that are specifically related to agriculture (e.g. with the Farm Accountancy Data Network providing a detailed description of agricultural inputs and practices). A key issue related to the use of ecological data in LCA method development will be sharing and ensuring data integrity, which is critical when data is transferred through interdisciplinary research and used in decision-making (Norton 1998). Finally, a crucial challenge in using local and regional data is to provide a high geographical coverage of impacts, while maintaining high spatial resolution.

Models. LCA characterisation models already rely on ecological models such as species-area relationships or habitat suitability models (for a more detailed review see Souza *et al*. 2015; Teillard *et al*. 2016). The use of agro-ecological models could help to develop LCA methods with better applicability in the context of agriculture. They include models investigating the effect of agricultural intensity (Teillard *et al.* 2015b) or high nature value farming (Doxa *et al.* 2010) on biodiversity. Moreover, ecological models that quantitatively link climate change (Thomas et al. 2004) or water use and nutrient pollution (Vörösmarty et al. 2010) to biodiversity change should be used to develop new LCA methods and strengthen the ability of LCA to account for the effect of drivers other than land use (Fig. 2).

Interpretation. The supply chain perspective of LCA necessitates a simplified view of biodiversity and the mechanisms affecting it. To avoid over-simplifications that may lead to ill-informed decision-making, ecological knowledge and expertise needs to be better incorporated to guide the interpretation of biodiversity LCA results in decision making.

5. Barriers to collaboration and implications for researchers and policy makers

To what extent the need for simplification in LCA can be reconciled with the complex and dynamic nature of biodiversity remains an open question. For instance, LCA is widely applied to GHG emissions and carbon dioxide equivalents (CO_2-eq) are used to aggregate emissions of different gases along the supply chain and across different locations. Could a universal measure such as the CO_2-eq be conceptualized for biodiversity? The biodiversity or ecosystem services damage potential are already used in LCA to aggregate impacts across processes and locations (Koellner et al. 2013), and further collaborations with ecologists could lead to more ecologically relevant measures. However, because conservation priorities can be highly context-dependent, universal biodiversity measures may not be sufficient to inform decision-making in certain situations (e.g. specific species, agro-ecosystems or production practices). The complementary use of ecological assessments could be used to fill knowledge gaps in LCA results in such situations (LEAP 2016).

Despite these barriers, excluding biodiversity from LCA or including it improperly could lead to decisions that are profoundly detrimental to biodiversity. For example, LCA with a focus on agricultural GHG emissions conclude that increasing milk yields among systems operating at relatively low levels of productivity is an option to reduce the enteric emissions of methane (CH_4) per unit production. Simplistically including biodiversity with land use as a sole driver could lead to the same conclusion. Intensive systems combine high yields and efficient conversion of feed into animal products, i.e. they use substantially less land and produce more than extensive systems. Therefore, their impacts on biodiversity through solely land use and per unit of product could be decreased. Nevertheless, intensive systems are often detrimental to biodiversity when they generate other environmental impacts such as water withdrawals and freshwater eutrophication, as well as coastal and marine pollution. A comprehensive assessment of the different environmental impacts of agriculture and their effect on biodiversity is necessary to properly uncover the trade-offs that can exist among different environmental dimensions. Importantly, this will also enable assessment of which mitigation options will improve the overall sustainability of agriculture, and not just improve specific environmental dimensions at the expense of others (burden-shifting).

Relevant assessments of the effects of agriculture on biodiversity in LCA will require reconciliation of the horizontal perspective of many ecological studies with the vertical and multi-site nature of food supply chains. Reconciliation should be both theoretical to derive new conceptual models, and practical to share data and specific methods. If joined, the combined perspective could dramatically advance methodology for the assessment of agricultural sustainability by: 1) improving the ability to measure and predict impacts on ecological systems, 2) improving the reporting of those impacts to the policy arena, the marketplace and the public; subsequent public policies, economic signals and awareness-raising can positively influence technologies and practices 'on the ground', and 3) ultimately contributing to the reconciliation of agriculture growth needed to meet growing demand and conservation of biodiversity and ecosystem services. Therefore, we stress the importance of combining a life cycle perspective with the understanding of the complexity of ecosystems, which can only be achieved through close collaboration between ecologists and LCA experts.

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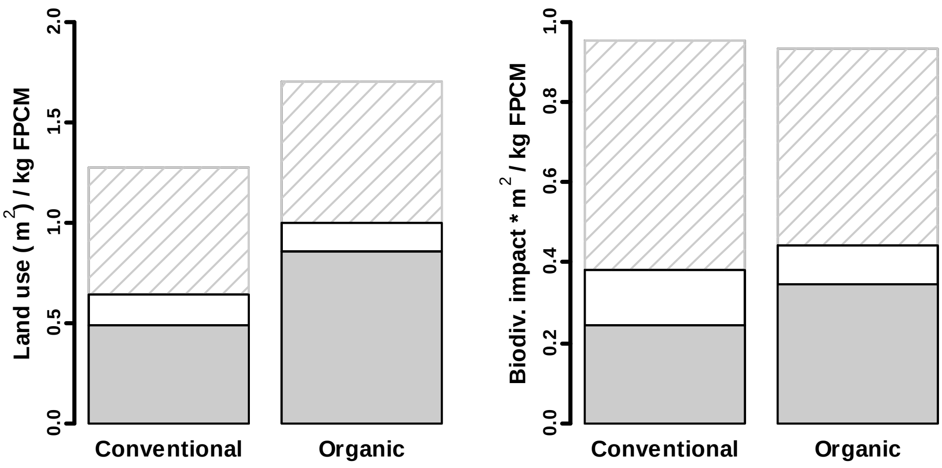
Table 1: Comparison of the major typical features of ecological indicator and LCA frameworks.

Feature type	**Typical features of ecological indicators**	**Typical features of LCA**
Perspective	Horizontal: the distribution of habitats and species is described over a generally contiguous space (and time)	Vertical: the full supply chain is the perspective used to describe the system and it structures the assessment
Approach	Uses indicators to describe the different elements of the environmental cause effect chain (pressure, state, response indicators)	Develops characterisation models (generally linear) linking the different elements of the environmental cause-effect chain (interventions, midpoint impacts, endpoint impacts)
Examples of goals	Monitor biodiversity, identify favourable practices or policies	Compare products, identify hotspots of impacts (spatial, or along the supply chain); compute potential impacts at large scale (region, country, world)
Scale of application	Typically at the farm to landscape scale. It is possible to include indicators of off-farm impacts, but relatively rarely done.	Typically at spatial range that is much higher than farm-scale, and can include and be appropriate for global-scale application
Functional unit	Impacts on biodiversity typically expressed per unit of area	Impacts on biodiversity typically expressed per unit of product
Environmental cause-effect chain		
Production	Described as spatially bounded (farm, landscape, region)	Described by a life cycle inventory, which may span the globe
Drivers of biodiversity change	Referred to as *drivers* or *pressures*	Referred to as *inventory flows* or *midpoint impacts*
Biodiversity	Referred to as *state indicators*	Referred to as *biodiversity indicators*
Conservation actions	Referred to as *response indicators*	Sometimes evaluated through alternate management options (e.g. land use Geyer et al. 2010; irrigation Verones et al. 2012) that can benefit conservation



(a) (b)

Figure 1: A comparison of conventional and organic dairy farms in their (a) land use and (b) estimated impact on biodiversity per unit of product (fat and protein corrected milk, FPCM), highlighting the importance of off-farm feed production (hatched area in bars). Land use data was obtained from an LCA study on Dutch dairy farms (Thomassen *et al.* 2008), and characterisation factors from Alkemade *et al.* (2009; 2012). Grey: contribution of on-farm grassland, white: contribution of on-farm feed crops, hatched: contribution of off-farm feed crops.

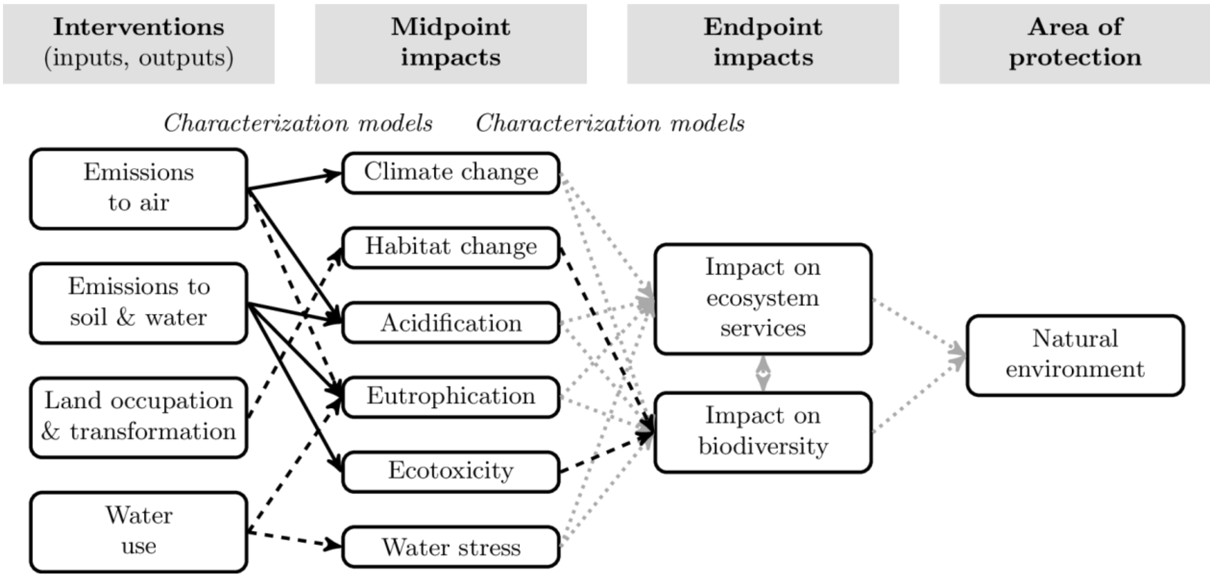


Figure 2: Main environmental cause-effect relationships linking interventions to midpoint and endpoint impact categories of the Natural Environment area of protection. Full black arrows indicate a high data/model availability and level of scientific consensus on the characterisation model to address an impact category, dashed black arrows indicate moderate data/model availability and level of consensus, and dotted grey arrows indicate low data/model availability and level of consensus.