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Life Cycle Assessment Based Evaluation of Regional Impacts from Agricultural Production at the Peruvian Coast

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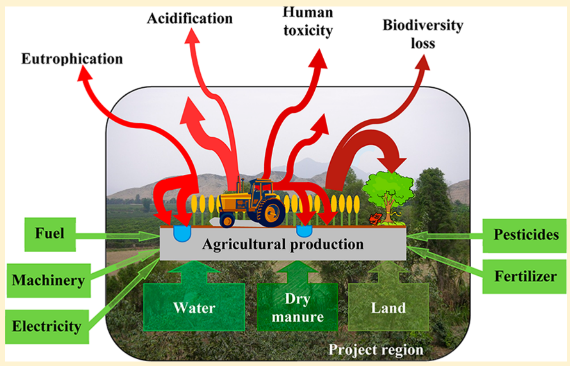

ABSTRACT: Crop and technology choices in agriculture, which largely define the impact of agricultural production on the environment, should be considered in agricultural development planning. A life cycle assessment of the dominant crops produced in a Peruvian coastal valley was realized, in order to establish regionalized life cycle inventories for Peruvian products and to provide the basis for a regional evaluation of the impacts of eutrophication, acidification, human toxicity, and biodiversity loss due to water use. Five scenarios for the year 2020 characterized by different crop combinations and irrigation systems were considered as development options. The results of the regional assessment showed that a business-as-usual scenario, extrapolating current trends of crop cultivation, would lead to an increase in nitrate leaching with eutrophying effects. On the other hand, scenarios of increased application of drip irrigation and of mandarin area expansion would lead to a decrease in nitrate leaching. In all scenarios the human toxicity potential would decrease slightly, while an increase in irrigation water use would benefit the biodiversity of a nearby groundwater-fed wetland. Comparisons with results from other studies confirmed the importance of regionalized life cycle inventories. The results can be used as decision support for local farmers and authorities.

■ INTRODUCTION

A life cycle assessment (LCA) is a compilation and evaluation of the inputs, outputs, and the potential environmental impacts of a product throughout its life cycle.[1] Interventions such as emissions, extraction of resources, and land use are quantified for all stages of the life cycle of a product in the inventory analysis (LCI) phase.[2] The potential contributions of these interventions to different impact categories are thereafter estimated in the life cycle impact assessment (LCIA) phase. Whereas some impact categories are of global nature, such as climate change, others have a more regional character, such as acidification, eutrophication, and toxicity.[3] In these cases, a regionalization of the LCI and/or of the LCIA can improve the accuracy of the results. So far the regionalization of LCIs is either restricted to country-specific data for technical processes (e.g., in the LCI database ecoinvent)[4] or to LCAs of a specific product in which the origin of the product is of special importance.[5,6] LCIA calculations pertaining to studies in European[7,8] and North American regions[9] have led to differences in impact scores of more than an order of magnitude when region- and time-specific characterization factors for acidification and eutrophication were used, demonstrating the importance of spatially and temporally explicit approaches. Basset-Mens et al.[10] showed that LCA-based estimations of eutrophication potential can be improved using spatially differentiated fate factors for nitrate. Verones et al.,[11] one of the few authors who have addressed developing countries, developed characterization factors for the impact of agricultural groundwater and surface water use on regional biodiversity in the arid coast of Peru, the same region investigated in this paper.

In this study, we carried out a LCA for the agricultural production in the lower part of the valley Chancay-Huaral, at the Peruvian coast. Due to its favorable climate and proximity to the capital, Lima, agriculture is of overriding importance, with 30% of the economically active population working in the agricultural sector.[12] Various scenarios for possible future development of agriculture in the region were set up in collaboration with local stakeholders, who requested regionally relevant outcomes of the study. Special attention was paid to the development of a regionalized LCI. Special care was also taken with the estimation of nitrate leaching from agricultural soils, which had an assumed high risk attached, owing to the existence of a shallow, unconfined aquifer, permeable soils, and intensive agricultural land use,[13] as well as the sensitivity to local conditions of flows into groundwater.[14] Furthermore, the application of urine, manure, and other fertilizers, constituting the main sources for ammonia, an important eutrophying and acidifying substance, were modeled in detail.

In the LCIA phase the categories climate change, eutrophication, acidification, human toxicity, and biodiversity

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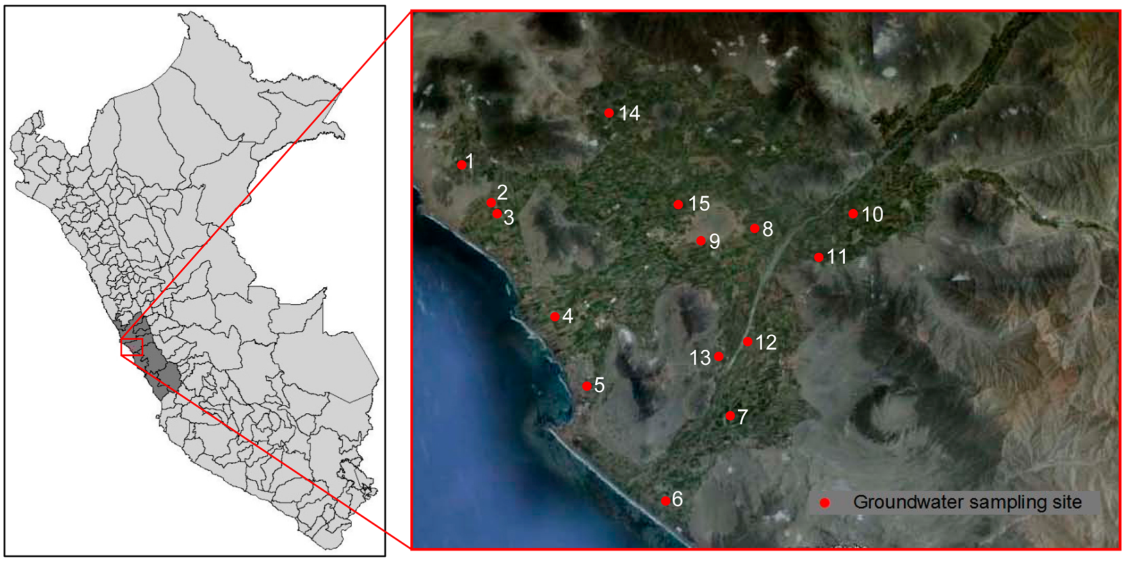

Figure 1. The project region in Peru. The map on the left shows Peru with the Lima region in dark gray. The red rectangle contains the project region and shows the position of the groundwater sampling sites.[66]

Table 1. Annual Characteristics of the Production System of Selected Agricultural Products in Chancay-Huaral

	hard maize	mandarins	potatoes	apples	peaches	avocados	strawberries	asparagus[a]
total planted area in district (ha)[67]	4660	3415	3212	2109	1690	1676	580	161
share of total agricultural area (%)[67]	18.14	13.29	12.50	8.21	6.58	6.52	2.26	0.63
productive life of a plant (years)	0.5[68]	35.00[69]	0.42[23]	20.00[68]	20.00[68]	25.00[70]	1.00[68]	13.00[26]
yield (t/ha; 2009−2010)	13.5[71]	30.27[67]	27.50[23]	13.13[67]	8.42[67]	10.60[67]	17.43[67]	8.35[67]
rooting depth (cm)[79]	100	100	40	60	100	60	30	100
irrigation (m^3/ha)[11]	10630	7310	10630	10630	9300	7310	9300	11960
electricity for irrigation (kWh/ha)[19]	4.67	3.21	4.67	4.67	4.08	3.21	4.08	5.25
fertilization								
dairy dry manure (kg/ha)	0	1600[72]	0	29[73]	0	2957[74]	5000[75]	30000[76]
chicken dry manure (kg/ha)	0	0	15200[23]	0	0	0	0	0
urea (kg N/ha)	230	428[72]	92[23]	190[73]	0	0	86[75]	230[76]
ammonium sulfate (kg N/ha)	0	0	52.5[23]	0	0	0	0	0
ammonium nitrate (kg N/ha)	0	0	0	0	148[77]	80[74]	0	0
other NH_4 sources (kg N/ha)	54	0	54[23]	0	0	28[74]	31[75]	65[76]
other NO_3 sources (kg N/ha)	0	128[72]	0	0	0	67[74]	0	0
pesticides (kg active substance/ha)	5.00[71]	17.00[72]	4.28[23]	9.60[75]	29.62[78]	8.50[69]	8.68[75]	29.45[76]
use of machinery (h/ha)	6.50[71]	0.57[72]	15.00[23]	0.03[c]	0.03[c]	0.56[69]	4.00[75]	21.06[76]
transport of production inputs (t km/ha)[b]								
transport, lorry (3.5−16 t)	0.0	63.9	152.0	0.29	0.00	29.6	50.0	300.0
private transport, pickup (1 t)	4.81	17.91	7.24	8.83	5.41	5.20	2.89	7.57

[a]Values for two harvests/year. [b]Assuming a 10 km distance for the delivery of local farmyard manure and broiler litter and a 5 km distance to a local agricultural retail center. [c]Same as mandarins, since no values for apples and peaches were found in the literature.

loss due to agricultural water use were assessed. The choice of these impact categories was based on results of studies that have identified them as important for agricultural production. For instance, Basset Mens et al.[10] showed that eutrophication is one of the main environmental impacts of farming systems, and regarding toxicity, a close connection between agriculture and the occurrence of pesticides in surface water and groundwater bodies has been reported.[15,16] Acidification of rural areas, which is especially influenced by nitrogen fertilizer management, can reduce production of agricultural soils. Water use has been included in this study due to the overriding importance of this resource at the Peruvian desert coast. The goal of including regionalized data is to achieve an accurate basis for providing recommendations in the context of local agricultural management in addition to providing LCI data for agricultural products from Peru that can be used in LCAs of food products.

■ MATERIALS AND METHODS

Project Region. The project region is the lower part of the valley of the river Chancay-Huaral in the province of Huaral, department Lima, Peru (see Figure 1). The valley comprises 25 692 ha of agricultural land, with agricultural production being entirely dependent on irrigation. A detailed description of the project region can be found in Verones et al.[11]

Goal and Scope of the Life Cycle Assessment. An attributional LCA, which, within a defined system, analyses the resource inputs and the emissions attributed to the production of a functional unit,[17] was applied to the dominant crops of the project region and to crops whose cultivated area is expected to increase in the future for economic reasons. The goal of the LCA was the estimation of the environmental impacts of the region's present and future agricultural production. These results provide useful information for local decision-makers and might be used as decision support for defining the future development of agriculture in the project region.

The LCI was calculated for the functional unit of 1 kg of fresh harvested crop, to allow for a comparison of the emissions generated by the production of the same crop produced in a different location. A LCIA was applied to the functional units of 1 kg of fresh harvested crop and 1 ha. Expressing the results for 1 kg of fresh harvested crop allows for a comparison with results from other regions. Using 1 ha as functional unit accounts for the regional character of the impact categories assessed, and results can be used for an evaluation of the impact of the agricultural activities in the project region. The crops hard maize and potatoes as well as the fruits mandarins, avocados, apples, and peaches were chosen because they are the most cultivated crops in the region (covering 65% of total agricultural area; see Table 1). Asparagus and strawberries were identified by local stakeholders as very cost-effective crops whose areas are likely to expand in the near future.

The analyzed system includes the use of land, irrigation water, machinery for agricultural production, and the transport of production inputs as well as the production and use of fuel, electricity, fertilizers, and pesticides. Roads and buildings are excluded from the system due to lack of information. Furthermore, foliar phosphate and trace element fertilizers are not taken into account, as very small amounts are used (annually no more than 3 L/ha), and seeds were excluded due to their small impact.[18] Local data were used whenever available (Table 1).

Life Cycle Inventory. Special attention was paid to the accurate estimation of emissions from production and use of fertilizers and manure. Resource inputs for and emissions from fertilizer production were taken from Nemecek and Kägi.[19] Transport distances for fertilizers imported into Peru were calculated according to the origin of the product as described in Bartl et al.[5] For fertilizers not mentioned in Bartl et al.,[5] the following transport distances were used: potassium nitrate from Chile (75, 25, and 1526 km transport by train, truck, and ship, respectively); magnesium sulfate from Germany (production process and transport distances in the producing country for stone meal from Nemecek and Kägi,[19] 11 942 km ship transport); ammonium sulfate from the United States (100 km train transport, 4854 km ship transport); ammonium nitrate from Russia (1150 km rail transport, 13 310 km sea transport). A local transport distance by truck of 90 km from the harbor to a regional storehouse was assumed for all fertilizers.

Dry manure is generally purchased from local producers. Due to the lack of a LCI for fattening cattle, it was assumed that all dry manure used for fertilization was dairy manure. Thus, the LCI for milk produced in a smallholder system at the Peruvian coast from Bartl et al.[5] was applied. For poultry litter the EcoInvent LCI "poultry manure, dried, at regional storehouse/kg/CH" was used.[19] Poultry manure was assumed to have 655 g dry matter (DM)/kg, 34 g N/kg DM, and 500 g available N/kg N.[20]

For modeling of the irrigation system it was assumed that 9% of the mandarin and avocado areas[21] and 75% of the asparagus areas[22] are irrigated with drip irrigation. For the remaining area a gravity and furrow irrigation system is used. One hectare of irrigated land is equipped with 9.2 m of sealed and 34.5 m of nonsealed irrigation channels.[23] The estimated dimensions were 3.0 × 1.7 m and 1.2 × 0.5 m for primary and secondary channels, respectively. Primary channels were assumed to be sealed with a 10 cm concrete layer with a lifetime of 40 years (data for concrete sealed slurry tank).[24] The lifetime of the nonsealed secondary channels was defined as 100 years, assuming regular and manual maintenance operations.

For the extraction of groundwater, a 300 kg electric pump (15-year lifetime)[24,25] with a 22 kW engine (22-year lifetime)[22] consuming 0.053 kWh/m^3 water (adapted from Nemecek and Kägi[19] for an average pumping depth of 10.6 m) is used. In the case of drip irrigation, the use of a water hose (8-year lifetime)[24] made of PVC (0.9 kg/m) was assumed to bring the water from the pump or a reservoir to the plants. The length of the water hose for fruit orchards was calculated for a tree stocking rate typical for a medium technology orchard. In the case of asparagus, a distance of 1.7 m between rows was defined.[26] For storage of surface water, a concrete sealed (same as for primary channels) water reservoir was assumed, with a sufficient size to store water for 1 week. LCIs for the materials needed (cast iron, polyvinyl chloride, concrete) and operations (excavation with a hydraulic digger) were taken from the ecoinvent database.[27−29]

The production of pesticides, electricity, and fuels as well as the transport of production inputs and the cultivation of agricultural plots were implemented as described by Bartl et al.[5]

Equations and assumptions used for the estimation of emissions from noncombustion agricultural sources are summarized in Bartl et al.[5] (Tables 3 and 4). Not mentioned in Bartl et al.,[5] but used in this study, is the formula for estimation of ammonia (NH_3) emissions from the application of poultry litter: kg NH_3-N emissions/ha = 20% of total N applied.[19]

Local nitrate emissions from agricultural sources were estimated using the Nitrogen-Index (version4.4) for Ecuador.[30] Input information for the Nitrogen-Index is shown in Table 1. Furthermore, the following additional input data were used: soil depth, 1.2 m;[31] soil organic matter, 1.23% (mean of three samples taken in Huacho-Irrigación San Felipe, September 2008); soil NO_3-N, 0 ppm (low soil NO_3-N concentrations can be expected for soils with a sandy texture and low organic matter content);[32] soil NH_4-N, 8.28 ppm;[33] bulk density, 1.55 g/cm^3;[34] soil pH, 7.77 (average of three samples taken in Huacho-Irrigación San Felipe, September 2008); NO_3-N concentration in irrigation water, 0.89 ppm for asparagus and 0.6 ppm for all other crops;[33] annual atmospheric N deposition, 1.8 kg/ha;[35] precipitation, 15.9 mm/year (year 2008, climate station Donoso).[36] The nutrient uptake indices (NUI) for the different fruits or crops form a key part of the Nitrogen-Index. Whenever available, the custom values offered by the tool were used. For the following crops, specific NUIs were estimated as follows: mandarin, 19.68 (89 kg annual N uptake/ha);[37] apple, 19.94 (52 kg annual N uptake/ha);[38] avocado, 21.15 (52 kg annual N uptake/ha);[39] peach, 9.2 (46 kg annual N uptake/ha).[40]

Carbon dioxide (CO_2) emissions from soil cultivation were calculated according to IPCC:[41] CO_2-C (kg/ha) = [soil C-stock − [soil C-stock × factor for land use (LDU) × factor for management regime (MR) × factor for input of organic matter (IOM)]]/20. The factors used were 0.69 (all plants) for LDU, 1.17 (mandarins, avocados, peaches, apples) and 1.0 (maize, potatoes, asparagus) for MR, and 0.92 (all plants) for IOM.[41]

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Table 2. Life Cycle Inventory Flows (aggregated for resource inputs, direct for emissions) for 1 kg of Selected Crops and Fruits

substance	hard maize	mandarins	potatoes	apples	peaches	avocados	strawberries	asparagus
Resource Inputs								
land (m^2a)	0.75	0.34	0.37	0.77	1.20	0.95	0.58	1.21
water (m^3)	1.15	0.57	0.54	1.15	1.60	0.99	0.68	1.99
local water (m^3)	0.79	0.24	0.39	0.81	1.10	0.69	0.53	1.43
energy (electricity and heat, kJ)	1370	1286	656	1644	2421	1046	607	2570
local energy (kJ)	1.24	0.39	0.61	1.28	1.75	1.10	0.85	2.36
Outputs to Air								
ammonia (g)	3.36	4.78	3.78	2.69	0.97	3.69	3.58	33.70
carbon dioxide, biogenic (g)	2.39	2.07	1.11	2.20	3.18	2.28	1.03	4.26
carbon dioxide, fossil (g)	181	182	72	168	193	146	78	384
carbon dioxide, soil (g)[a]	155	49	76	112	175	139	120	251
carbon monoxide (mg)	308	187	141	209	230	224	113	485
nitrouse oxide (mg)	927	1057	1227	309	709	697	407	782
methane (mg)	253	316	109	257	308	209	103	1333
nitrogen oxides (mg)	729	786	380	609	981	989	315	1476
sulfur dioxide (mg)	680	680	371	841	962	638	346	1355
Outputs to Water (fresh water and oceans)								
nitrate (g)	58.76	1.05	108.91	3.40	3.72	0.86	30.26	0.58
phosphate (mg)	637	745	310	568	621	747	284	1243
phosphorus (mg)	0.37	0.53	0.18	0.39	0.39	0.45	0.17	1.03
pesticides (mg active ingredient)	3.33	5.53	1.56	7.31	43.71	9.91	4.98	33.58
Outputs to Soils								
pesticides (mg active ingredient)	366	547	154	723	4472	980	493	3321
heavy metals (mg)	6.7	25.0	3.9	19.7	23.0	28.1	8.0	45.1

[a]Released by soil cultivation.

Life Cycle Impact Assessment. The impact categories climate change, terrestrial acidification, freshwater eutrophication, and human toxicity were included in the LCA, using SimaPro 7.3.0 LCA software.[42] The climate change potential was calculated according to the IPCC method with a time frame of 100 years.[43] ReCiPe v1.05 (end point method, hierarchist version)[44] was used for calculating eutrophication and acidification potentials. For the assessment of human toxicity the USEtox method[45] was applied. Furthermore, regional biodiversity loss due to agricultural water use was estimated according to Verones et al.[11]

Sensitivity Analysis. The sensitivity of the LCIA results to a 10% increase in the use of fertilizers, pesticides, and irrigation water was tested. For this purpose, total amounts of N and P_2O_5 from both mineral and organic fertilizers, as well as all individual pesticides and irrigation water amounts, were incremented individually by 10% and the relative changes of the LCIA results were recorded.

Regionalization. To evaluate the regional impact of agricultural production, exclusively local processes and the respective local emissions were selected from the LCI as inputs for the LCIA. Local processes included combustion of fossil fuels for field work and regional transport of production inputs, as well as application of fertilizers and manure, and manure production. For the process of manure production, it was assumed that all feeds except maize grain and stover were produced outside the project region.[5]

Scenarios. Scenarios were developed in order to evaluate future impacts of regional agricultural production in 2020. The total agricultural area in the year 2010 (25 692 ha) was defined as the maximum area that can be used for agricultural purposes. An expansion of the total agricultural area would thus not be possible, and scenarios consist of changes in the size of area cultivated with each of the project crops. According to information provided by local stakeholders, the area of mandarins, asparagus, and strawberries cultivated is expected to grow in the future, mainly for economic reasons. As described in Verones et al.[11] three scenarios for 2020 were calculated for these crops ("increase mandarins", "increase asparagus", "increase strawberries"), assuming a continuation of the average annual growth trends between 2001 and 2010. Among the project crops, the areas with apples and peaches are decreasing in all scenarios making available area for an extension of the other crops. Moreover, a scenario assuming a shift to more drip irrigation for crops where drip irrigation is already applied ("increase drip-irrigation") was calculated (on new areas of mandarin, avocado, strawberry, and asparagus). It was assumed that 50% less water is used[46] and that the yield increases by 30%[47] with drip irrigation compared to a gravity irrigation system. Finally, a trend scenario ("trend") assuming a continuation of the growth rates observed between 2001 and 2010 until 2020 was calculated for all project crops. It was assumed that, except for the irrigation scenario, the irrigation system would stay the same as in 2010.

RESULTS AND DISCUSSION

Regionalized Life Cycle Inventory. On average, 99% of the land used in the production process of the crops can be found in the project region, making land use an important regional impact (Table 2). The quantity of water applied for asparagus production is more than twice as high as the average amount used for the other crops but is comparable with the 1.33 m^3 water/kg fresh asparagus reported for the Ica region (Peruvian coast south of Lima).[48] Asparagus also stands out with airborne emissions being on average more than twice as high as the emissions from the other crops. Responsible for these high emissions is the use of large quantities of dry manure and the resulting ammonia and methane emissions during

Table 3. Climate Change, Eutrophication, Acidification, and Human Toxicity Potentials for 1 kg of Selected Crops and Fruits[a]

	hard maize	mandarins	potatoes	apples	peaches	avocados	strawberries	asparagus
climate change potential[51] (kg CO_2 equiv)	6.22×10^{-1}	5.56×10^{-1}	5.18×10^{-1}	3.81×10^{-1}	5.91×10^{-1}	5.00×10^{-1}	3.24×10^{-1}	9.06×10^{-1}
total freshwater eutrophication (species· yr)[b]	9.26×10^{-12}	1.08×10^{-11}	4.50×10^{-12}	8.25×10^{-12}	9.02×10^{-12}	1.09×10^{-11}	4.13×10^{-12}	1.81×10^{-11}
eutrophication due to regional agricultural activities (species·yr)[b]								
fertilizer, manure and pesticide applications	7.52×10^{-14}	3.35×10^{-14}	3.70×10^{-14}	7.73×10^{-14}	1.20×10^{-13}	9.57×10^{-14}	5.82×10^{-14}	1.22×10^{-13}
total terrestrial acidification (species·yr)[b]	5.40×10^{-11}	7.44×10^{-11}	5.70×10^{-11}	4.51×10^{-11}	2.25×10^{-11}	5.94×10^{-11}	5.39×10^{-11}	4.91×10^{-10}
acidification due to regional agricultural activities (species·yr)[b]								
combustion[c]	1.07×10^{-12}	2.82×10^{-13}	3.79×10^{-13}	4.21×10^{-13}	6.38×10^{-13}	1.14×10^{-12}	4.79×10^{-13}	1.07×10^{-12}
fertilizer, manure and pesticide applications	4.73×10^{-11}	6.56×10^{-11}	5.39×10^{-11}	3.81×10^{-11}	1.28×10^{-11}	5.15×10^{-11}	5.08×10^{-11}	4.78×10^{-10}
total human toxicity (CTUh)[d]	4.81×10^{-9}	$1.85 \times 10^{-1}0$	$3.27 \times 10^{-1}0$	2.68×10^{-9}	2.83×10^{-9}	$7.13 \times 10^{-1}0$	2.37×10^{-9}	5.57×10^{-9}
human toxicity due to regional agricultural activities (CTUh)[d]								
combustion[c]	4.35×10^{-13}	1.31×10^{-12}	1.13×10^{-12}	6.09×10^{-13}	6.43×10^{-13}	7.31×10^{-13}	5.71×10^{-13}	5.74×10^{-12}
fertilizer, manure and pesticide applications	4.77×10^{-9}	6.69×10^{-11}	$3.07 \times 10^{-1}0$	2.64×10^{-9}	2.76×10^{-9}	$6.11 \times 10^{-1}0$	2.35×10^{-9}	7.42×10^{-12}

[a]Local emissions from manure production are not shown, as they comprise less than 1% of total local emissions. [b]Number of species lost during a year. [c]Use of machinery for soil cultivation and local transport of production inputs. [d]Comparative toxic units, providing the estimated increase in morbidity in the total human population per unit mass of a chemical emitted (cases/kg).

application and production. Airborne ammonia emissions for Peruvian asparagus production estimated by Stoessel et al.[49] are more than 2000% lower than the values from our study. The reason for these differences is the assumption of a Swiss production environment and practices applied to Peru in the study of Stoessel et al.[49] At the Peruvian coast the application of large quantities of manure is common with the objective to maintain or increase the low soil organic matter content. This large difference between the two studies emphasizes the limitations of extrapolations between different production locations and the importance of regional LCIs.

The Nitrogen-Index tool estimated that the regional average for the leached fraction of applied N is 30%, which is within the range of results published in other studies (maize, 32%;[50] mandarins, 33%;[51] potatoes, 45%;[51] strawberries, 21%[52]). High leaching losses for maize and potatoes are due to management and annual growth parameters, and an estimated 10% of irrigation water is applied preplanting, which may leach residual soil nitrate. In contrast, the leached fraction of N applied was estimated to be small for mandarins, avocados, asparagus, and apples, mainly due to permanent soil cover and the lack of tillage. Ledgard et al.[53] have also shown that more than 60% of the N applied to asparagus remained in the soil at the end of the harvest period. Nevertheless, amounts of residual nitrate in the soil are high for all the perennial fruits and represent a significant leaching potential from the sandy soils in the project region.[54]

The Nitrogen-Index toolś results were sensitive to some input data such as annual nitrogen uptake by aboveground biomass and dry matter of the fruits. Thus, the use of this model for calculation of LCI data was an important source of uncertainty. But due to lack of local literature data we assumed the results calculated with the Nitrogen-Index to be the best available data. The reliability of the tool was also confirmed by Delgado et al.,[55] who stated that the index correctly assessed the NO_3-N leaching losses when tested against measured data.

Life Cycle Impact Assessment. For the base year 2010, impacts were calculated for the functional unit of 1 kg of fresh harvested product (Table 3). Climate change potentials calculated in this study are on average higher than estimated for the same crops by other authors. Cook et al.[56] estimated total CO_2 equivalents being 91%, 71%, and 83% lower than the values from our study for potatoes and apples from the United States and asparagus from Peru, respectively. A review by Mordini et al.[57] indicates that strawberry production in Europe (8 studies) produces 113% more CO_2 equiv per kg strawberry than indicated by our study for Peruvian strawberries (Table 3). The higher emission of greenhouse gases for the Peruvian potatoes, apples, and asparagus are most probably due to high amounts of manure used for production. In the case of strawberries, production in Peru is basic, with all field work being manual and fruits grown on soil without any protection, such as straw layers, plastic film or polytunnels. Furthermore, agricultural production in Peru is year-round, and multiple harvests are practiced annually. These results emphasize the importance of regional LCIs, taking into account the characteristics of the production environment and management practices.

The ReCiPe method for eutrophication considers phosphorus as the limiting factor in freshwater environments. Therefore, only P compounds are provided for assessment of freshwater eutrophication.[44] A contamination of the river with substances originating from agricultural land is a minor problem in the region, as soil erosion in the study region was classified to be low.[58] As nitrogen is usually the limiting factor in marine waters,[59] the nitrogen contained in the excess irrigation water contributes to marine eutrophication and should be assessed. Nevertheless, so far no valid method at the end point level exists for the evaluation of marine eutrophication. An assessment of marine eutrophication at midpoint level was not performed due to lack of data regarding the amount of nitrogen from agricultural sources that reaches the ocean.

Table 4. Regional Potentials for Eutrophication, Acidification, River and Wetland Biodiversity Losses Due to Water Use (all species·yr), and Human Toxicity (CTUh)[a] for 1 ha in the Years 2010 and 2020 under Different Scenario Assumptions

	base year 2010[b]	trend[c]	increase mandarins[d]	increase asparagus[e]	increase strawberries[f]	increase drip-irrigation[g]
freshwater eutrophication	1.22×10^{-9}	1.18×10^{-9}	1.20×10^{-9}	1.24×10^{-9}	1.21×10^{-9}	1.15×10^{-9}
terrestrial acidification	1.23×10^{-6}	1.56×10^{-6}	1.37×10^{-6}	1.58×10^{-6}	1.23×10^{-6}	1.50×10^{-6}
wetland biodiversity loss[h]	-1.13×10^{-11}	-1.13×10^{-11}	-1.20×10^{-11}	-1.12×10^{-11}	-1.12×10^{-11}	-1.05×10^{-11}
river biodiversity loss[h]	2.14×10^{-12}	2.15×10^{-12}	2.07×10^{-12}	2.16×10^{-12}	2.14×10^{-12}	1.84×10^{-12}
human toxicity	3.30×10^{-5}	2.94×10^{-5}	2.93×10^{-5}	3.26×10^{-5}	3.32×10^{-5}	2.70×10^{-5}

[a]Comparative toxic units, providing the estimated increase in morbidity in the total human population per unit mass of a chemical emitted (cases/kg). [b]193 kg of hard maize, 317 kg of mandarins, 271 kg of potatoes, 85 kg of apples, 44 kg of peaches, 55 kg of avocados, 31 of kg strawberries, and 4 kg of asparagus. [c]206 kg of hard maize, 328 kg of mandarins, 359 kg of potatoes, 0 kg of apples, 0 kg of peaches, 53 kg of avocados, 34 kg of strawberries, 20 kg of asparagus. [d]168 kg of hard maize, 430 kg of mandarins, 236 kg of potatoes, 60 kg of apples, 27 kg of peaches, 48 kg of avocados, 27 kg of strawberries, 4 kg of asparagus. [e]190 kg of hard maize, 313 kg of mandarins, 267 kg of potatoes, 72 kg of apples, 33 kg of peaches, 54 kg of avocados, 31 kg of strawberries, 41 kg of asparagus. [f]190 kg of hard maize, 313 kg of mandarins, 267 kg of potatoes, 80 kg of apples, 40 kg of peaches, 54 kg of avocados, 51 kg of strawberries, 4 kg of asparagus. [g]164 kg of hard maize, 419 kg of mandarins, 230 kg of potatoes, 29 kg of apples, 5 kg of peaches, 66 kg of avocados, 44 kg of strawberries, 43 kg of asparagus. [h]Biodiversity loss due to water use, adapted from Verones et al.[11]

Although not evaluated by the LCIA method used, nitrate emissions from agricultural land are of major concern in the project region due to the aquifer underlying the area. No limits of nitrate concentrations have been defined for aquifers in Peru, but environmental standards for surface water bodies set a maximum concentration of 10 mg NO_3-N/L.[60] According to the Nitrogen-Index, 225 kg N/ha are annually leached into the aquifer, which has an estimated total volume of 6.40×10^9 m^3.[11] Thus the NO_3-N concentration in groundwater would be as low as 0.81 mg NO_3-N/L (assuming that 90% of nitrogen in groundwater is present as NO_3-N and 10% as NH_4-N).[33] But this concentration can only be seen as a rough estimate, since other pollution sources exist. Livestock production, especially pig farms, constitutes one of these pollution sources.[21] Nevertheless, livestock production has not been included in the LCA due to a lack of adequate LCIs. Analysis of 15 water samples taken specifically for this project from wells in the project region indicated that at the time of the study no risk for nitrate contamination existed. They also showed that nitrate concentrations are lower in altitudes greater than 100 m above sea level, where fruit orchards dominate, and larger at lower altitudes, where maize, potatoes, and vegetables are the principal crops. NO_3-N concentrations (mg/L) measured in the higher parts were 1.36, 1.53, 0.18, 1.42, 1.73, 1.75, 3.55, and 1.87 for sampling points 8, 9, 10, 11, 12, 13, 14, and 15, respectively (Figure 1). In the lower areas, NO_3-N concentrations (mg/L) were 6.30, 4.06, 5.70, 3.66, 0.00, 2.79, and 6.87 for sampling points 1, 2, 3, 4, 5, 6, and 7, respectively (Figure 1).

Regional ammonia emissions, originating mainly from manure and urea, are responsible for 94% of the total acidification potential. The amount of fertilization thus strongly influences the acidification potential of each crop (Table 3). For asparagus, the average values of acidification potential per kg crop is about 9 times the average of the other crops. This is caused by high amounts of dairy manure used for asparagus production. Nitrogen fertilization has also been shown by other authors to be a key parameter for many impacts in most crops.[61] Nevertheless, the sensitivity to acidification of the soil in the study region is low, due to a 100% base saturation level and a cation exchange capacity as low as 4.8 me/100 g.[62]

Averaging over all crops, 70% of human toxicity potential can be attributed to pesticides applied regionally (Table 3). In particular, the production of 1 kg hard maize has a comparatively high human toxicity potential. More than 90% of noncarcinogenic human toxicity potential of maize is due to high emissions of acephate and methamidophos into agricultural soils. Acephate is an organophosphorus compound that is converted to methamidophos in the soil,[63] which is another, even more potent, organophosphate insecticide classified as a restricted use pesticide.[64]

According to Table 3, asparagus shows a comparatively low contribution of regional emissions to the total human toxicity potential. For mandarins and avocados, the regional shares of total human toxicity are also below the average. This is due to the use of drip irrigation, which was assumed to be applied on 9% of the mandarin and avocado area and on 75% of the asparagus area. For drip irrigation, polyvinyl chloride, a substance reported to be toxic to humans,[65] is used for the production of water hoses. The highest risk was shown for the population living near or working in vinyl chloride polymerization facilities;[65] its toxicity potential is thus not of direct importance to the study region but should be considered from a life-cycle perspective.

Scenarios. Five scenarios estimating possible regional impacts of agricultural production in 2020 were developed to provide local decision makers and farmers with guidance for the planning of future agricultural production developments in the project region (Table 4). The functional unit used was 1 ha. Table 4 shows negative values for the impact category wetland biodiversity loss due to water use, because irrigation water infiltrates into the aquifer, which is the only water supply for the highly biodiverse coastal wetland. Water withdrawal from surface water and its use for irrigation thus benefit the wetland through additional recharge to the groundwater. On the other hand, the biodiversity of the river is compromised by withdrawals (Table 4; for more detailed information see Verones et al.).[11] The reduction or only slight increase (<1%) in the human toxicity potential in the scenarios compared to the baseline is due to a decrease in the total area of the three crops hard maize, peaches, and apples, which have the highest regional toxicity potential per kilogram of crop. If eutrophication and human toxicity are considered to be hot spots for the project region, then the scenarios "increase mandarins" and especially the scenario "increase drip-irrigation" imply an improvement of the current situation. In such a case, compared to the year 2010, a reduction in nitrate leaching equal to 7% would take place for both scenarios "increase mandarins" and "increase drip-irrigation". For the impact category human toxicity, a reduction equal to 11% and 18% would occur for the aforementioned scenarios, respectively, due to a change in the crop composition. An additional benefit would be the reduced use of irrigation water for these two scenarios compared to the current situation. The "increase asparagus" scenario differs only slightly from the situation in 2010 (small decreases in eutrophication and toxicity potentials and a 6% increase in water use). A continuation of the past growth trend can be considered as the worst choice due to a predicted increase in nitrate leaching (+32%). Human toxicity potential on the other hand would decrease by 11% under this option.

Sensitivity Analysis. The use of literature data constituted a crucial source of uncertainty. Therefore, the effects on the outcome of the study of the choices made regarding input data for fertilizers, pesticides, and irrigation water were evaluated. A 10% increase in the amounts of organic and mineral fertilizers led to a substantial increase in eutrophication and acidification potentials by 8.5 and 9.2%, respectively. Climate change potential and human toxicity were less affected (+4% and <1%, respectively). The sensitivity of the climate change, eutrophication, and acidification potentials to a 10% increase in pesticide use was below 1%, whereas human toxicity increased by 5.9%. These results indicate that, depending on the target impact category, special attention has to be paid to the collection and estimation of particular input data. For eutrophication and acidification and, to a lesser extent, also for the climate change potential, these particularly important input data concern the production (especially for manure) and application of fertilizers. The data quality regarding the quantity of pesticides used is of importance for the impact category human toxicity, and good data quality concerning the quantity of irrigation water used is necessary for a sound estimation of biodiversity loss due to water use.

Practical Implications. The estimation of local impacts by selecting exclusively local processes as input for a LCIA is a simplified method for regionalization of LCA results. A bottleneck for the LCA of agricultural production is the lack of appropriate regionalized LCIA methods. Moreover, no generic method exists that takes into account eutrophication of groundwater bodies as well as marine eutrophication at the end point level. Agricultural production has impacts other than the ones analyzed in this study, such as salinization or biodiversity loss due to land use, which would also be of interest for the project region. A complete LCIA including all impacts is needed to avoid problem shifting from one impact category to another.

Results showed that the region would benefit most from an improvement of the current irrigation system shifting to more drip irrigation. However, there is a trade-off with diminished recharge to the groundwater, and thus, infiltration into the wetland would be reduced. It is not evident at present whether eutrophication or water quantity has larger effects on wetland biodiversity, which highlights a clear research need for adequate impact methods for eutrophying effects in specific ecosystems. A continuation of the past growth trend would result in an increase in nitrate leaching to the aquifer.

Regional LCIs comprise a valuable database for LCA practitioners estimating the impact of food production. Good inventory data of agricultural production systems in the Southern Hemisphere are typically scarce, and comparison to European data shows that extrapolations are of limited value. The LCIA results can also be used as decision support by regional authorities and local farmers. A precondition for the use of the results as decision support would be the integration of livestock production, which is a major polluter in the project region.

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Notes

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