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LCA FOR AGRICULTURE

Modelling environmental effects of selected agricultural management strategies with regional statistically based screening LCA

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Abstract

Purpose Despite the farm being considered by many as the most suitable level of decision-making and strategic management in agriculture, there is an increasing interest in evaluating agricultural management strategies at the regional level. Recent initiatives attempted to aggregate and generalise farm-level lifecycle inventory (LCI) data and lifecycle impact assessment (LCIA) results to describe the environmental performance of agricultural regions. This article describes our development and application of a regional statistics-based approach for constructing *virtual representative farms* (VRFs), representing dominant farm types for a given region, as a tool for comparing alternative regional agricultural strategies in contexts of insufficient farm (e.g. LCI) data.

Methods Based on statistical sources, we constructed VRFs of the dominant farm types in the largely agricultural region of Brittany, France. Environmental impacts of different agricultural management strategies were estimated at the regional level by modelling the strategies as changes in VRF-based LCIs, calculating LCIAs and extrapolating their mean per-ha impacts to the total land use in the region. Based on this assessment, performed using a regional lifecycle assessment framework, we analysed relative environmental impacts of each management strategy on the region. A strategy-comparison table was built to allow decision makers to understand the potential regional environmental consequences of implementing each strategy.

Results and discussion Once VRFs impact assessment results were extrapolated to the regional level, all strategies show environmental impacts per ha similar to those of the baseline, with differences ranging from −15 to +6%. The scenario featuring centralised fodder drying by 50% of cattle farms (50FOD) is the only one featuring surpluses for all products, due to associated cattle diet adjustments including reduced maize silage intake and partial substitution of concentrate feeds. The scenario featuring grass specialisation by all cattle farms (100GRA) shows a large deficit of grassland products, suggesting that a region-wide extensification strategy would not be self-sufficient.

Conclusions The method developed enables comparing environmental consequences of region-wide implementation of agricultural strategies, yet, for our case study, it is particularly difficult to identify a "best" one. Nonetheless, the method serves as an initial step for preselecting strategies to investigate at a more detailed level. Prioritisation of a given strategy would likely be based on the environmental pressures considered most pressing by regional decision makers.

Keywords Farm management strategies · Lifecycle assessment · Regional assessment · Virtual farms

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1 Introduction

Despite the farm being considered as the most suitable level of decision making and strategic management in agriculture (Del Prado et al. 2013), there is an increasing interest in evaluating agricultural management strategies at the regional level (Payraudeau and van der Werf 2005; Sadok et al. 2009; Bartl et al. 2012; Acosta-Alba et al. 2012). A region, including an agricultural one, can be defined in various ways: as a natural geographic entity (e.g. a catchment), as a network of cooperating productive areas (e.g. a farm network) or as a geo-political territorial entity (e.g. a municipality), among others.

Recent initiatives attempted to aggregate and generalise farm-level lifecycle inventory (LCI) data and lifecycle impact assessment (LCIA) results to describe the environmental performance of agricultural regions—reviews of such approaches are given in Payraudeau and van der Werf (2005) and Avadí et al. (2016). These endeavours are data-intensive, for a large and representative sample of farms within the studied region is necessary for meaningful extrapolations (generalisations). A common element of extrapolation approaches involves constructing farm typologies and modelling real or virtual farms representative of each farm type in the typology, which constitutes a challenging endeavour (Vayssières et al. 2011). The approach of basing screening LCAs on statistical sources at a scale larger than the process or product scale has been used to characterise all activities in a region (Loiseau et al. 2012) and contrasting agricultural Technological Management Routes (i.e. a logical set of field operations designed by farmers) (Salou et al. 2017), but, as far as we know, never before has contrast to several agricultural strategies been massively implemented at the regional level. This article describes our development and application of a regional statistics-based approach for constructing *virtual representative farms* (VRFs), representing dominant farm types for a given region, as a tool for comparing alternative regional agricultural strategies in contexts of insufficient farm (e.g. LCI) data.

To test the method, we applied it to a French administrative, and largely agricultural, region —Brittany—and compared environmental impacts of different agricultural management strategies at the farm-type and regional levels. Based on this assessment, performed using the lifecycle assessment (LCA) framework, at the screening level (Jensen et al. 1997), we attempted to understand relations between agricultural practises and relative environmental performance of each management strategy. A strategy-comparison table was built to allow decision makers in the region to understand regional environmental consequences of implementing each strategy.

1.1 Case study

Among French administrative regions, Brittany has the highest combined production volume of agricultural products, producing (in 2013) 58% of the national production of swine, 43% of eggs, 35% of poultry, 21–36% of various types of beef (i.e. from dairy and suckler systems), 22% of cow milk and 24% of maize (for fodder) and high percentages of the national production of some vegetables (e.g. 84% of cauliflower) (CCI 2013). In 2010, Brittany contained roughly 34,500 farms on 1.64 million ha of usable agricultural area (UAA), which covers 62% of the region (CCI 2013; CAB 2014). Breton farming activities encompass a wide variety of farm types and agricultural practises. Most farms are medium- and large-sized enterprises, with a mean UAA of 60 ha (AGRESTE 2011; CAB 2014) and combined crop and animal production (mixed farms). The most common farming systems in Brittany are centred on dairy cattle (29%), followed by swine (10%) and poultry (9%) and a variety of mixed farms featuring combinations of cattle, other animals and crops (AGRESTE 2011; CAB 2014). Most swine and poultry production is intensive, confined animal production, but some farmers producing swine and poultry, and most farmers producing cattle grow crops on land fertilised with the resulting manure (Ellies 2014). Regional agricultural land use is dominated by cereal production (34%) and temporary grassland (30%), followed by silage maize (20%), permanent grassland (8%), oilseed crops (2%) and fresh vegetables and tubers (4%), with the remaining 2% corresponding to other crops and land uses such as flowers, seed production, fruit and fallows (AGRESTE 2011; CAB 2014). The region is not self-sufficient in animal feed: despite producing 8.2 million t of agricultural products for animal feeding (in 2013), it imported an additional 4.1 million t of these products, mainly soya bean meal (1.9 million t) (CAB 2014). Agricultural activities provided the equivalent of 27,500 full-time jobs and produced EUR 9.14 billion in agricultural produce, 68% of it from animal products (CAB 2014). Some coastal areas in Brittany have a history of eutrophication problems related to agricultural activities; one such area is the Lieue de Grève catchment (Gascuel et al. 2015), where eutrophication is controlled by N loads resulting mainly from agricultural practises (e.g. over-fertilisation, permanent-grassland ploughing, bare soils in winter) and manure management (Corson and Avadí 2015).

1.2 Management strategies

Several agricultural management strategies were explored, based on European regional strategies described and analysed in the CANTOGETHER project (http://www.fp7cantogether.eu/) and previous research on Brittany's agriculture (GRA, SIL and FOD are aimed exclusively at cattle systems):

- GRA—grass specialisation (Delaby et al. 2015): relies primarily on grassland production to feed cattle. This scenario limits stocking density (e.g. below 1.4 livestock units (LSU)/ha) and aims to decrease eutrophying emissions and farm (and thus regional) dependence on imported feed—mainly Brazilian soya bean meal (Lehuger et al. 2009)—and fertilisers. This strategy is commensurate with extensification and may also entail re-distributing land use to improve access to grasslands by cattle.

- SIL—maize silage specialisation (Cadoret 2008): relies largely on maize silage production to feed cattle. This scenario reduces dependence on grazing. It aims to increase milk production per cow (i.e. feeding maize, with higher energy content than grass) and produce cattle feed on fields that are too far from the stable to be grazed practically. This strategy is commensurate with intensification.
- FOD—centralised fodder drying (Corson and Avadí 2015; Regan et al. 2015): aims to provide animal farms with winter fodder by drying fodder with coal in a centralised furnace. It aims to reduce the need for off-farm winter fodders and/or partially replace concentrate feeds.
- REW—rewilding: the practice of setting aside portions of agricultural land to be re-naturalised. Such re-naturalisation may or not imply certain human activities, such as grass cutting, tree and bush trimming, enclosing by fences, afforestation, etc. It is similar in intention to the "land sparing" strategy, in which some agricultural area is spared from exploitation while yields are increased in the remaining area (Green et al. 2005).
- GME—grain and manure exchange among farms (Regan et al. 2015): a collaboration strategy aiming to complement the requirements and outputs of crop- and animal-specialised farms, in which crop farms provide feed and bedding materials and receive animal manure for fertilisation. It also aims to increase regional self-sufficiency in animal feed.

2 Materials and methods

Firstly, we modified the farm typology described in Avadí et al. (2016), consisting of "dairy", "beef", "dairy + beef", "swine" and "crop-only" farms, to include "poultry" (broiler and egg) farms, and renamed beef as "suckler" (as beef describes a product from both dairy and suckler systems). The original typology was developed for the Lieue de Grève catchment, a predominantly cattle- and crop-producing area of Brittany. The updated typology represented the most common agricultural practises in Brittany in terms of land used to grow different crops, feeding strategies, manure management and soil management, as well as an average set of pedo-climatic conditions (Table 1). Moreover, all farm types included crop production, since landless swine and poultry farms were not explicitly modelled, as no data were available for these types of farms in Brittany (all farms featuring confined animal production were assumed to also produce crops). The dairy + beef farm type was eliminated from the revised typology and assimilated into the dairy or suckler types because statistical data did not explicitly represent these farms.

Secondly, VRFs were constructed for each farm type (according to the typology) following a modular approach, in which farms are modelled as an aggregation of parameterisable building blocks representing farm components (e.g. crop 1, crop 2, milk production, animal rearing). Animal production was modelled in greater detail for cattle and swine than for poultry, for which fewer data were available; therefore, poultry farms were modelled solely based on their land use and animal feed consumption (thus excluding infrastructure, energy and water consumption).

Importantly, the land use of each VRF was assumed to equal that at the regional level: 34% cereals, 30% temporary grassland, 8% permanent grassland, 20% maize silage and other annual forages, 4% vegetables, 2% oil seeds and 2% other crops. Including grasslands in swine and crop-only farms may be disputed, these farms represent 36% of the region's land use, while cattle farms (which tend to devote much UAA to grasslands) represent more than 51%; this simplification allowed rapid modelling of the VRFs while keeping the total land use aligned with regional statistics, yet it may have influenced results significantly (see uncertainty and sensitivity analysis strategy below). Inventory inputs for each VRF were allocated among animal products and crops, based on the proportion of the farm's UAA devoted either to producing feed inputs to be used on the farm or to crops for sale. For the dairy VRF, allocation between milk and live weight of animals sold (cull cows and calves) was based on a biophysical key (allocation factor for fat-and-protein-corrected milk (FPCM) = 1–5.7717 × [mass sold animals/mass FPCM]) as recommended by the International Dairy Federation and the FAO (FAO 2010; IDF 2010). All other allocations used economic keys, following the French agricultural database AGRIBALYSE® v.1.2 (Koch and Salou 2015). Lifecycle inventories were constructed using AGRIBALYSE data, which include crop and livestock processes representing "France" and "Northwest France" (e.g. Brittany). Since AGRIBALYSE animal processes do not express all diet ingredients in dry matter (DM), VRF inventories were adjusted to DM when including wheat (86.8% DM), grazed grass (20% DM), grass silage (33.5% DM), hay (85% DM) and soya bean meal (87.6% DM).

Thirdly, mean environmental impacts were calculated per farm type (i.e., per VRF). These means were then linearly extrapolated to the total UAA of each farm type within the region. To simplify calculations, we assumed that farms contained only UAA (i.e. no non-agricultural land). Impacts were calculated according to two functional units: 1 ha UAA

Table 1 Dominant pedo-climatic conditions and agricultural production characteristics in Brittany in 2010

Region	Brittany, north-western France				
Average AGRIBALYSE soil features[a]	Soil type: Acrisol, sand content: 5–10% (coarse), land cover: crop/shrub or grass, mean slope: 5%, mean slope length: 91 m				
Weather[a]	Precipitation: 700–1200 mm/yr., mean annual temperature: 12 °C				
Regional characteristics[b]					
Total UAA in the region (ha)	1,653,063 in 34,447 farms				
Total cattle production	Cattle head: 2,058,139; beef production: 188,853 t from 129,461 head from suckler systems and 582,742 from dairy systems (712,203 head total); milk production: 4930 million L from 733,491 dairy cows; cattle concentrate feed production: 1.06 million t				
Total swine production	Swine head: 14,512,610, meat production: 1,303,067 t, swine concentrate feed production: 4.09 million t				
Total poultry production	Broilers: 352.9 million, meat production: 571.3 thousand t; layers: 16.9 million, eggs: 5010.3 million, poultry concentrate feed production: 3.2 million t				
Top 5 crop types (% UAA, yield in t DM/ha/year)	Cereals (34.3%, 6.0), grasslands (temporary: 29.9%, 6.7; permanent: 7.5%, 7.4), annual forages (mainly maize: 20.1%, 10.8), vegetables (including potatoes, tubers, legumes (pulses) and leafy vegetables: 4.5%, 4.6), oil seeds (2.2%, 3.1)				
Mean fertiliser inputs (kg/ha UAA)	N: 77, P_2O_5: 20, K_2O: 8				
Manure management	Slurry/manure mix, covered pit, field spreading				
Characteristics per farm type[b]	Dairy	Suckler	Swine	Poultry	Crop-only
Total regional UAA (ha), % of total	746,025, 45%	98,781, 6%	197,296, 12%	215,710, 13%	395,251, 24%
Number of farms	9947	1733	3344	4070	3319
Mean farm UAA (ha)	75	57	59 (<1 ha buildings)	53 (<0.25 ha buildings)	119
Animal production (head/farm)	Dairy cattle (75)	Beef cattle (75)	Swine (4340)	Poultry (90860)	N/A
Milk production	6721 L/head/yr., 33.1 g protein/L, 42.1 g fat/L	N/A	N/A	N/A	N/A
Animal feeding strategy[c]					
Ration type	Grassland products + maize silage	Grassland products + maize silage	Concentrate feed	Concentrate feed	N/A
Daily intake per head (kg DM)[d]	16.5	17.4	3.3–4.6	0.016	N/A
Grassland products (%)	65–90	95–97	0	0	N/A
Maize silage and cereals (%)	1–30	2–3	0	0	N/A
Concentrate feed (%)	1–10	1–2	100	100	N/A

More complex farm types are identified from simpler ones depending on their dominant production (e.g. a farm producing swine and beef in addition to crops would be classified as either "swine" or "suckler"; farms producing both milk and beef would be classified as "dairy" or suckler depending on the predominant output). Crop-only farms include all UAA occupied by other farm types and land uses, namely highly mixed farms (e.g. with more than three main co-products), greenhouses, flowers, fruits, orchards, small ruminants and other herbivores, other protein crops and fallows. The percentages of crops indicated in "Top 5 crop types" were assumed for all farm types. Mean farm and herd sizes were obtained by dividing regional totals by the number of farms of each type; thus, no variability around means was calculated. Mean milk yield per cow was obtained by dividing total milk production by the number of dairy cows; thus, no variability around the mean was calculated. Mean protein and fat contents of milk are provided, without uncertainty data, in statistical sources. Animal ration composition and yields of all crops, including grasslands, were taken from AGRIBALYSE lifecycle inventories

DM dry matter, *UAA* usable agricultural area

[a] EC_JRC (2005)

[b] AGRESTE (2013); CAGO (2011); AGRESTE (2015); CAB (2013); CCI (2013); CAB (2014)

[c] Agabriel (2010); Koch and Salou (2015)

[d] Agabriel (2010)

in Brittany (which includes animal production and thus the impacts associated with the land used elsewhere for growing animal feed inputs consumed in Brittany) and 1 kg of animal product produced by Breton farms (FPCM and liveweight of sold animals). This model represented the *status quo* of environmental performance in Brittany's agricultural sector (baseline).

Finally, alternative scenarios, representing possible combinations of agricultural management strategies—also varying in extents of implementation, e.g. percentage of farms of a given type implementing a specific strategy—were built by modifying the VRFs to represent the effects of said strategies, and re-extrapolating them. These scenarios, intended to represent realistic agricultural strategies implementable at the regional level, include grass or maize silage specialisation of all dairy farms (100GRA and 100SIL, respectively), centralised fodder drying by half of the region's cattle farms (50FOD), rewilding 10% of grassland by half of the region's farms (50REW) and one of many possible levels of implementation of the grain-and-manure-exchange strategy in which half of the region's swine farms replace all imported feed ingredients (except soya bean meal) with ingredients produced from crops grown by the same swine farms and the region's crop-only farms, displacing cash crops (e.g. wheat) (50GME) (Table 2). All scenarios assume that the number of each type of animal remains constant, despite for instance changes in milk yield that could prompt adjustments in herd size, as modelled in Avadí et al. (2016). All scenarios include the poultry VRF, yet its results are not presented separately due to limitations in modelling it.

The case-study baseline was compared to the alternative scenarios, and the relative regional effects of implementing each management strategy were compared. Scenario comparison included regional mass balances, identifying differences between estimated regional production and estimated consumption of animal-feed inputs, expressed as surpluses or deficits. These mass balances considered the total production of feed inputs by all farm types and all production of concentrate feed in the region. They contrasted this production with the feed requirements of all cattle, swine and chickens in the region (based on the population of each type of animal in regional statistics (Table 1), which were satisfied by a combination of regionally produced feeds and imports. Deficits thus represented imports, while surpluses represented feed inputs either stocked or exported. It is useful to compare mass balances because regional self-sufficiency in livestock feed constitutes a limiting factor for the livestock sector from both economic and environmental perspectives. The overall method is detailed in Table 3.

All LCAs were performed at the screening level, because inventories of VRFs do not represent actual farms but a statistics-based definition of them. For these screening LCAs, AGRIBALYSE v1.2 was used to model the foreground processes, the *ecoinvent* v2.2 database (Frischknecht et al. 2007) was used as a source of background processes and SimaPro v8.0 was used as the computational tool. The impact categories and impact-assessment methods retained were climate change (global warming potential) (IPCC 2006; IPCC 2014), non-renewable energy use (fossil and nuclear), acidification potential, eutrophication potential, land occupation, human toxicity and aquatic (freshwater) and terrestrial ecotoxicity (Guinée et al. 2002). The decision to use toxicity categories of the CML method rather than the USEtox consensus method (Rosenbaum et al. 2008) complies with the methodological choices of the CANTOGETHER project (CML baseline 2001 includes characterisation factors for more substances than USEtox and has been widely used for agricultural LCAs). All LCA models were based on AGRIBALYSE (as a source of foreground processes) and its direct-emission models, which consider average pedo-climatic conditions—agri-environmental zonation (Hijbeek et al. 2014)—of modelled agricultural production (Koch and Salou 2015). Parameters for calculating field emissions were updated in line with average pedo-climatic conditions in Brittany. AGRIBALYSE direct emissions are calculated using both French (e.g. CORPEN, ARVALIS, DEAC) and international (e.g. IPCC, EMEP/EEA, RUSLE2, SALCA-P) models (Appendix D in Koch and Salou 2015).

Uncertainty in data used to construct VRFs for screening purposes, as well as sensitivity of scenarios to this uncertainty, were investigated for key inventory items (i.e. milk yield and land use). We propagated available uncertainty data from AGRIBALYSE (including those for background data from ecoinvent), plus an arbitrary uncertainty range in milk yields of ±10% for all scenarios using Monte Carlo propagation (95% confidence, 1000 runs). Such variation in milk yields is reasonable, as observed from a sample of 88 dairy farms in the Lieue de Grève. Under these conditions, values for 39% of the input data used (i.e. the most influential inventory items) were varied based on the uncertainty data. Moreover, impacts of our VRFs were compared to those of alternative VRFs built for the Lieue de Grève by Avadí et al. (2016) using detailed farm data, to highlight the influence of different land-use assumptions. As a part of this test, alternative VRFs for suckler and swine farms were created, featuring more likely land uses: more grasslands for suckler farms (70% grasslands, 15% winter wheat and 15% maize silage) and no grasslands for swine farms (25% durum wheat, 25% spring barley, 25% maize grain and 25% rapeseed; a typical Lieue de Grève swine farm land use). Unfortunately, uncertainty in animal rations, another key inventory item, could not be investigated due to lack of data. Finally, LCIA toxicity results of CML baseline 2001 and USEtox methods were compared, as they often differ greatly among LCA studies.

3 Results and discussion

3.1 Baseline results

The statistics- and AGRIBALYSE-based inventories for Brittany (Electronic Supplementary Material A) led to baseline impact-assessment results (Fig. 1, Electronic Supplementary Material B) consistent with—yet generally lower than—previous ones for the Lieue de Grève catchment in Brittany (Avadí et al. 2016) (Table 4). Differences in impact

Table 2 Baseline and scenarios for implementation of agricultural management strategies in Brittany

Scenario	Description and modelling deviations from the baseline	Remarks
Baseline (all farm types)	Current total land use and agricultural production in the region. Each farm type is modelled as a VRF, assuming the same distribution of land use for all farm types, as follows: • Land use of all VRFs: 34% cereals, 30% temporary grassland, 8% permanent grassland, 20% maize silage and other annual forages, 4% vegetables, 2% oil seeds, 2% others (not modelled). • Dairy-farm animal rations and milk yields (mean milk yield: 7618 L/yr): ◦ 25% of farms ➔ 40% grassland products, 42% maize silage and cereals, 10% concentrate feed and 8% wheat. Of TFA, 66% devoted to grasslands and 34% to silage maize. Dairy-farm milk yield per dairy cow: 6721 L/yr. ◦ 8% of farms ➔ rations, milk yield and land-use distribution as in 100GRA ◦ 67% of farms ➔ rations, milk yield and land-use distribution as in 100SIL • Suckler-farm animal rations: 83% grassland products, 5% maize silage, 6% wheat and 6% concentrate feed. • Swine- and poultry-farm animal rations: 100% concentrate feeds.	Simplified baseline assuming the same land use for all VRFs (except for forage land and grasslands in dairy farms), and three animal feeding strategies, in percentages common in the region
100GRA (dairy farms)	Grass specialisation • All dairy farms increase grassland area to 90% of TFA. Non-forage land use remains unchanged. • Dairy cattle rations are adjusted to include <5% maize silage, <5% concentrate feed and 6% wheat; the remaining ≈84% are grassland products. • Milk yield per dairy cow is reduced to 5545 L/year, following AGRIBALYSE documentation for Northwest France lowland grass-specialised systems.	Exchange of fields to improve access to grasslands (not explicitly modelled)
100SIL (dairy farms)	Maize silage specialisation • All dairy farms increase silage maize area to 40% of TFA. Non-forage land use remains unchanged. • Dairy cattle rations are adjusted to include 53% maize silage, 27% grassland products, 11% concentrate feed and 9% wheat. • Milk yield per dairy cow is increased to 8200 L/year, following AGRIBALYSE documentation for Northwest France lowland maize-dominated systems.	
50FOD (dairy and suckler farms)	Centralised fodder drying • 50% of cattle farms grow and dehydrate lucerne (10% of UAA, equivalent to 17% of TFA in cattle farms, displacing grasslands) to replace concentrate feed (ratio 2.5 kg lucerne: 1 kg concentrate feed). • Dairy cattle rations are adjusted to include 36% maize silage, 7% wheat, 22% dehydrated lucerne (no concentrate feed) and 35% grassland products. • Suckler cattle rations are adjusted to include 5% maize silage, 5% wheat, 2% concentrate feed, 2% milk for calf, 7% dehydrated lucerne and 77% grassland products. • Lucerne dehydration is assumed to be coal-powered; transportation, yield, water content and energy-demand values are from Corson and Avadí (2015).	Partial replacement of concentrate feed by dehydrated lucerne
	Rewilding	

Table 2 (continued)

Scenario	Description and modelling deviations from the baseline	Remarks
50REW (all farm types)	• 50% of all farms set aside 10% of grassland, as a path to rewilding.	Modelled as rewilding of agricultural land only
50GME (swine and crop-only farms)	Grain and manure exchange • 50% of swine farms satisfy all their animal feed inputs (except for soya bean products) with crops grown by themselves and by crop-only farms in the region. • Concentrate feed, modelled as "Pig, French average, growing feed, conv prod, at farm gate" from AGRIBALYSE (Koch and Salou 2015), was replaced with a simplified mix: 61% wheat, 15% maize grain, 6% soya bean meal, 13% rapeseed meal and 5% minerals.	Aimed at feed self-sufficiency

All animal-diet values refer to dry matter amounts

TFA total forage area, *UAA* usable agricultural area, *VF* virtual representative farm

are due in part to differences in variability among farms within the smaller (Lieue de Grève) and larger (Brittany) regions; farms in the latter have more diverse sizes, cattle feeding strategies, etc. Moreover, due to the screening nature of the inventories for VRFs, certain relevant inventory items such as animal rations and land use were represented roughly. Results nonetheless are consistent with others in the literature (Table 4). For instance, the potential climate change impact of milk, previously estimated as 0.8–1.5 kg CO_2 per kg FPCM (de Vries and de Boer 2010; Nguyen et al. 2013; Dalgaard et al. 2014; Salou et al. 2014), was 0.9 kg CO_2 per kg FPCM for the Lieue de Grève (Avadí et al. 2016) and 0.8 kg CO_2 per kg FPCM for Brittany (this study).

Once VRF results were extrapolated to the regional level, all strategies show environmental impacts per ha UAA similar to those of the baseline, with differences ranging from −15 to +6% (Fig. 2). The largest differences are found for the 50GME scenario, in which half of swine farms replace all imported feed ingredients with locally grown ones, and for the 100GRA scenario, in which 44% of all regional UAA is devoted to grasslands, versus 37% in the baseline. The reduction in aquatic and terrestrial toxicity impacts associated with 50GME (−10 and −12%, respectively) is larger than the differences in all other impact categories of the scenario (±1%) due to avoided toxicity impacts associated with commercial swine feed and cash crops such as wheat. In the 100GRA scenario (grassland specialisation, extensification), its reduction in human toxicity (−15%), driven by decreased consumption of maize silage and wheat, is larger than its other deviations from the baseline (−8 to +3%).

3.2 Scenario comparison

About 45% of Brittany's UAA is occupied by dairy farms. Extrapolated impacts of dairy farms per ha UAA and per kg FPCM (Fig. 3) show larger differences among scenarios than those of other farm types. Per ha UAA, the 100GRA scenario has the lowest impacts among scenarios, except for climate change, acidification and land occupation. Per kg FPCM, the 100GRA scenario also has the lowest impacts for all three toxicity categories and energy use, but the 100SIL scenario

Table 3 Steps of the method and case-specific implementation with virtual representative farms (VRFs)

Step	Method	Brittany case study
1	Construct a farm typology	Dairy + crops, beef (suckler) + crops, swine + crops, poultry + crops, crop-only
2	Construct VRFs based on regional statistics	VRFs representative of Brittany's agricultural production were constructed based on regional statistics and the AGRIBALYSE lifecycle inventory database.
3	Estimate environmental impacts per VRF type	Lifecycle impact assessment of each farm type was performed, using VRFs as the source of life cycle inventories.
4	Extrapolate VRF type results to the total agricultural land use in the region	Regional statistics were the basis for linear extrapolation of environmental impacts estimated per VRF type.
5	Construct scenarios of agricultural management practises	VRF lifecycle inventories were modified to represent effects of specific agricultural management practises derived from the CANTOGETHER project. Environmental impacts for the scenarios were estimated by recalculating life cycle impact assessments and re-extrapolating them to the total land use in the region.

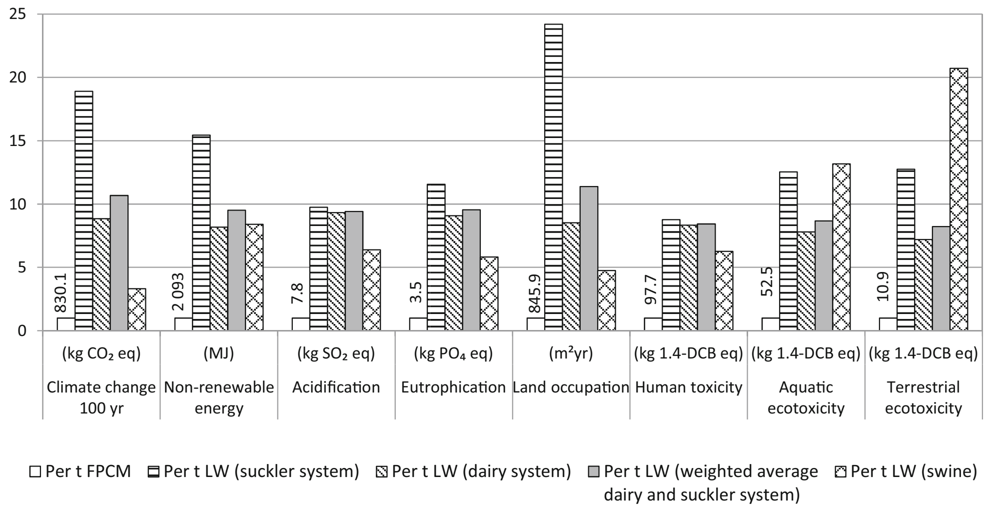

Fig. 1 Environmental impacts per kg live weight (LW) of animals produced by animal production systems (suckler, dairy, swine) in the regional baseline for Brittany, expressed as multiples of the impact per ton of fat-and-protein-corrected milk (FPCM) (*white bar*, dairy system). *Numbers above white bars* represent absolute values of impacts per t FPCM

(maize silage specialisation) has the lowest impacts for climate change, acidification, eutrophication and land occupation. The relatively large difference in human toxicity impact between 100SIL and 100GRA is driven by their respective percentages of maize silage, wheat and grassland products in cattle diets. The 100GRA and 50FOD scenarios have higher land occupation per kg FPCM, driven by the increased land occupation necessary to produce cash crops and lucerne, respectively.

Salou et al. (2017) recently determined that intensification (e.g. maize silage specialisation) increased all impacts per ha of on- and off-farm land occupied, but when impacts were expressed per kg FPCM, land occupation and eutrophication decreased with intensification, while the other impacts were not affected. Though our results per kg FPCM (Fig. 3b) differ from theirs, when disaggregated into main contributors to impacts, impacts of 100SIL are generally lower than those of 100GRA (except for energy use, due to the energy embedded in higher percentages of maize silage and soya bean meal in diets) (Fig. 4).

Modelling the same land use for all VRFs (representing identified farm types), based on total land use and product outputs from regional statistics, caused results to differ from those of previous studies. Our impact estimates are largely determined by the way both the baseline and strategies were defined and modelled. For instance, feeding strategies of baseline cattle and swine farms were assumed to be weighted averages of dominant practises, and the same land use (crops harvested, UAA of each crop) was assumed for all farm types; both assumptions oversimplify reality. If grasslands in swine farms had been modelled as either wheat or wheat and maize, all impacts per ha of swine farms would have increased by 2–5% (except for ecotoxicity

Table 4 Comparison of baseline results for Brittany (this study and AGRIBALYSE processes) with mean results for OECD countries, France and the Lieue de Grève catchment

Impact category	Unit	Milk (kg FPCM)					Animal from suckler system (kg LW)			Swine (kg LW)		
		OECD	France	Brittany (AGRIBALYSE)	Lieue de Grève	Brittany (this study)	OECD	France	Brittany (this study)	OECD	France	Brittany (this study)
Climate change	kg CO_2 eq/kg	0.8–1.5	1.1	0.8–1.0	0.9	0.8	11.0–25.3	11.7	15.7	2.3–6.4	2.6	2.8
Energy use	MJ/kg	1.5–2.8	4.0	2.7–3.0	1.8	2.1	27.8–40.7	30.1	32.4	15.0–18.0	16.5	17.6
Land occupation	m^2yr/kg	1.2–1.9	2.5	1.1–1.6	1.3	0.8	23.0–38.5	24.8	20.5	4.1–7.5	4.7	4.0

Reference values for Organisation for Economic Cooperation and Development (OECD) countries came from recent publications (de Vries and de Boer 2010; Reckmann et al. 2013; Nguyen et al. 2013; Dalgaard et al. 2014; González-García et al. 2015). Reference values for France were obtained from Salou et al. (2014). Impacts per kg FPCM produced in Brittany (Northwest France) were calculated in this study using AGRIBALYSE processes. Reference values for the Lieue de Grève catchment in Brittany came from Avadí et al. (2016)

FPCM kg fat-and-protein-corrected milk, *LW* liveweight

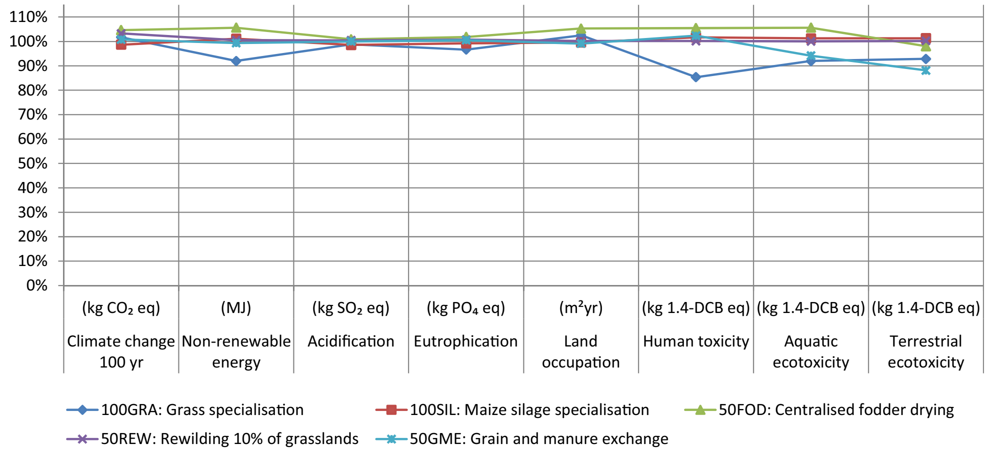

Fig. 2 Environmental impacts per mean ha of usable agricultural area, relative to those of the baseline, of scenarios implementing agricultural management strategies in Brittany

impacts, by 11–15%), mainly due the higher resource use and emissions associated with crops than with grassland. The approach followed was developed for illustrative purposes, but further applications should model the baseline and scenarios in more detail, as far as data availability allows. Moreover, economic assessment of strategies should be performed as well to complement environmental assessment. Only then may strategies be identified that have lower environmental impacts and are economically feasible.

Comparison of scenarios shows regional deficits and surpluses of key agricultural products (limiting factors to

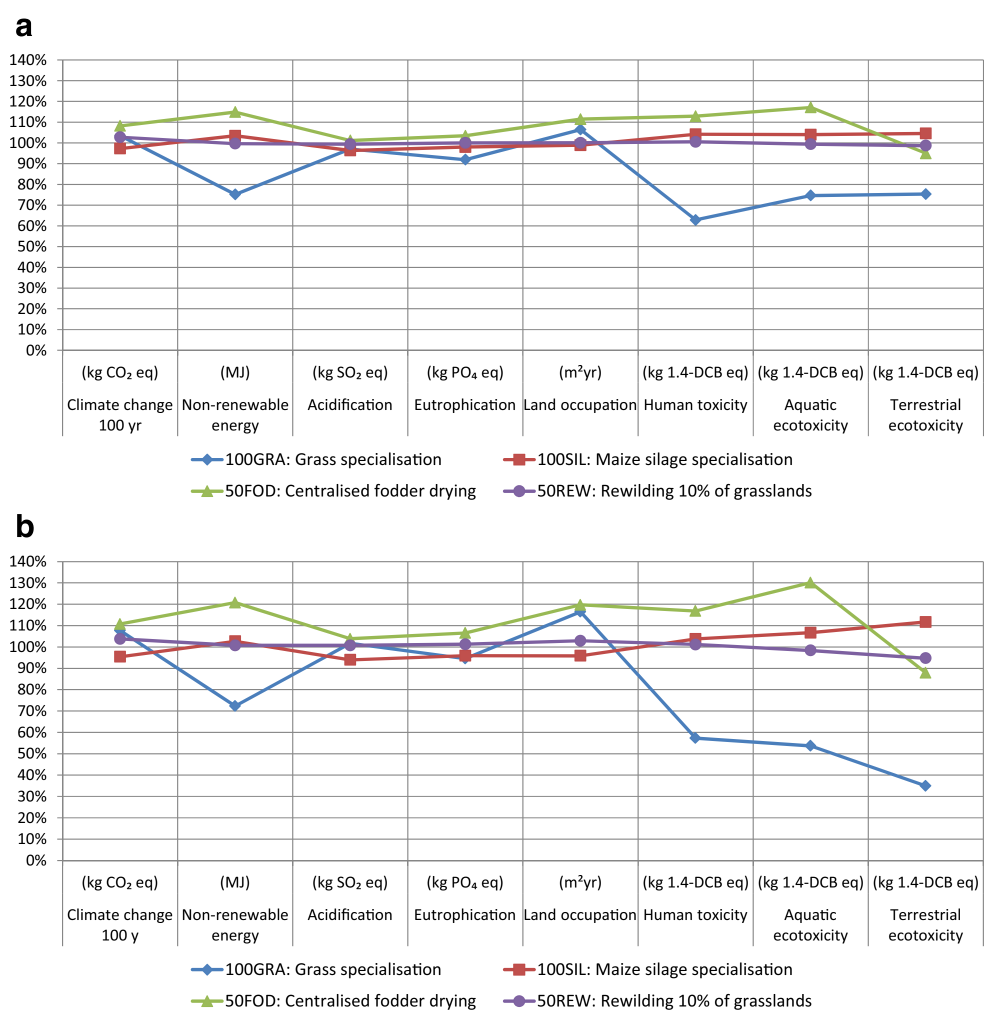

Fig. 3 Environmental impacts, relative to the baseline, associated with scenarios of implementation of agricultural management strategies on dairy farms in Brittany **a** per ha usable agricultural area and **b** per kg fat-and-protein-corrected milk

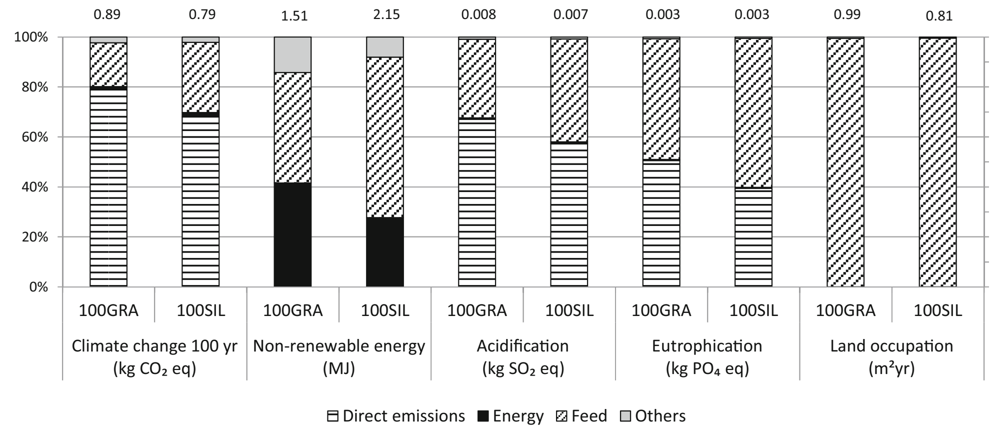

Fig. 4 Relative contributions of direct emissions, energy and feed to environmental impacts of two extreme scenarios of the dairy-system-intensification spectrum (100GRA: grass specialisation, 100SIL: maize silage specialisation) applied to dairy farms in Brittany, per kg of fat-and-protein-corrected milk, disaggregated into main contributors to impacts. *Numbers above bars* indicate absolute values of impacts

livestock production, namely grassland products, maize silage and animal feeds produced in the region—which include imported inputs, such as soya bean meal), as well as the relative environmental burden of each strategy-implementation scenario (Table 5 and Fig. 5). The baseline regional scenario shows a surplus of grassland products and a deficit of maize silage, which are partially due to the assumptions made regarding cattle diets (the major consumers of these forages). Nonetheless, these forage surpluses are in line with those reported for the region in the reference period (2009–2010) (AGRESTE 2015). Scenario 50REW is very similar to the baseline, except for slightly smaller production volumes of grassland products and maize silage, due to the UAA that was set aside for rewilding. Scenario 50FOD is the only one featuring surpluses for all products, due to associated cattle diet adjustments including reduced maize silage intake and partial substitution of concentrate feeds. Scenario 100GRA shows a large deficit of grassland products, suggesting that a region-wide extensification strategy would not be self-sufficient. Scenarios 100SIL and 50GME involve relatively small maize silage deficits that would be easy to overcome, for instance, by converting grasslands to silage maize.

The comparison table may support agricultural decision making at the regional level. Nonetheless, factors driving agricultural management differ among stakeholders. For instance, agricultural and environmental authorities in Brittany may favour strategies which reduce eutrophication, an ongoing issue in the region (Gascuel et al. 2015; Levain et al. 2015), while farmers may base their preferences on socio-economic criteria and lean towards farm-level strategies that maximise economic return and/or reduce labour.

Our method may be extended to add detail to the LCIs and/or impact categories. For instance, if available, more detailed data on land use per farm type would undoubtedly increase differences in the representation of farm types. Impact categories such as water scarcity and impact on biodiversity or full carbon accounting (i.e. considering both emissions and sequestration) would enrich the scenarios by adding criteria for comparison.

3.3 Uncertainty and sensitivity analysis

LCIs constructed with statistical data are by definition highly uncertain. In this study, we were interested in the influence of uncertainty in milk yields, land use and animal rations, but regional statistics did not contain estimates of uncertainty in these data (thus, certain uncertainties were estimated based on assumptions, as described in the Sect. 2). Once uncertainty was propagated, pairwise comparison of the extreme scenarios 100GRA and 100SIL confirmed their relative impacts (Fig. 3, Electronic Supplementary Material C): 100SIL has larger impacts than do 100GRA per ha more than 90% of the time (except for climate change and land occupation, for which the opposite is true, and for acidification, for which 100GRA is larger than 100SIL 52% of the time) and per kg FPCM (except for acidification, which behaves like the per-ha test).

When VRFs in this study were compared to those built with detailed farm data from the Lieue de Grève by Avadí et al. (2016), large differences were observed (Fig. 6), driven by the modelling of land use, animal rations and animal stocking density. Indeed, assuming the same land use percentages for all farm types distorted estimates of environmental impacts per ha, even though cumulative land use at the regional level agrees with regional statistics. For suckler farms, modified land use (i.e. grasslands increased from 38 to 70% of UAA by decreasing annual-crop UAA) does not affect impacts greatly, except for decreasing toxicity impacts, due to lower amounts of fertilisers and pesticides applied (Fig. 6b). Predicted impacts are, however, larger than those of suckler farms for the Lieue de Grève, because mean stocking density (livestock units/ha grassland) is higher (3.5 vs. 2.3,

Table 5 Strategy-comparison table

Scenario	Mass balances	Environmental impacts
Baseline	• Grassland-product surplus 774 kt • Maize silage deficit 125 kt • Cattle-feed surplus 207 kt • Swine-feed surplus 327 kt • Poultry-feed deficit 6927 kt	
100GRA	• Grassland-product deficit −2525 kt • Maize silage surplus 2094 kt • Larger cattle-feed surplus +236%	• Per ha UAA: generally lower than the baseline • Per kg FPCM: generally lower than the baseline (−5 to −65%) except for climate change, acidification and land occupation (+2 to +16%)
100SIL	• Larger grassland-product surplus +68% • Larger maize silage deficit +236% • Smaller cattle-feed surplus −33%	• Per ha UAA: equivalent to the baseline • Per kg FPCM: around the baseline (−6% for acidification to +12% for terrestrial ecotoxicity)
50FOD	• Smaller grassland-product surplus −20% • Maize silage surplus 275 kt • Larger cattle-feed surplus +202%	• Per ha UAA: equivalent to the baseline • Per kg FPCM: generally higher than the baseline (+4 to +21%) except for aquatic and terrestrial ecotoxicity (−12% each)
50REW	• Less UAA in the region −1.5% • Smaller grassland-product surplus −18% • Larger maize silage deficit +57%	• Per ha UAA: equivalent to the baseline • Per kg FPCM: equivalent to the baseline
50GME	• Grassland-product deficit 449 kt • Larger maize silage deficit +252% • Larger swine-feed surplus +575% (54% of regional production)	• Per ha UAA: equivalent to the baseline for all impact categories except aquatic and terrestrial ecotoxicity (−12% each)

Masses (DM), in terms of surpluses or deficits, represent the balance between regional production and consumption (including imported concentrate feed). Percentages denoted as "smaller" or "larger" represent deviation from the baseline

GRA grass specialisation, *SIL* maize silage specialisation, *GME* grain and manure exchange, *FOD* centralised fodder drying, *REW* rewilding, *UAA* usable agricultural area, *FPCM* fat-and-protein-corrected milk

respectively). For swine farms, modified land use (i.e. all grasslands replaced by annual crops) increases impacts of swine farms in this study, which are larger than impacts of swine farms for the Lieue de Grève (Fig. 6c). The increase in VRF impacts is explained by larger per-ha emissions from annual crops than grasslands. The larger impacts in this study

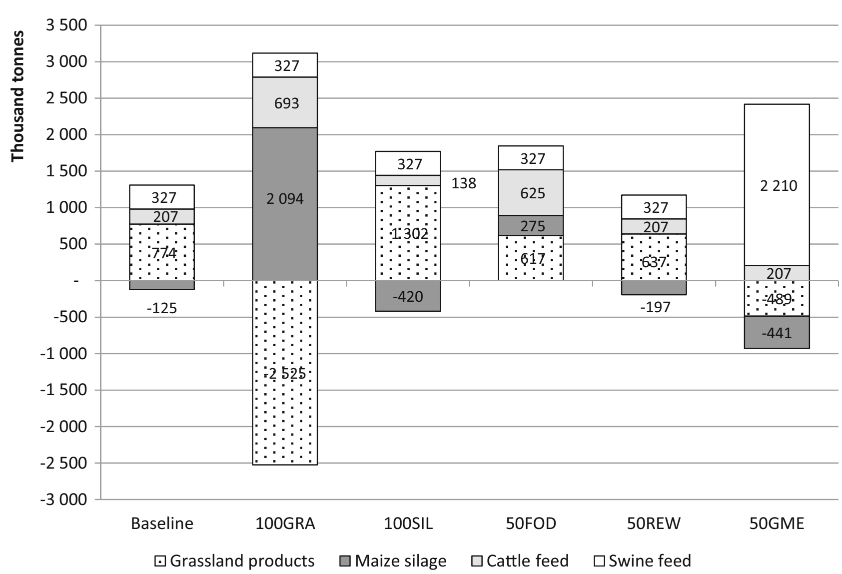

Fig. 5 Total regional masses (kt DM) of key inputs to animal feeds in Bretagne corresponding to scenarios of implementation of agricultural management strategies (100GRA: grass specialisation, 100SIL: maize silage specialisation, 50FOD: centralised fodder drying, 50REW: rewilding, 50GME: grain and manure exchange). *Bars* below zero represent regional deficits

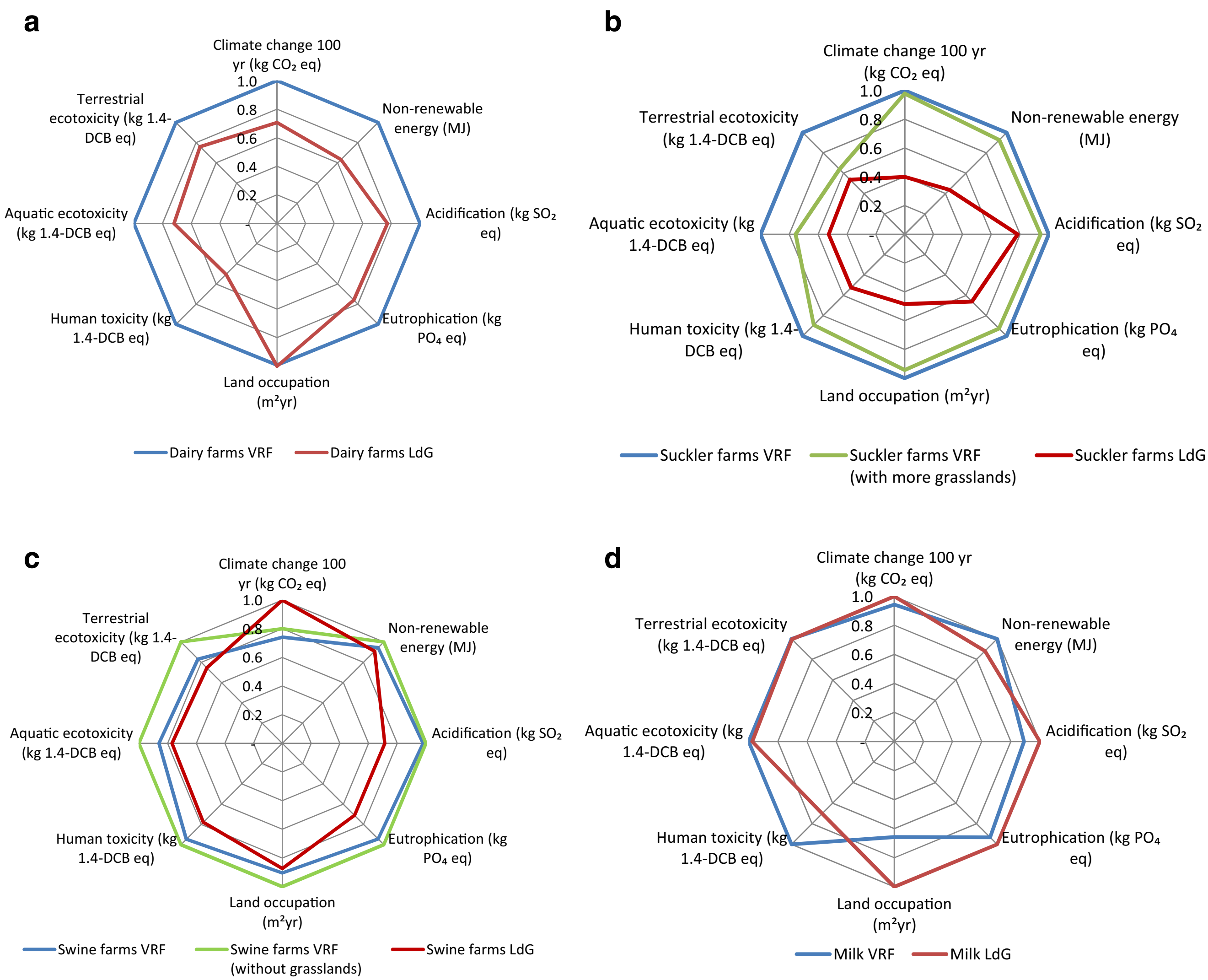

Fig. 6 Comparison of relative environmental impacts of the statistics-based baseline for Brittany (VRF) to those based on farm data for the Lieue de Grève (LdG) (Avadí et al. 2016), **a** per ha of dairy farm, **b** per ha of suckler farm, **c** per ha of swine farm, and **d** per kg fat-and-protein-corrected milk

than for the Lieue de Grève are explained by two factors related to swine rearing: (a) use of generic animal rations in this study, compared to more detailed animal rations for the Lieue de Grève and (b) higher stocking density (for swine farms of ≈59 ha, 3377 swine in this study (Brittany mean) vs. 1692 swine for the Lieue de Grève). For impacts per kg FPCM, statistics-based results are remarkably similar to those based on individual farm data, because impacts do not depend directly on land use or stocking density.

Ecotoxicity results of CML and USEtox for the impact categories common to the two models generally agree in attributing the lowest toxicity impacts to the 100GRA scenario (Fig. 7). For both models, impacts of all scenarios are driven mainly by production of wheat, animal feed and maize silage, but for CML, an additional influential inventory item is slurry management.

Based on these analyses, the statistics-based model is sensitive to land-use modelling, but less so to estimates of milk

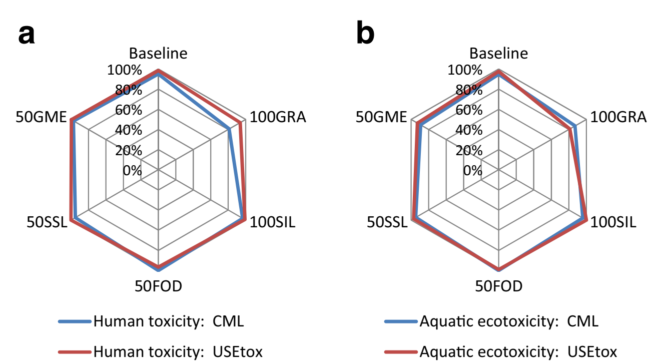

Fig. 7 Relative **a** human toxicity and **b** freshwater ecotoxicity impacts per ha of study scenarios based on CML and USEtox models

yields. Future statistics-based regional LCA studies of agricultural regions should pay attention to land use in particular.

4 Conclusions

The method developed enables comparing environmental consequences of region-wide implementation of agricultural strategies, yet at a screening level and limited by data and modelling assumptions, notably the modelling of land use among farm types. Nonetheless, it may serve as a first step for preselecting strategies to investigate at a more detailed level, which would involve collection of primary data. For our case study, it is difficult to identify a "best" strategy, but as strategy prioritisation would likely be based on the environmental pressures considered most pressing by regional decision makers, we assert that strategy comparison and prioritisation, rather than strategy selection, is the goal of the method. The modelling approach, as well as the quality and detail level of data sources used (i.e. regional statistics, existing agricultural databases), determine the credibility of the screening environmental assessment. Furthermore, environmental ranking of strategies should be supplemented by socio-economic assessments to consider factors driving various stakeholders and enable decision making based on the three classic dimensions of sustainability.

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