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Life cycle assessment applied to pea-wheat intercrops: A new method for handling the impacts of co-products

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ABSTRACT

Cereal-legume intercrops (ICs) are a promising way to combine high productivity and ecological benefits in temperate agroecosystems. This study aims to apply a life cycle assessment (LCA) to ICs by testing several methods of co-product handling to ascertain the environmental impacts of the co-products. Several classic methods of allocation and system expansion were compared, and additional methods were proposed to better analyse the impacts of ICs and sole crops (SCs), taking into account complementarities between species that may provide benefits for each species as well as global benefits compared to the SCs of an equivalent area or production. Unfertilised ICs produce wheat and pea crops that have a lower impact with regards to climate change (CC), acidification (AC), terrestrial ecotoxicity (TE) or cumulative energy demand (CED) than N-fertilised SC wheat (W100 N) and unfertilised SC pea (P100 N0), regardless of the allocation method or functional unit (kg of grains of wheat, of pea, or 1 ha). Unfertilised ICs exhibited a higher and lower eutrophication (EU) impact when compared to W100 N and P100 N0, respectively. Concerning land occupation (LO), the results were highly variable depending on the allocation method and either increased or decreased the impact of ICs relative to the impact of SCs. Classic allocation methods strongly affected the results, and system expansion yielded surprising results, emphasising the benefits of interspecific complementarity. We then redefined our functional unit to assess the impact of ICs apart from those of SCs (equivalence of area or production). These comparisons demonstrated that ICs always allowed for a significant decrease in environmental impacts when compared to SCs based on the equivalence of production. Based on the equivalence of crop area, similar trends were observed, except for EU and LO, where there was little difference in impact between ICs and SCs.

1. Introduction

In recent decades, it has become increasingly important to redesign cropping systems (Altieri, 1989) to limit the use of non-renewable natural resources and chemical inputs and to improve their efficiency (Tilman et al., 2002). Cereal-legume intercropping is an effective way to improve the nitrogen (N) efficiency of agro-ecosystems (Hauggaard-Nielsen et al., 2001) and to limit losses to the environment (Hauggaard-Nielsen et al., 2003).

Intercropping is the growth of two or more species in the same field for a significant period, with variations in the species, their respective densities and spatial arrangements (Willey, 1979). Apart from its frequent use in pastures, this practice is not widespread in temperate agroecosystems. However, cereal-legume intercrops (ICs) are gaining interest in Europe due to increasing awareness of environmental damage arising from the intensive use of fertilisers and pesticides and to the increasing cost of these inputs. Currently, ICs are widespread in organic farming but may have interesting potential uses in conventional farming systems, particularly for the development of low-input multi-use crops.

Intercropping has been shown to increase the per hectare yield in comparison to the average yields of its components grown as sole crops (SCs). In addition, intercropping increases the N concentration in cereal grains compared to SC cereal and decreases weed competition and N leaching compared to SC pea. These

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advantages are assumed to be largely linked to the complementary use in time and space of N sources by the different components of the IC (Corre-Hellou et al., 2006; Jensen, 1996; Naudin et al., 2010; Corre-Hellou et al., 2011). The advantages of ICs (in terms of grain yield, N acquisition, or gross margin) over SCs are often assessed by using the land equivalent ratio (LER) concept. An LER on grain yield is calculated as the ratio of the sole cropping area required to produce the same yield as a unit area of IC (De Wit and Van den Bergh, 1965; Willey and Osiru, 1972; Vandermeer, 1989). LER values above 1 indicate a benefit of intercropping over sole cropping and have been reported for many grain legume-cereal ICs (Jensen, 1996; Ofori and Stern, 1987). However, LER values have been found to vary from 1 to 1.4, with higher values occurring at low soil N availability or when other biotic stresses occur (Corre-Hellou et al., 2011).

Thus, ICs can contribute to the development of cropping systems that combine higher productivity, yield stability, lower input levels and ecological benefits. However, few studies have assessed the environmental benefits of ICs relative to SCs using a multicriteria approach. Pelzer et al. (2012) demonstrated that cereal-legume ICs decreased the estimated consumption of energy per ton of harvested grains by 30–50% compared to conventionally managed SC wheat. In addition, ICs were shown to have similar gross margins to SC wheat and decrease pesticide use compared to SCs.

Life Cycle Assessment (LCA) is a method that assesses the impact of a product by considering all stages of its life cycle. LCA is considered a "cradle to grave" method of assessing resource use and emissions to the environment from the extraction of resources through each step of the production process, including product parts and recycling or final disposal (Guinée et al., 2002). In the case of product systems that yield several co-products, impacts must be allocated among the co-products. This allocation is used for cereal-legume ICs, and the estimated impacts of the co-products can depend on the allocation method (Ekvall and Finnveden, 2001; Heijungs and Guinée, 2007). Several allocation methods are proposed: i) mass allocation based on physical flows, ii) economic allocation based on mass flows weighted by economic values of co-products, and iii) allocations based on significant characteristics of co-products, such as energetic values or protein content. However, there is no consensus as to which allocation method is best (Ardente and Cellura, 2011). Mass allocation has limitations when co-products differ in value, such as in the case of gold extraction (an extreme example for illustration), where mass allocation results in very modest impacts for pure gold (Norgate and Haque, 2012; Rio Tinto, 2006). In the example presented here, economic allocation would be more appropriate. However, economic allocation may not be relevant if prices are highly variable from year to year and may produce results with short-term validity (Ardente and Cellura, 2011). ISO standards (ISO 14044, 2006) advise avoiding allocation by using system expansion methodologies (Ekvall and Finnveden, 2001). However, selecting a comparable process that is suitable for system expansion can be difficult and can have significant effects on the results (Niederl-Schmidinger and Narodoslawsky, 2008).

Similar to other environmental assessment methods, LCA has primarily been used to assess SCs. Its use for more complex practices, such as intercropping, may raise methodological questions concerning the functional unit, the allocation of impacts between the two co-products and the comparison of the results between ICs and SCs. Therefore, the aim of this study was to investigate the methodological aspects of using LCA to assess the environmental impacts of wheat–pea ICs compared to their SCs. Initially, LCA was used to compare ICs and SCs in terms of their impact per kg of grains, as well as per ha. Several methods of co-product handling were compared, including allocation (mass, economic, and based on the N yield in grains) and system expansion. This first step was primarily based on results from a single field experiment in western France. In the second step, other methods were explored to better analyse the impacts of ICs and SCs. These methods take into account the particularities of ICs, such as complementarities between species, which may produce benefits for each species and global benefits compared to SCs of equivalent area or production.

2. Materials and methods

We applied LCA to experimental results obtained at one location over the course of one year. This field experiment was carried out in western France from 2007 to 2008 (see Naudin et al., 2010).

2.1. Crop management

Winter field pea (*Pisum sativum* L.) and winter wheat (*Triticum aestivum* L.) were sown as SCs at 80 and 260 pl m^{-2}, respectively. Winter pea-wheat ICs were grown in a substitutive design, with each species sown at half its SC density and both species mixed within the rows (Table 1). Straw was left on the soil and not harvested. The previous crop was rapeseed (harvested on 26th June 2007), and the subsequent crop was maize (sown on 23rd April 2009). In the scenarios studied here, we assumed that ICs and SCs were followed by a catch crop, such as oats sown during the autumn in 2008, before sowing the maize.

Pests were controlled with pesticides when required, leading to differences in pest management among the crops (Tables 1, 2 and 3). No irrigation was provided. The mean inorganic soil N, measured in February (end of winter), was 59 kg N ha^{-1} in the 0–90 cm soil layer. Pea SCs (P100 N0) and unfertilised ICs (P50W50 N0) were always grown without applied N. N was applied as NH_4NO_3 on wheat SCs (W100 N) and on N-fertilised ICs (P50W50 N) (Table 1). For further details on field experiment methods, see Naudin et al. (2010).

Primary inputs, such as P, K and limestone; diesel consumption; and agricultural machinery are listed in Table 2 and were defined according to experiment management and technical recommendations by an expert panel that included members of the agricultural marketing cooperative Terrena (Ancenis), crop technical institute (Arvalis-Institut du Végétal), farmers associations of western France, and agronomic scientists. The majority of the technical recommendations concerned tillage and pest management and were designed to reflect mean crop management in western France.

2.2. First step: comparison of co-product handling methods to estimate impacts of SCs and ICs per kg of grain and per ha

2.2.1. LCA: evaluation methodology

Potential impacts were estimated using the LCA method. The temporal system boundaries were from tillage for the studied crops to tillage for the next crop (a catch crop established before sowing maize). The length of this period was one year for all crops. The functional units were 1 kg of grain (of either wheat or pea, including the grain sorting process in the case of intercropping) and 1 ha. Indirect emissions and resource use associated with the production and delivery of inputs for crop production (manufactured fertilisers, pesticides, agricultural machinery, diesel) were from the ecoinvent 2007 database, version 2.0 (Nemecek and Kägi, 2007). The production of seed for sowing assumed that the inputs required for seed production were similar to those required for the corresponding crop.