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Environmental sustainability assessment from planetary boundaries perspective – A case study of an organic sheep farm in Finland

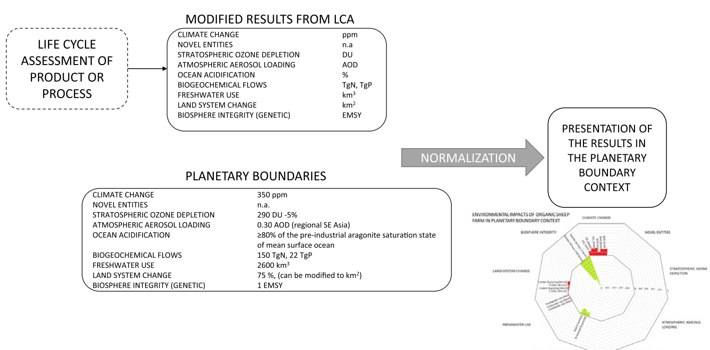
V. Uusitalo [a,*], A. Kuokkanen [a], K. Grönman [a], N. Ko [b], H. Mäkinen [a], K. Koistinen [a]

[a] *Lappeenranta-Lahti University of Technology, School of Energy Systems, Sustainability Science, P.O. Box 20, 53851 Lappeenranta, Finland*
[b] *Fraunhofer Institute, Fraunhofer Institute for Building Physics, Stuttgart, Germany*

HIGHLIGHTS

- A framework to present environmental impacts in planetary boundary context is developed.
- This enables a new way for combining magnitudes of environmental impacts from a process.
- Organic sheep farm with five environmental impact categories is used as an example case.
- Positive impacts to biodiversity are far greater than negative impacts on climate change.

GRAPHICAL ABSTRACT



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ABSTRACT

Food production processes may have both positive and negative environmental sustainability impacts. This makes decision-making challenging in the transition towards more sustainable food production systems. In this paper, a new method for presenting environmental impacts in the context of planetary boundaries is demonstrated. This will help food and agricultural producers compare the magnitudes of various environmental impacts.

The environmental sustainability impacts of an organic sheep farm in the boreal climate zone in Finland are studied herein first using a life cycle assessment method. The results are then normalized and presented in a planetary boundary framework to ascertain the extent of different environmental impacts.

The results show that in the planetary boundary context, there are positive impacts of sheep grazing on biosphere integrity (genetic diversity) and biogeochemical flows and negative impacts on climate change, land use or freshwater use. Magnitudes of the impacts greatly dependent on the assumptions made especially regarding biosphere integrity impacts. In the future, it is crucial that decision-making be based on the evaluation of various environmental impacts and that the focus be more on complex sustainability thinking, rather than on one single environmental impact.

This research demonstrates that results from a life cycle assessment can be modified and presented in a planetary boundaries context. A planetary boundary framework approach similar to that proposed herein could be further used to identify different environmental sustainability perspectives and to help one better recognize the multi-functional aspects of the ecosystem processes.

* Corresponding author.
E-mail address: ville.uusitalo@lut.fi (V. Uusitalo).

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1. Introduction

Agriculture is one of the key drivers of change in the functioning of the Earth's system. It is vital to humanity, and approximately 40% of the Earth's total surface is utilized for food production (Foley et al. 2011). Globally, agriculture causes 75% of deforestation (Vermeulen et al. 2013) and accounts for 13% of total greenhouse gas emissions (GHG), when emissions from the forestry sector and land-use change are taken into consideration (CAIT 2014). Moreover, land-use change is an important driver of global biodiversity loss (UNEP-RIVM, 2003, Zebisch et al. 2004, Tilman et al. 2001). It has been projected that Earth is currently facing the sixth mass extinction (Barnosky et al. 2011). Biodiversity is the cornerstone for securing the provisioning of ecosystem services needed for humanity (Balvanera et al., 2006, Cardinale et al. 2007); therefore, biodiversity loss can trigger non-linear and unpredictable outcomes in ecosystem functioning (Metzger et al. 2006; Foley et al. 2005). Interest has been raised concerning the design of a more sustainable form of agriculture that would bring humanity closer to the limits of the Earth system's ability to produce food fairly now and for future generations.

The planetary boundary (PB) framework proposed by Rockström et al. (2009) was the first attempt at quantifying thresholds for the key environmental functions within which people can safely operate, often called the *safe operating space* or herein, *safe operational zone*. They outlined nine boundaries and quantified the current state of seven of them. According to Rockström et al.'s (2009) and Steffen et al.'s (2015) evaluations, the thresholds have already been transgressed in the areas of biodiversity, biogeochemical flows of nitrogen and phosphorus (N and P), climate change and land-system change.

Typical life cycle assessment (LCA) studies of agricultural systems have included some environmental impacts, most commonly (and at the very least) global warming impacts. However, from a single process, impacts related to different Earth functions may be positive or negative. In addition, it is challenging to compare the magnitudes of different impacts. Therefore, it would be interesting to understand the impacts of a single product or process from a PB perspective, which would also help producers and decision makers during the transition to more sustainable systems. The development of this kind of link between LCA and PB has been called for by Bjørn et al. (2015).

Previous attempts to combine life cycle assessment with the planetary boundaries framework have mostly taken a top-down approach. Sundin et al. (2015) combined a PB framework with LCA by dividing environmental impact reduction targets for different market sectors and products. Also, Clift et al. (2017) called for the allocation of a safe operating space between companies and different sectors. According to Ryberg et al. (2016), it is especially challenging to model and include Earth system processes as impact categories in LCA. However, they view that PB-based LCA impacts assessment would be highly relevant in the environmental sustainability performance assessment of products and systems. Wolf et al. (2017) attempted to combine LCA and PB frameworks for food companies by using absolute environmental sustainability assessment methods in which the general principle is to compare the environmental footprint of a company with its assigned share of the environmental budget. Uusitalo et al. (2018) presented the environmental impacts of roach fish production according to a PB framework by using ILCD and CML normalizations. However, they did not normalize results in terms of planetary boundaries.

Planetary boundaries as well as the current state of each subcategory are presented using absolute values (Steffen et al. 2015). However, LCA studies usually present results as relative environmental impacts. Bjørn et al. (2016) demonstrated that it is possible to modify LCA indicators from being merely relative to being absolute indicators of environmental sustainability. Chandrakumar and McLaren (2018) and Dong and Hauschild (2017) found that some of the categories or indicators are represented in both LCA and PB. These previous studies suggest that if it is possible to use LCA methodology to calculate absolute values for a functional unit, then it is possible to modify LCA units to corresponding units of PBs. Presenting the environmental impacts of a product or a process in comparison with the safe operational zone values of PBs has not been done thus far.

The aim of this paper is to create a practical method to enable food and agricultural producers and politicians to understand environmental sustainability impacts in a planetary boundaries context. The need for developing such a method has been recognized earlier by Clift et al. (2017) and Bjørn et al. (2015). Organic sheep farming in Finland is used as a test case for the approach, as it seems to have both negative and positive impacts from the PB perspective.

The primary goal of small-scale organic sheep farming is two-fold: to protect very endangered rural biotopes and their biodiversity, but simultaneously to produce wool and meat. It is also assumed to have a positive impact on nutrient cycling. However, meat production in general is often blamed for causing high global warming impacts (Nijdam et al. 2012; Ripoll-Bosch et al. 2013). In Finland, 10% of all species were estimated to be endangered in 2010, and the number has been constantly increasing (Putkuri et al. 2013; Tiainen et al. 2015). More than 95% of rural biotopes are regarded as endangered (Kontula and Raunio 2013). The preservation of rural area and the low intensity management of grasslands are important for many plant and animal species in Finland (Hellström et al., 2003). The main driver of change of rural habitats is the intensification of agriculture, which has resulted in the decline of low intensity managed grasslands. This, in turn, has resulted in habitat loss and fragmentation in Finland (Roslin 1999) and in many parts of Europe (Gibson et al. 1987, Eriksson et al. 1995, Stampfli and Zeiter, 1999). For instance, in Finland, reduction of cattle farming over the last 50 years has resulted in the loss of 15% of the original 47 dung beetle species (Roslin 1999). A solution for preventing habitat loss and fragmentation could be mechanical devices that mimic grazing, but those cannot offer some of the ecosystem services provided by grazing animals, such as nutrient recycling, decomposition, seed spreading and habitat for species dependent on animal manure. Another solution, perhaps more impressive in terms of animal health and biodiversity, is a transition towards traditional grazing in animal production. Combining agricultural production priorities with biodiversity conservation is challenging (Tscharntke et al. 2012), but small-scale organic farming —organic sheep production— may help to combine different sustainability targets.

The main innovations of this study are outlined as follows:

- Development of a method to normalize LCA results to correspond the safe operational zone values of the planetary boundary categories
- Provision of guidelines for future research for presenting LCA results in a PB context
- Testing of how this works using an organic sheep farm as an example
- Provision of environmental sustainability data for an organic sheep farm

2. Materials and methods

This chapter first describes the approach developed to depict life cycle environmental impacts in a planetary boundary context. It then presents the life cycle assessment conducted for the Finnish organic sheep farming case. Finally, it presents the results in a PB context.

2.1. Developing a methodology for presenting LCA results in a planetary boundaries context

In this paper, the focus is placed on the five planetary functions that have been evaluated as being the most critical for providing safe conditions for humanity. These categories are climate change, biosphere integrity, biogeochemical flows, land-system change and freshwater use

(Rockström et al. 2009; Steffen et al. 2015). There are indeed other functions presented by Rockström et al. (2009) and Steffen et al. (2015), but these functions have either been evaluated as being within a safe zone or there are not enough data to evaluate them yet.

The climate change category in the PB framework is defined as the CO_2 concentration in the atmosphere. The current state of this category is 397 ppm of CO_2, exceeding the planetary boundary, which is 350 ppm of CO_2 (Steffen et al. 2015). One challenge in combining the LCA impacts with the CO_2 concentration is that LCA typically calculates global warming impacts as CO_2eq, and this also includes other gases such as CH_4 and N_2O, which do not impact the CO_2 ppm concentration in the atmosphere. To assess LCA results in the PB context, CO_2 emissions (as a mass) have to be converted into a concentration in the atmosphere in the form of ppm. According to records of the Global Greenhouse Gas Reference Network (2017), atmospheric CO_2 concentrations rose by 3.0 ppm between 2015 and 2016. Annual global greenhouse gas emissions for the same period are approximately 35 $GtCO_2$, plus an additional 4 $GtCO_2$ if land-use change is also included. In addition, other greenhouse gases such as CH_2, N_2O and F-gases create 10 $GtCO_2$eq emissions (Olivier et al. 2017). According to the data presented above, it can be calculated that one $GtCO_2$ (including land-use change) increases the atmospheric ppm concentration by 0.0796 ppm, and if other greenhouse gas emissions are included, then one $GtCO_2$eq corresponds to 0.0612 ppm. By using these assumptions, CO_2 emissions from an LCA study can be compared to the CO_2 concentrations of the planetary boundary climate change category.

Biosphere integrity is divided into two main categories: functional diversity and genetic diversity. However, because of the lack of data on functional diversity, we concentrate on genetic diversity (Steffen et al. 2015). The PB for genetic diversity is 1 extinction per million species years (EMSP), which is assumed to be the natural background extinction rate. The current state is estimated to be 100–1000 times higher (Steffen et al. 2015). It is challenging to assess genetic biodiversity impacts using an LCA approach, but such methods are currently being developed. Michelsen and Lindner (2015) compared different methods of including biodiversity impacts in LCA land-use analysis. However, researchers have not reached a consensus concerning how biodiversity impacts could be included in LCA studies.

Biogeochemical flows have been defined separately for phosphorus (P) and nitrogen (N). The global limit for P is 11 $Tg_P\ a^{-1}$ transmitted from freshwater into the ocean, and the current value is 22 $Tg_P\ a^{-1}$. The global limit for N is 62 $Tg_N\ a^{-1}$, which is defined as the industrial and intentional biological fixation of N. The current value is 150 $Tg_N\ a^{-1}$. There is also a separate regional level of 6.2 $Tg_P\ a^{-1}$ for phosphorous (Steffen et al. 2015).

Land-use change is defined as an area of forest land as a percentage of original forests; and for boreal, temperate and tropical forests, as a percentage of potential forests. The current state of global forests is 62%. The boundary for global forests is 75%, and for boreal forests, 85% (Steffen et al. 2015). According to the (World Bank 2017), the global land area was 129,733,173 km^2, and currently 31% is covered by forests. Boreal forests cover approximately 16,600,000 km^2 (Global Forest Atlas 2018). LCA data for land-use change related to forest cover could be compared directly to these figures, depending on the forest type.

The freshwater use category is defined based on "blue" water consumption, and the PB is set to 4000 $km^3\ a^{-1}$. Currently, it is estimated that 2600 km^3 water is used. There are also specific limits for local river basins (Steffen et al. 2015).

This paper focuses on five PB categories: climate change, biosphere integrity, biogeochemical flows, land-system change and freshwater use. Three other categories were not included in this study: novel entities, stratospheric ozone depletion and atmospheric aerosol loading. The novel entities category cannot be included because the planetary boundary has not been defined for the category. The PB for stratospheric ozone depletion is defined based on the pre-industrial level of 290 Dobson Units (DU), and a 5% reduction to the level is recommended. Dobson Units represent O_3 concentration in the stratosphere, and this is applicable over Antarctica. The stratospheric ozone hole is recovering, and the importance of this category is decreasing. Atmospheric aerosol loading is calculated as Aerosol Optical Depth (AOD), and a PB is defined only regionally for South-East Asia (Steffen et al. 2015). Challenges might surface in producing data for this category with life cycle assessment.

By using LCA, most of the categories presented in the planetary boundaries framework can be calculated as absolute values. It is then possible to correlate different categories with planetary boundaries by using a normalization process. After this, the normalization results related to a product or process can be presented in the PB framework to display the impacts in comparison to each other. Fig. 1 presents an approach developed to present the impacts of a product or process in a planetary boundary context. Normalization has been done using the following equation:

$$n_i = \frac{r_i}{z_i}, \tag{1}$$

where

n is the normalized results,
r is the modified results from the life cycle assessment,
z is the safe operational zone (Steffen et al. (2015)), and
i is the planetary boundary category.

2.2. Data collection and a life cycle assessment model for an organic sheep farm

Life cycle assessment methodology is used to evaluate environmental impacts related to the five selected PB categories (climate change, ocean acidification, biogeochemical flows, freshwater use, land-system change and biosphere integrity (genetic diversity)). The LCA model is based on the instructions and guidelines of ISO, 14040 and ISO, 14044. The functional unit of the study is the operation of a Finnish organic sheep farm (OSF) for one year, consisting of annual meat (1000 kg), wool (114 kg) and biomass (400 kg) production, of grazing on biodiversity hotspots (10 ha) and of 22 sheep sold living. This is presented in more detailed in Fig. 3. The example sheep farm is located in the Päijät-Häme region of Finland. In previous studies, the environmental impacts have been allocated to different products, and the functional unit has typically been one kg of sheep meat. However, in this paper, we present the impacts related to the entire process of raising and keeping sheep, because it is a more comprehensive approach than that of merely focusing on a single product (and thus allocation can be avoided). Defining a main product for the process is challenging because financial income for the farm is generated from different sources; viz., from meat production, biodiversity protection and wool. Income may also be gained from other side-flow uses and farm-related services, such as accommodation services.

Organic sheep farm processes have various inputs and outputs. Typically, sheep graze during the summer, but during the winter, they must be fed with concentrated feed and dried grass. The main physical products are wool, meat, hides and other biomass that can be used, for example, as feed for animals used in fur production, as tallow for energy production or as pet food. Sheep digestion produces manure and methane. Manure on fields or in storage leads to nitrogen emissions (e.g. in the form of N_2O and NH_3) (Wiedemann et al. 2015). Farming operations also require the use of energy in transportation, electricity and heat. Biodiversity protection as an ecosystem service can be considered as the main output of the process. Inputs and outputs of the sheep farming process are presented in Fig. 2.

System boundaries, main processes and products for the LCA model are presented in Fig. 3. Initial data for the model have been gathered from two main sources. Primary data (Fig. 3) related to the example OSF have been gathered directly from the farm, and the values represent the farm operations over the entire year 2016. The secondary data, for

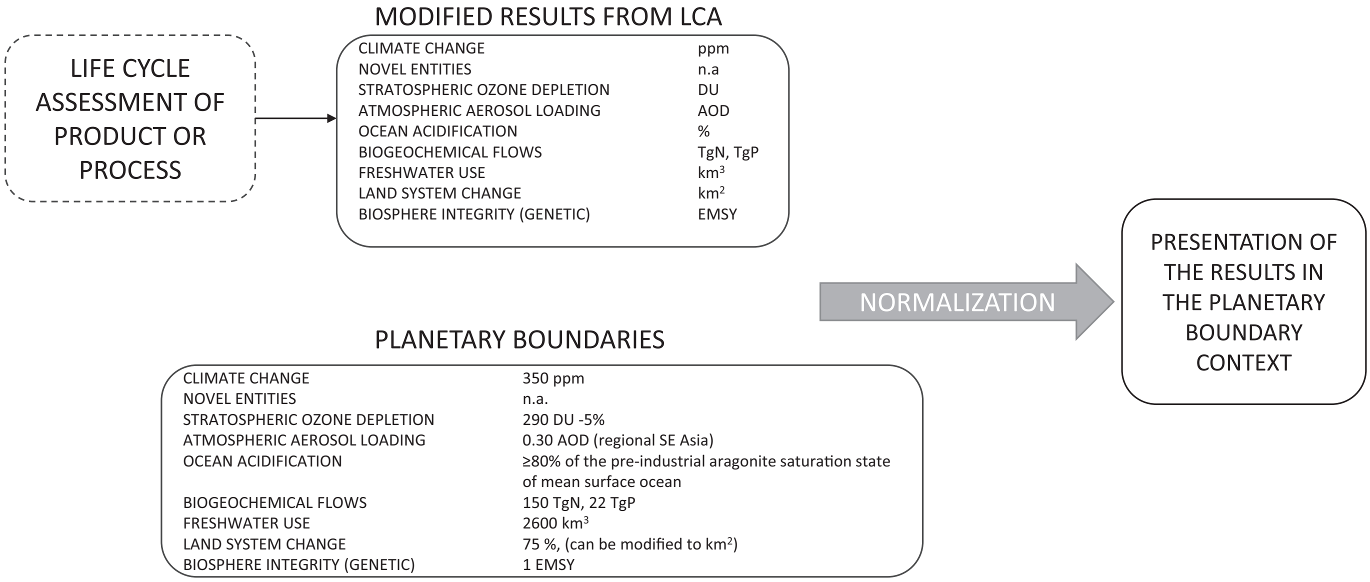

Fig. 1. Description of the method for presenting the impacts of a product or process in the planetary boundary context.

example those related to energy and fodder production, are gathered from the literature (Table 1). Variation of initial data is presented in parentheses and used to calculate minimum and maximum environmental impacts.

Forage crops (including legumes and grasses) are produced as hay and as forage swards for grazing purposes. Some surplus grass, oats and peas are also sold to other farms. Adult (ad) sheep and some of the first calendar year (1cy) sheep graze at pastures close to the farm. Some of the 1cy sheep are transported to biodiversity hotspots requiring grazing. The main reason for this grazing is the protection of *Parnassius mnemosyne* butterfly habitat. According to Kuusisaari and Lumiaro (2018), grazing in one of the biodiversity hotspots has already increased the butterfly population significantly, but it is not precisely known how many similar farms are required to prevent the butterfly species from going extinct. Therefore, in this paper the quantity is roughly assumed to be between 1 and 100. After the summer of 2016, some of the sheep were transported to a slaughterhouse. Some (9 ad and 13 1cy) sheep were sold to other farms. In addition, a few sheep died during the summer from ingesting poisonous plants. The transportation distance from the farm to the biodiversity hotspot pasture and from the farm to the slaughterhouse is approximately 60 km in each case. Four ad and five 1cy sheep can fit in one transportation direction,

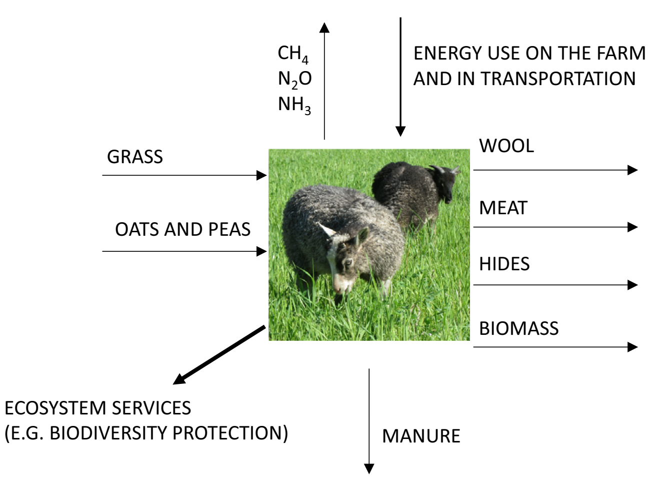

Fig. 2. Inputs and outputs of sheep production.

and a farmer visits the pasture 10 times during the summer. Transportation is assumed to be carried out by a 1.2 t payload diesel EURO 3 van using 2.9 MJ km^{-1} diesel with 220 gCO_{2eq} km^{-1} emissions (Lipasto database). Daily blue water consumption from rivers and a well has been assumed to be 4 (2–6) liters per sheep.

The OSF has fields for fodder production in two locations, with a total area of 6.7 ha. In addition, biodiversity protection is carried out at two hotspots and on a farm site, with a total area of 10.0 ha. In this research, no detailed analysis of biodiversity impacts related to these specific sites is carried out.

In addition to outputs from the system under study, mass stock of sheep on the farm also increases during the summer. One third of ad sheep weigh 35 kg at the beginning of the year, and they gain 10 kg of weight during the year. Two thirds of ad sheep weigh 45 kg at the beginning of the year, and they do not gain any more weight. A 1cy sheep weighs 30 kg at the end of the year.

Methane emissions from sheep digestion are one main greenhouse gas source of the OSF process. Wiedemann et al. (2015) present methane emissions based on sheep weight. The higher the mass of the sheep, the higher the methane emissions. According to Regina et al. (2014), an average sheep in Finland emits 8.4. $kgCH_4$ a^{-1}. The weight of an average sheep in Finland has been assumed to range from 65 to 100 kg. Hence, methane emissions vary from 0.08 to 0.13 $kgCH_4$ kg^{-1}. It is notable that the sheep in the example OSF are significantly smaller than the average Finnish sheep and this has been taken into account in the methane emission calculations. It is assumed that 0.0221 kg nitrogen is in fodder and grass, 0.037 kg in peas and 0.021 kg in oats (Kunelius et al. 1996; Maaseutuvirasto 2008). Nitrogen mainly ends up in manure, and a portion of it is emitted as N_2O and NH_3 (Wiedemann et al. 2015). N_2O is also produced from NH_3. A portion of nitrogen in feed and grass will wind up in wool and sheep biomass. Approximately 3.5% of sheep mass is nitrogen, and 10–14% of wool is nitrogen.

Grazing impacts on soil carbon studied by either increasing or decreasing the carbon amount depends on grazing intensity (Martinsen et al. 2011). According to Conant et al. (2001), many factors affect soil carbon change when grazing begins or changes. According to (Liu et al. 2012), light grazing can add soil organic carbon (SOC) by 20% compared to conditions without grazing. As reported by Martinsen et al. (2011), light grazing can add soil carbon in low-alpine grasslands by 5% during a seven-year test period. For the purposes of this paper, we have been using data gathered by Martinsen et al. (2011) for the

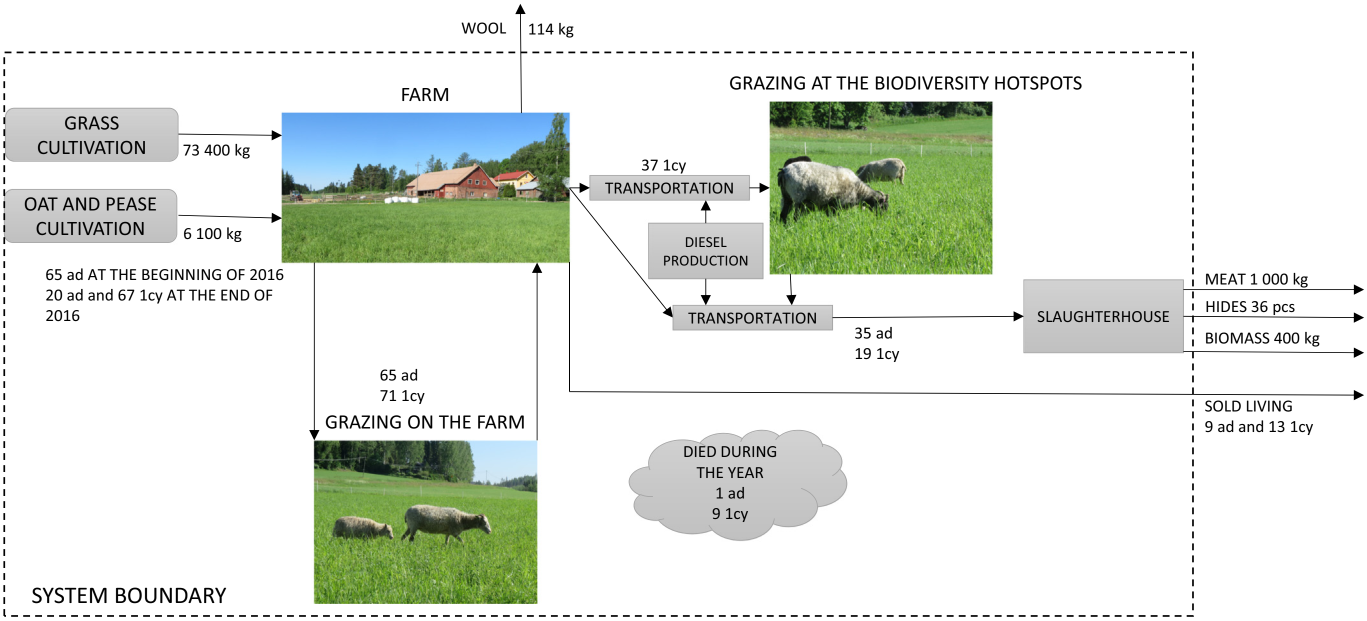

Fig. 3. Life Cycle Assessment model for an organic sheep farming system. Primary data on inputs, outputs and stock are shown. Note: ad = adult (sheep); 1cy = first calendar year (lamb); pcs = pieces.

Norwegian willow-shrub biotope, as it can be assumed to be relatively close to Finnish willow-grass biotopes. The soil carbon over the first seven years is 0.76 (0.64–0.80) $kg_C\ m^{-2}$.

3. Results and discussions

3.1. Climate change

Fig. 4 presents GHG emissions from the organic sheep farm (OSF) for the example year 2016 using the CML characterization method. As can be seen in the figure, N_2O from manure and enteric CH_4 have the highest impact on global warming, followed by fodder production. According to the results, grazing impacts on soil carbon are at a relatively low level compared to enteric CH_4 and manure N_2O emissions. In addition, the soil carbon amount will stabilize over the years. The impacts from soil carbon changes especially occur when grazing starts in a new area. The results are highly dependent on GHG emission factors. In particular, enteric CH_4 and manure N_2O rates may vary highly, depending on the initial data.

OSF operations lead to intensification of climate change mainly owing to enteric methane emissions, manure-related N_2O emissions, and feed production-related emissions. Sheep production has typically been blamed for relatively high GHG emissions when compared to other ways of producing protein (Nijdam et al. 2012), which is in line with our results. According to Ledgard et al. (2010), the majority of GHG emissions appertain to farm processes, which has been confirmed in this research. However, the importance of manure N_2O is higher than that presented by Ledgard et al. (2010). The role of methane emission is roughly at the same level as that presented by Nijdam et al. (2012). There is high variation in enteric methane and manure N_2O emissions in the literature. Biswass et al. (2010) also concluded that methane and N_2O are the main contributors to sheep farm GHG emissions.

According to Liu et al. (2012), light grazing could add soil organic carbon, which would lead to sequestration of carbon. However, calculating the exact rate of carbon sequestration would require additional SOC measurements under boreal climate zone conditions. Therefore, there is still uncertainty about the total climate change impacts of the OSF. The Norwegian data used in this paper do, however, suggest that light

Table 1
Secondary data sources for the Life Cycle Assessment model. Values in parentheses are used in the sensitivity analysis.

Secondary data	Amount	Data source
Grass cultivation for feed	200 (150–250) $gCO_2eq\ kg^{-1}$	Mogensen et al. 2012
Pea cultivation	490 (440–540) $gCO_2eq\ kg^{-1}$	Nette et al. 2016
Oat cultivation	330 (300–350) $gCO_2eq\ kg^{-1}$	Finér 2009
Diesel production	88 $gCO_2eq\ MJ^{-1}$	BioGrace
N_2O from manure	1.25% (0.4–2.0%) of nitrogen	Regina et al. 2014; Wiedemann et al., 2015
NH_3 from manure	0.1 kg $NH_3\ kg_N^{-1}$	Wiedemann et al., 2015
Indirect N_2O from NH_3	0.01 kg $N_2O\ kg_{NH3}^{-1}$	Wiedemann et al., 2015
Nitrogen in grass	0.0221 kg N kg^{-1}	Kunelius et al. 1996
Nitrogen in peas	0.037 kg N kg^{-1}	Nykänen et al. 2012
Nitrogen in oats	0.021 kg N kg^{-1}	Yara

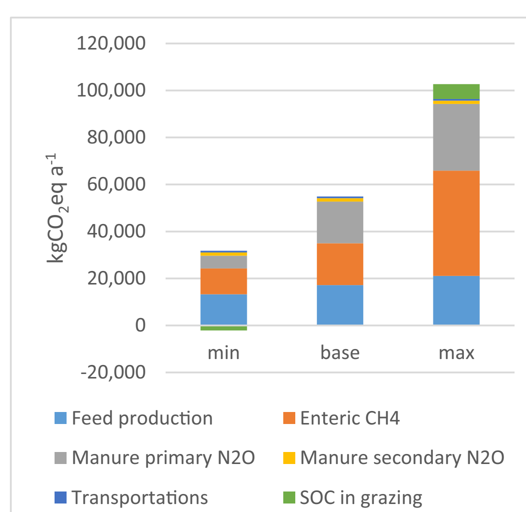

Fig. 4. Annual GHG emissions from different sources on the organic sheep farm. Note: SOC = soil organic carbon.

grazing has the potential to increase SOC, but the carbon sequestration is at a low level compared to the direct GHG emissions from farming. It is clear that grazing has impacts on soil organic carbon storage (Piñeiro et al. 2010). After just having started, grazing could provide the possibility to sequestrate carbon for a short period of time. Thereafter, carbon sequestration is balanced. According to Laca et al. (2010), grazing may hold great potential for carbon sequestration in the short term, but the magnitude of the impact varies from positive to negative according to previous studies (Martinsen et al. 2011; Johnson and Matchett 2001; Leifeld and Fuhrer 2009).

3.2. Biogeochemical flows (nitrogen)

Nitrogen is removed from fields through the consumption of fodder. A portion of nitrogen in fodder is released into the air as N_2O and NH_3 through sheep digestion. This was also demonstrated by data collected by Wiedemann et al. (2015). Wu et al. (2014) showed that limiting grazing increases nitrogen amounts in soils. (Phosphorous, on the other hand, remains in manure and is recirculated back to the fields. Therefore, phosphorous removal through grazing is assumed to be minimal.) In addition, grazing releases a portion of nitrogen into the air from grass similar to the release from fodder consumption. Nitrogen is also removed in the forms of sheep biomass and wool. The calculated nitrogen removal from fields is 202 kg through fodder nitrogen release into the air; 132 kg through sheep biomass, including wool; and 226 kg through grazing N_2O release into the air.

The results presented in this paper on biogeochemical flows can be regarded as an indication only, and an exact analysis would require measurements, especially of soil nutrient changes through grazing. Therefore, the results are incomplete. In addition to nitrogen removed from plants into the atmosphere, there may be changes in nutrient contents of soils, but these changes were not studied here due to the lack of relevant data. This would also require more detailed measurements. The OSF differs from conventional sheep production, except in terms of production volume and of a surplus of nutrients impacting the grassland vegetation (Hellström et al. 2003).

3.3. Land-system change

The total land area required for fodder production is 6.7 ha, with the total grazing area being 10.0 ha. The grazing area may be divided into on-farm grazing and grazing at biodiversity hotspots. Organic sheep farming uses land and may lead to land-use change. However, it is not clear what the natural state of lands under pasture would be, whether or not there is land-use change, and if there is, how dramatic the change is. The area used by the OSF could be covered by forest. It is also possible that due to wildlife grazing, it could be natural meadows. In the case of meadows, the land-use change would not be as significant, although without grazing, the proportion of the trees would slowly increase, and this would reduce the endangered biotope in the long term.

3.4. Biosphere integrity (genetic diversity)

The primary goal of sheep grazing in Finland is to protect and save the most endangered biotopes, including the endangered *Parnassius mnemosyne* butterfly. However, it is not clear how many species can be saved from extinction due to OSF grazing operations. The analysis of this paper is based on the assumption that this one butterfly species can be saved from extinction due to OSF. According to Johansson et al. (2017), *Parnassius mnemosyne* butterfly populations in southern Scandinavia are larger in areas with light grazing compared to areas with heavy or no grazing. The *Parnassius mnemosyne* butterfly is at high risk of extinction in southern Scandinavia within the coming decade, but light grazing reduces this risk significantly (Johansson et al. 2017). According to Kuusisaari and Lumiaro (2018), the *Parnassius mnemosyne* butterfly population grew 2.5-fold within a year in the biodiversity hotspot where the sheep of the OSF were grazing. In addition, if this particular butterfly is saved from extinction, it is likely that other species requiring a similar biotope could also be saved. Sheep grazing may also affect biodiversity in that animals are able to spread plant propagules (Hellström et al. 2003).

3.5. Freshwater use

The OSF consumes freshwater from a local river and well, particularly as drinking water for the sheep. Annual blue water withdrawal is 88 (44–103) m^3. There may also be additional evaporation from water systems, but this is not included in the study.

3.6. Organic sheep farm operations presented in the planetary boundary context

Table 2 presents the LCA analysis results converted into the absolute values utilized in the planetary boundaries. These values have been compared to the safe operational zone limits of PBs in each category (Steffen et al. 2015). Variation due to the main assumptions is also included in the table.

The final step is to present the results presented in Table 2 in the PB context (Fig. 5). The color red is used to present impacts that are taking humankind further away from a safe operational zone, and green presents the impacts that help humankind stay within a safe operational zone. The scale in the figure is logarithmic.

As can be seen in Fig. 5 and Table 2, from the PB perspective, biosphere integrity impacts (regarding genetic diversity) contain positive impacts that are many times higher than in other categories. There is a caveat to this: great uncertainties exist in relation to the biodiversity impacts of the OSF process studied, so more research should be focused on this issue in the future. The positive impacts on biogeochemical flows (nitrogen) and negative impacts on global warming are relatively at the same levels. Land-system change and freshwater use impacts are lower. The land-system change planetary boundary is defined according to changes in forest cover. However, to enable protection of rural biotopes, the natural regeneration of forests is avoided by grazing. In this OSF case, to achieve positive impacts on biosphere integrity, negative impacts on land-system change by definition cannot be avoided. Freshwater use has minimal impacts compared to the other categories studied here. Based on the analysis, it seems that despite the high GHG emissions, positive environmental sustainability impacts could be gained from the biogeochemical flow and biosphere integrity (genetic diversity) planetary boundary categories.

Our main goal has been to create an approach for presenting LCA results in a PB context. This paper demonstrates that this can be achieved relatively easily, despite the challenges of some of the PBs, such as biosphere integrity. Maier et al. (2019) have created a model to include biodiversity impacts in LCA, which would help produce more precise data on biosphere integrity impacts, too. Other challenges have presented themselves as well. As mentioned earlier in this paper, climate change impacts are presented only as CO_2 in PBs, but LCAs typically also include other GHGs. There are challenges in converting CO_2 emissions from a product or process into ppm in the atmosphere, and this should be studied in more detail in the future. Other PBs are presented in units that are more easily calculated using LCA. However, it should be borne in mind that there is still much uncertainty surrounding PBs and safe operational zones in general. Some of the environmental challenges are local, but the localization of impacts cannot be considered in the PB approach.

In the future, it would be interesting to study what the economic costs would be of sustaining biodiversity without grazing, or (in a different vein) what the costs would be of mitigating GHG emissions with optional methods, such as investing in renewable energy.

Only one example farm was used in this analysis. If we had included various farms, the impacts and magnitude of impacts might differ. However, we argue that due to the high variation used in the initial data of

Table 2
The organic sheep farm operation based on LCA, safe operational zones of PBs (Steffen et al. 2015) and the normalized results.

	Emissions based on LCA converted into absolute values [r_i]	PB safe operational zone limit [z_i]	Normalized results [n_i]
Climate change			
CO_2 only (min)	2.28E−6 ppm of CO_2	350 ppm of CO_2	6.52E−9
CO_2 only (base)	4.22E−6 ppm of CO_2	350 ppm of CO_2	1.21E−8
CO_2 only (max)	7.90E−6 ppm of CO_2	350 ppm of CO_2	2.26E−8
GHGs (min)	1.82E−6 ppm of CO_2	350 ppm of CO_2	5.19E−9
GHGs (base)	3.36E−6 ppm of CO_2	350 ppm of CO_2	9.60E−9
GHGs (max)	6.19E−6 ppm of CO_2	350 ppm of CO_2	1.80E−8
Biogeochemical flows			
N total removal	−5.61E−7 Tg of N	62 Tg of N	−9.05E−9
N removal by grazing	−2.26E−7 Tg of N	62 Tg of N	−3.65E−9
Freshwater use			
Freshwater use (min)	8.8E−8 km^3	4000 km^3	1.1E−11
Freshwater use (base)	4.4E−8 km^3	4000 km^3	2.2E−11
Freshwater use (max)	1.3E−7 km^3	4000 km^3	3.3E−11
Land-system change			
Land use for fodder production	0.00067 km^2	10,054,321 km^2 (world forests)	6.7E−11
Total land use (fodder production and grazing on a farm site and biodiversity hotspots)	0.00167 km^2	10,054,321 km^2 (world forests)	1.7E−10
Land use for fodder production	0.00067 km^2	2,490,000 km^2 (boreal forests)	2.7E−10
Total land use (fodder production and grazing on a farm site and biodiversity hotspots)	0.00167 km^2	2,490,000 km^2 (boreal forests)	6.7E−10
Biosphere integrity			
Genetic BD loss	−1.0 EMSY (one farm)	8.7 EMSY	−1.15E−1
Genetic BD loss	−0.01 EMSY (10 farms)	8.7 EMSY	−1.15E−3

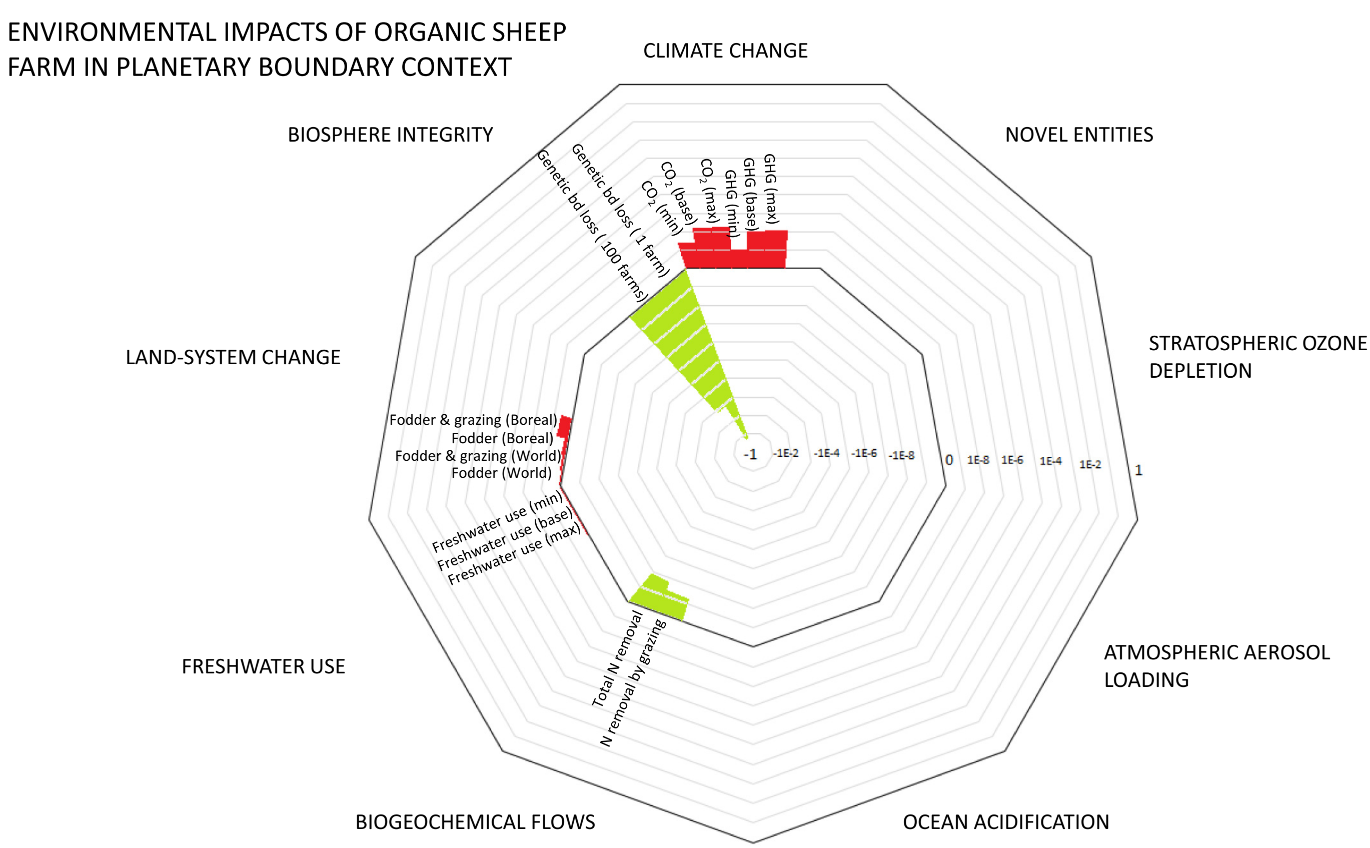

Fig. 5. Environmental impacts of organic sheep farming normalized to correspond to the safe operational zones of the planetary boundaries. Red represents a negative impact; green, a positive one. Note: bd = biodiversity.

the LCA part, it is unlikely that the conclusions drawn from the results would change significantly. This paper works as an example of an approach to evaluate the magnitudes of different environmental impacts from a PB perspective, and using one example farm was enough to demonstrate the process. In the future, it would also be critical to carry out comparative studies, for instance between organic and non-organic sheep farms. To enable the comparison, another functional unit should be chosen, such as annual meat production.

It is important for one to understand the environmental impacts concerning different sustainability dimensions instead of simply comparing different products from a single sustainability impact perspective. For example, only comparing proteins from a carbon footprint perspective may lead to incorrect conclusions from a biodiversity perspective. We propose that others also use the approach presented in this paper to be better equipped in other production sustainability assessments.

4. Conclusions

This paper is the first attempt to present LCA results for a process using a planetary boundary perspective, by normalizing LCA results to correspond to safe operational zone values. Our aim is to ease decision- making for food and agricultural producers and politicians in view of making the transition towards more sustainable food production systems possible, by presenting environmental impacts in a comparative manner.

According to the results, there are positive impacts of sheep farming on rural biotope biodiversity protection and biogeochemical flows and negative impacts on climate, fresh water use and land-system change. Thus, it is critical that various sustainability perspectives for decision-making purposes be included. Including only a single impact category or encountering challenges in comparing different impacts could possibly lead to incorrect decisions taken as relate to the bigger picture.

This research has shown that it is possible to convert LCA results into a form where they can be directly compared to PBs. There are challenges in presenting LCA results in applicable units for some of the categories, but this area could be further developed to overcome those.

We propose that others use a similar PB framework approach in their studies to provide a more holistic picture of processes under research. Combining LCA and PB approaches does, however, require further development and more case examples.

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