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Faba beans for biorefinery feedstock or feed? Greenhouse gas and energy balances of different applications

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A B S T R A C T

Legumes have been proposed as biorefinery feedstock primarily due to their low nitrogen fertilizer demand, low fossil energy-related greenhouse gas emissions and high protein content, enabling efficient protein feed, food or amino acid production. Grain legumes (pulses) occupy approx. 1.2% of the arable land in Sweden, with faba bean, which is used as a protein feed, being one of the most common. Utilization of the whole crop, including the beans and the remaining aboveground biomass, can enable co-production of feed, food and/or fuel in high quantities, as faba bean has potentially high total biomass yield. In this study, Consequential Life Cycle Assessment (CLCA) was used to analyze a change from the current use of faba bean as protein feed for dairy cows (Reference scenario) to two alternative uses where the whole crop is harvested: whole crop processing in a green biorefinery producing ethanol, protein concentrate feed and fuel briquettes (Biorefinery scenario), or with the whole crop used as roughage feed (Roughage scenario). Impacts on climate change, arable land use and primary fossil energy use were considered. The changed use of faba bean resulted in changes in the feedstuff requirements for dairy cows, which were highly influential for the results. Whole crop harvesting as opposed to bean harvesting with return of crop residues resulted in increased climate impact and energy use during the agricultural and processing stages. On including substitution effects of the products, the Biorefinery scenario resulted in +25, −20% and −100% change for climate impact, arable land use and energy use, respectively, in relation to the Reference situation. The increase in climate impact was primarily due to soil carbon changes and increased demand for marginal grain. When the whole faba bean crop was used as roughage (Roughage scenario), the corresponding changes were +164%, −130% and +167% for climate change, arable land use and energy use, respectively. The increased impact was due to increased use of feed grain as a result of using the protein-rich roughage.

1. Introduction

Use of fossil resources to meet energy and material needs is unsustainable, as fossil resources are non-renewable and their combustion causes severe environmental problems. Therefore, a shift to renewable alternatives is required. In order to provide renewable energy and materials, an array of different renewable resources will be needed. In a biobased economy, biomass will be utilized for the production of food and fiber, but also for the production of fuels and chemicals (Dale and Kim, 2010). Biomass is a limited resource and needs to be utilized efficiently, as reflected in the definition of the biorefinery concept by the International Energy Agency (IEA) Task 42 on Biorefineries as: "…the sustainable processing of biomass into a spectrum of marketable products and energy".

In a so-called green biorefinery, fresh or ensiled biomass is processed into a variety of high-value products (Kromus et al., 2010). The bulk volume of green biomass, such as grass or legumes, is commonly used as roughage in animal feeds. Separation of the green biomass into a green juice and a fiber-rich press cake, a process called green crop fractionation, enables combined production of non-food and food products from green biomass (Carlsson, 1997).

Use of legume crops for bioenergy has been questioned, since they use solar energy to fix nitrogen (N), which could lead to lower yields and therefore lower land use efficiency for the production of bioenergy (Brehmer et al., 2008). Although some legumes can be associated with lower energy yield per hectare, the use of solar energy instead of fossil energy can be important for reducing fossil energy demand. Legume crops tend to give rise to lower fossil energy-related CO_2 emissions than other crops due to their fixation of N, resulting in lower mineral N fertilizer demand (Jensen et al., 2011). This can make them particularly interesting as biorefinery feedstock. Moreover, the high protein content in legumes can be utilized, while valuable co-products such as bioenergy are also obtained (Jensen et al., 2011). Furthermore, legumes have positive crop rotation effects in cereal-dominated crop rotations, including decreased disease pressure, nitrogen delivery to the following crops and a yield

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increase in the following crop (Kirkegaard et al., 2008). Thus, faba bean (FB), in particular older varieties, can be of interest as a feedstock for biorefineries (Jensen et al., 2010).

Utilizing the whole crop (i.e. including aboveground crop residues) can decrease the competition for land, since the function of food or feed production can be maintained, while the remaining biomass (the aboveground crop residues) can be utilized for other purposes. However, the removal of crop residues has been questioned, since recycling of crop residues to soil is very important for maintaining soil quality and reducing soil erosion (Lal, 2008). Life cycle assessment (LCA) studies on biofuel production from agricultural residues have shown that soil organic carbon (SOC) changes due to residue harvesting can have a very important impact on the greenhouse gas (GHG) balance of biofuels (e.g. Liska et al., 2014; Whittaker et al., 2014) and biorefinery systems (Cherubini and Ulgiati, 2010). For legumes in particular, concerns have been raised that harvesting the whole crop can have negative impacts on soil carbon and soil fertility (Jensen et al., 2011).

The present study considered whole crop harvesting of FB and its subsequent use as a feedstock for a green biorefinery or as roughage animal feed, compared with harvesting the beans for use as protein feed and returning crop residues to the soil. The roughage feed application represented an alternative whole-crop use to biorefinery processing and allowed the effect of whole crop harvesting, but without the separation into different co-products, to be investigated. The effects of whole crop harvesting, including SOC changes and the impact of nitrogen delivery to the following crop, were assessed.

The cultivation of N-fixing crops such as FB has decreased over time with the increase in mineral fertilizer use (Crews and Peoples, 2004). However, FB cultivation has increased in the last five years in Sweden (SS, 2013), driven by the demand for local or domestically produced protein feed (Sverigeförsöken, 2012). Sweden imports large quantities of its protein feed (61% of the total used) (LRF, 2012), mainly in the form of soybean meal and rapeseed meal (SBA, 2011a). Around 40% of the imported soybean meal and 60% of the imported rapeseed meal is used for cattle (SBA, 2011a). Today grain legumes (mainly FB and peas) occupy 1.2% (30,000 ha) of the arable land in Sweden, mainly in south-western and eastern parts of the country (SBA, 2013). In the EU, 70% of protein feed is imported (European Parliament, 2011).

Life cycle assessment is a method for assessing the environmental impact of a product or service from “cradle to grave” (ISO, 2006a, 2006b). Previous LCA studies on biorefinery systems and products have primarily focused on so-called lignocellulosic biorefineries (e.g. Cherubini and Jungmeier, 2010; Cherubini and Ulgiati, 2010; Earles et al., 2011), which use lignocellulosic biomass such as cereal straw, grasses and forest residues and commonly produce biofuels (ethanol) and/or chemicals and various co-products. LCA studies on utilizing legumes as feedstock for biofuel production include e.g. ethanol production from alfalfa stems considered to be a co-product to alfalfa leaves used for feed (González-García et al., 2010) and biodiesel production from soybean oil (co-produced with soybean meal) (Kim and Dale, 2005). To our knowledge, the present study is the first LCA study on a green biorefinery system utilizing green crop fractionation and concentrating the proteins from the green biomass.

2. Aim

The aim of this study was to assess the climate impact, arable land use and fossil energy use of changing from the current use of faba beans as protein feed to two types of whole FB plant utilization: biorefinery processing and roughage feed. The specific objective was to analyze the most environmentally beneficial use of available FB production (with regard to the three impact categories assessed).

3. Materials and methods

Climate impact (global warming potential in a 100-year perspective, GWP_{100}), arable land use and energy use (fossil primary energy) were assessed using LCA. Three scenarios were included:

- *Reference* (*I*): The current use of FB beans as protein feed, with the remaining biomass returned to the soil.
- *Biorefinery* (*II*): All aboveground biomass harvested and processed in a biorefinery to produce ethanol, protein concentrate feed and fuel briquettes.
- *Roughage* (*III*): All aboveground biomass harvested, ensiled and used as roughage feed.

The analysis focused on environmental impacts, whereas for a sustainability assessment economic and social impacts would need to be considered.

3.1. LCA approach

Since the aim of the study was to assess the impact of *changing* from the present use of FB to two other potential uses, a consequential LCA approach (CLCA) was applied. CLCA “aims at describing how the environmentally relevant physical flows to and from the technical system will change in response to changes in the life cycle” (Ekvall and Weidema, 2004, p. 161). Generally in CLCA, allocation is avoided by system expansion and data from marginal technologies are included, rather than average data. The term ‘marginal technology’ refers to the technology affected by marginal changes (Weidema et al., 1999). When identifying the technologies affected by a change, it is important to consider the scale of the change. The scale is considered to be small (marginal) if it does not affect determining parameters for the entire market situation (Weidema, 2003). The changes in the present study were identified as being small in relation to the Swedish agricultural and energy system. Similarly, the time horizon is significant as it determines the technologies affected and if the change affects capital investment (Weidema et al., 1999). In this study, the change was considered to be long-term to mid-term (up to 10 years), as the utilization of FB in a biorefinery involves the construction and running of a biorefinery and is therefore regarded as being likely to affect the capacity investment of the technologies affected.

In LCA methodology, it is often assumed that a change in demand results in a corresponding change in the production of the specific product. However, changes in demand are likely to result in various effects on the production of the specific product and other products. For example, increased demand might result in a higher price, resulting in reduced use of the product (negative feedback mechanism) or increased use as the product becomes more established on the market (positive feedback mechanism) (Ekvall and Weidema, 2004). These effects are complicated to model and therefore simplifications are often required (Ekvall and Weidema, 2004). For practical reasons, changes in demand for a product were assumed here to result in an equivalent change in the affected process.

3.2. System boundaries and functional unit

The study included FB cropping, harvesting, transportation and further processing to final products (Fig. 1). Building material and machinery, transportation to the consumer and the use of the end-products were not included. Faba bean cultivation was assumed to take place in Västra Götaland in south-west Sweden.

The basis of the comparison (the functional unit) was set to be production of FB from 1 ha of land, utilized either as animal protein feed (scenario (I)) or animal roughage (scenario (III)) or as the products from a biorefinery (liquid fuel, protein feed and solid fuel) (scenario (II)). The aim was to assess the impact of changed use of FB and the