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The price of protein: Review of land use and carbon footprints from life cycle assessments of animal food products and their substitutes

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ABSTRACT

Animal husbandry, aquaculture and fishery have major impacts on the environment. In order to identify the range of impacts and the most important factors thereof, as well as to identify what are the main causes of the differences between products, we analysed 52 life cycle assessment studies (LCAs) of animal and vegetal sources of protein. Our analysis was focused only on land requirement and carbon footprints.

In a general conclusion it can be said that the carbon footprint of the most climate-friendly protein sources is up to 100 times smaller than those of the most climate-unfriendly. The differences between footprints of the various products were found mainly to be due to differences in production systems. The outcomes for pork and poultry show much more homogeneity than for beef and seafood. This is largely because both beef and seafood production show a wide variety of production systems.

Land use (occupation), comprising both arable land and grasslands, also varies strongly, ranging from negligible for seafood to up to 2100 m^2 y kg^{-1} of protein from extensive cattle farming. From farm to fork the feed production and animal husbandry are by far the most important contributors to the environmental impacts.

Introduction

The role of animal husbandry in climate change and loss of biodiversity has been highlighted in several studies in the past decade (e.g. Kramer, 2000; Steinfeld et al., 2006; Garnett, 2008; FAO, 2009). These publications provide the larger picture of the impacts of livestock production on a global scale. More focus and detail can be found in environmental life cycle assessment (LCA) studies of animal food products, many of which were also published the past few years.

In an LCA the environmental impacts of a product is quantified as much as possible in a consistent and standardized way. De Vries and De Boer (2010) have reviewed a selection of LCA studies on animal products. Other meta-publications on LCAs of food products include Yan et al. (2011), Roy et al. (2009), Flachowsky and Hachenberg (2009) and González et al. (2011). These publications mainly focus on greenhouse gases and carbon labelling, or include a limited group of products or a limited number of studies. The present review presents a broader view, based on the analysis of 52 LCA studies on meat, milk, seafood and other sources of protein. The goals were to:

- Identify the ranges in land requirements and carbon footprints of different sources of protein.
- Identify the most important inputs and processes in the life cycles.
- Identify what are the main causes of differences.

We focused on land use (occupation) and greenhouse gas emissions because these aspects are very relevant to damage to ecosystems and consequential global loss of biodiversity (Alkemade et al., 2009; Rockstrom et al., 2009).

Methods

A method commonly used to analyse the environmental impacts of products is the environmental life cycle assessment (LCA). It is an internationally recognized method, and the ISO standards (ISO 14040 and 14044) provide guidelines for conducting LCAs. They can be used to identify the most important contributors in a production chain (gravity analysis or contribution analysis), or to make a systematic comparison of different products or production methods. Many different environmental impact categories can be quantified in LCAs.

When they are only aimed at quantifying greenhouse gases the method is often referred to as carbon footprinting. For this type of LCA specific guidelines have been written (BSI, 2008).

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In recent years, a large number of LCAs of agricultural products have been published. There are specific methodological issues in LCAs for agricultural and fishery products, such as: (Ayer et al., 2007; Pelletier et al., 2007; Andersson, 2000; Guinée, 2002; Thrane, 2006).

- There are physical limits to production, mainly caused by the pace of photosynthesis and availability of fertile land. Production is not very flexible.
- Boundaries between natural and economic systems cannot always be clearly defined. Are crop fields part of the natural environment, or are they production sites? LCA methodology requires clear system boundaries.
- Environmental effects are often local and difficult to quantify, such as soil degradation, groundwater depletion and natural habitat fragmentation.
- Some effects have to be discounted over a certain period of time, such as those on biodiversity and changes in soil organic carbon.
- In many cases agriculture or fishery produces more than one product (co-production). The environmental pressure has to be allocated between the different products.
- Land is often included as a resource. Land use as a resource indicator has to be interpreted with care, as there are many different types and intensities of land use, all with different impacts on the present and surrounding ecosystem. Moreover, land can be made more fertile by increased inputs. Certain studies differentiate between several types of land use. In the impact assessment phase of LCA, where emissions and used resources are aggregated and converted of into environmental impact categories, land use (and sometimes also land use change) is often regarded as an indicator for loss of biodiversity, taking into account quality (intensity) and quantity.

Life cycle assessments mostly are based on averages, representing a given production system. Such studies are also known as 'attributional LCAs' (ALCAs) (Ekvall and Weidema, 2004). Averages may be taken from only a few farms or from national statistics. They can represent actual farms or modeled farms. Another type of LCA describes marginal rather than the average effects, which are the result of new, additional production. The marginal pressure often deviates from the average environmental pressure because the most fertile soils already have been cultivated, and additional production usually takes place on 'new' less productive land. Also this additional production may displace other products from the market. Such change-oriented LCAs are known as 'consequential LCAs' (CLCAs) (Ekvall and Weidema, 2004). These two methods may differ strongly in terms of application area, aim, scope, timescale, uncertainty and outcome (Brander et al., 2009; Thomassen et al., 2008a).

Selection of LCA studies

For the purposes of this study 52 LCA studies were examined, which are listed in Table 1. More details are presented in the annex. We wanted to include as many studies as possible in order to have a robust range and to be able to examine the differences. For this reason some grey literature was also included. CLCAs and other LCAs that use system expansion were excluded because of the different scope, making them less comparable with regular LCAs. Studies that did not describe the production system and method in detail were excluded as well.

Most of the included LCAs have been published in peer reviewed journals. Some were published in reports, (e.g. Blonk et al., 2008, 2009; Ponsioen et al., 2010; Williams et al., 2006; Cederberg et al., 2009a; Hirschfeld et al., 2008). We only selected reports which were executed or commissioned by non-commercial scientific institutes (universities or governments).

Table 1
Overview of LCA studies reviewed.

Beef	*Pork*
Blonk et al. (2008)	Zhu and van Ierland (2004)
Casey and Holden (2006)	Basset-Mens and van der Werf (2005)
Cederberg et al. (2009a,b)	Williams et al. (2006)
Edward-Jones et al. (2009)	Cederberg and Flysjö (2004a)
FAO (2010)	Blonk et al. (2008)
Flachowsky and Hachenberg (2009)	Eriksson et al. (2005)
Hirschfeld et al. (2008)	Kool et al. (2009)
Nguyen et al. (2010)	Hirschfeld et al. (2008)
Ogino et al. (2007)	*Poultry products*
Pelletier et al. (2010)	Blonk et al. (2008)
Peters et al., 2009	Katajajuuri (2007)
Phetteplace et al., 2001	Mollenhorst et al. (2006)
Ponsioen et al., 2010	Vergé et al. (2009)
Vergé et al., 2008	Williams et al. (2006)
Williams et al., 2006	*Seafood (incl. freshwater fish)*
Sheepmeat	Aubin et al. (2009)
Edward-Jones et al. (2009)	Blonk et al. (2009)
Peters et al. (2009)	Ellingsen et al. (2009)
Williams et al. (2006)	Gronroos et al. (2006)
Blonk et al. (2008)	Iribarren et al. (2010a)
Milk and cheese	Iribarren et al. (2010b)
Berlin (2002)	Pelletier et al. (2009)
Blonk et al. (2008)	Ramos et al. (2011)
Casey and Holden (2005)	Silvenius and Grönroos (2003)
Cederberg and Flysjo (2004b)	Svanes et al. (2011a,b)
FAO (2010)	Vazquez-Rowe et al. (2010)
Haas et al. (2001)	Vázquez-Rowe et al. (2011)
Hirschfeld et al. (2008)	Vázquez-Rowe et al. (2012)
Sheane et al. (2011)	Ziegler and Valentinsson (2008)
Thomassen et al. (2008b)	Ziegler et al. (2003)
Vergé et al. (2007)	Ziegler et al. (2011)
Weiske et al. (2006)	*Meat substitutes*
Williams et al. (2006)	Blonk et al. (2008)
	Pulses
	Blonk et al. (2008)
	Nemecek et al. (2005)
	Sheenan et al. (1998)

All of the studies quantified the emission of greenhouse gasses, 17 of them also reported eutrophication and 18 also reported land use. Several studies compared conventional production methods with alternative methods, such as free range production systems. Most studies covered one product or type of product, others covered many different types of products (e.g. Blonk et al., 2008; Williams et al., 2006).

Data used for the LCAs sometimes were based on a single farm and in other cases on complete national industries. Often a typical farm or production system was modeled based on national statistics. Most of the LCAs were focused on European or North American production processes, covering a variety of production systems. The studies were published between 1998 and 2011. Most of the data stem from the late 1990s up to around 2005. All studies describe the situation in a certain year, therefore no time series are presented. Only Cederberg et al. (2009b) compares Swedish 1990 data with 2005 data, using several LCA studies.

Methodological issues

By-products and allocation

There are many co-production processes in agriculture and much recycling takes place, as a result of which the environmental pressures often have to be divided over several products or life cycles, also known as allocation. Rapeseed, soybeans and sunflowers, for example, supply both oil and fodder. At the end of the production chain animals provide a wide range of products, such as various cuts of meat, fat, hide and bones. A technique often used