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Modeling the Local Biodiversity Impacts of Agricultural Water Use: Case Study of a Wetland in the Coastal Arid Area of Peru

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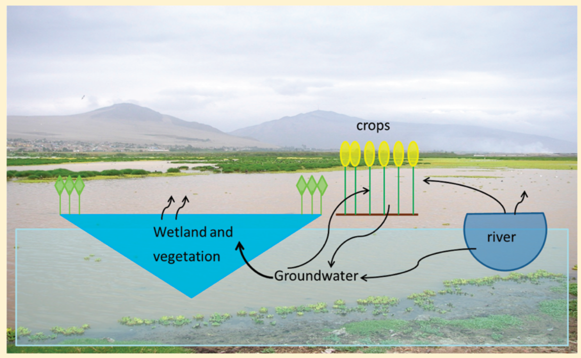
Supporting Information

ABSTRACT: Global water use is dominated by agriculture and has considerable influence on people's livelihood and ecosystems, especially in semiarid and arid regions. Methods to address the impacts of water withdrawal and consumption on terrestrial and aquatic ecosystems within life cycle assessment are still sparse and very generic. Regionalized characterization factors (CFs) for a groundwater-fed wetland at the arid coast of Peru are developed for groundwater and surface water withdrawal and consumption in order to address the spatial dependency of water use related impacts. Several agricultural scenarios for 2020 were developed in a workshop with local stakeholders and used for calculating total biodiversity impacts. In contrast to assumptions used in top-down approaches (e.g., Pfister et al. Environ. Sci Technol. 2009, 43, 4098), irrigation with surface water leads in this specific region to benefits for the groundwater-fed wetland, due to additional groundwater recharge from surplus irrigation water. However, irrigation with groundwater leads to ecological damage to the wetland. The CFs derived from the different scenarios are similar and can thus be used as general CFs for this region, helping local decision-makers to plan future agricultural development, including irrigation technologies, crop choices, and protection of the wetland.



INTRODUCTION

Water withdrawal for irrigation constitutes 70% of all freshwater withdrawals.[2] In northern Africa, India, the western United States, and the South American Pacific coastline, more than 75% of the agricultural production depends on irrigation.[2] Both groundwater and surface water are used for irrigation and there are numerous examples of aquifers being depleted and of reduced surface water levels in rivers due to agricultural water abstractions. The related impacts on ecosystems are manifold. In this work we concentrate on wetland ecosystems only. It is estimated that globally more than 50% of all wetlands have been lost, mostly due to agricultural drainage.[3] Assessing the impacts and balancing wetland conservation and local socio-economic development are thus crucial for the persistence of remaining wetlands.

Life cycle assessment (LCA) is a method for assessing the total environmental impact that is created through the life cycle of a product or process.[4] Approaches for assessing environmental impacts from water use on ecosystems are so far scarce. Pfister et al.[1] have developed a global methodology for assessing the impact from freshwater consumption on ecosystems. However, assessing damage to a local scale is difficult with this method, since it is based on remote sensing data and does not distinguish surface water from groundwater consumption. An approach for assessing the local impacts of groundwater abstractions on terrestrial ecosystems has been published by van Zelm et al.[5] This method is specific to The Netherlands, and the developed factors and the methodological approach cannot be easily applied to other regions, due to the complexity of the models and the large data demands. Thus, there is a need for additional regionalized studies regarding the impact of water use on ecosystems, as there is for assessing the applicability of global, water-use related approaches to regional levels.

We have selected a case study area in an arid region, where agricultural activities require irrigation and areas with native vegetation are restricted to small wetlands. The studied wetland, "Santa Rosa", harbors a large variety of fauna and flora and belongs to the most biodiverse wetlands in the coastal region of Peru.[6,7] Agriculture constitutes both the most important water source, supplying the wetland with infiltrated

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irrigation water, and its largest menace,[8] mainly due to contamination with nutrients and agrochemicals. Quality changes are not assessed in this paper.

The aims of this study were (a) to develop characterization factors (CFs) for the environmental impact of agricultural water use on natural wetland vegetation, taking into account local conditions, (b) to check the validity of existing generic characterization factors by comparing them to the local ones developed here, and (c) to provide a basis for environmental decision-making for agricultural management in the region. CFs are developed in terms of potentially disappeared fractions of species (PDF)[9] in the wetland itself by differentiating the source and amount of water used and the consumptive shares (i.e., the amount of water that is evaporated, incorporated into products, or diverted to other watersheds or the sea[10]). PDF is also used in other life cycle impact assessment (LCIA) methods for ecosystem damage (e.g., ref 11) and thus our factors can be compared with other approaches. The CF values are calculated in five steps: (1) Different scenarios and respective water balances are modeled. (2) The hydrological changes which can be expected in Santa Rosa for each scenario are calculated and used to determine fate factors. (3) The ecological effects of hydrological changes are modeled for each scenario. (4) Fate and effect factors for each scenario are combined to derive scenario-specific CF values. (5) CFs are generalized for application in LCA.

■ MATERIALS AND METHODS

Case Study Area Description. The relevant area for the case study is the lower part of the watershed of the river Chancay-Huaral in the province of Huaral, Peru, at 77° W and 11° S. The size of the total watershed is 3095 km^2.[12] The case study area stretches from the river measuring station Santo Domingo to the coast (1245 km^2), covering the main aquifer extent and the area where most agricultural activities and population are located. Santo Domingo is the only measuring station for river flow in the valley and is used as the starting point for inflow of the water balance. The agricultural area in the lower valley covers about 260 km^2 with a total of 64 different crops.[13] Main crops grown in 2010 were yellow maize, mandarins, potatoes, and apples. Additionally, there are large numbers of cows and chicken. In higher regions outside the study area livestock is also present in smaller numbers, mostly on natural pastures. Almost the entire agricultural area in the lower valley is irrigated, and all crops except asparagus are irrigated with gravity and furrow irrigation. Asparagus is assumed to have a drip irrigation system.[14]

For calculating groundwater level changes only the area with an extensive aquifer is of importance (569 km^2). More details on the region are given in the Supporting Information (SI) (sections S2, S3, and S5).

The wetland Santa Rosa has a size of 36 ha of which 10 ha are open water[15] with a maximum depth of 3 m.[16] It is the most important area with natural vegetation and wildlife in Chancay-Huaral. Moreover, compared with other coastal Peruvian wetlands, Santa Rosa is particularly species rich,[7] harboring 51 plant and 73 bird species.[6] The wetland is almost exclusively fed by exfiltrating groundwater and has no outflow.

Establishing the Water Balance. A water balance is determined through its inputs, outputs, and storage within the system for a certain time period. It is always specific to one region, but principles and procedures remain the same everywhere. The steady-state water balance equation for the project area is shown in eq 1.

$$Q = I + P + \mathrm{GWI} - \mathrm{Ex} - \mathrm{ET} + \mathrm{GWR_S} + \mathrm{GWR_I} + \mathrm{RF} - \mathrm{RWW} - \mathrm{GWW} \quad (1)$$

where Q is the river flow to the Sea, I is the river inflow into the area, P is precipitation, GWI is groundwater inflow to the area, and GWR is groundwater recharge within the area from river seepage (subscript S) and excess irrigation (subscript I) (see also Figure 1 and section S1 of the SI for flows and acronyms).

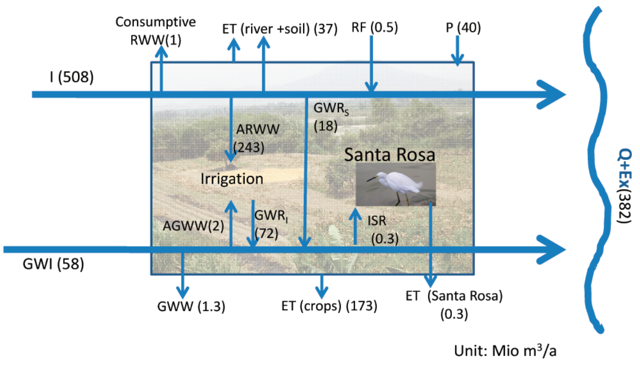

Figure 1. Scheme of the water balance for the lower valley of Chancay-Huaral with the respective magnitude of the flows. River and aquifer have inflows from the upper valley. The arrows "consumptive RWW" and "GWW" encompass water withdrawals for industrial, livestock, mining, and domestic purposes. Acronyms are introduced in the main text and eqs 1, 4, and 5 and are summarized in SI (section S1).

Ex is the exfiltration of groundwater at the coast, ET is evapotranspiration, and RF is the return flow to the river from domestic and industrial groundwater use, such as discharged wastewater. RWW is water withdrawal from the river, and GWW is water withdrawal from groundwater. While measurements can provide data for precipitation and river flows, groundwater flow interactions are complex and require modeling.

Parameterization of the Water Balance. Precipitation (P) was adopted from New et al.[17] The river Chancay-Huaral is fed by precipitation and snowmelt, which is stored in 33 lakes in the Andes and flows from 4800 m above sea level into the Pacific Ocean. There are no glaciers in the basin which could contribute to river flow.[18] Flow changes related to glacier melt due to climate change will thus not affect the watershed. The stakeholders of the region demonstrate farsightedness by controlling the outflow of most lakes, a measure which is proposed for adaptation to climate change in the Andes.[19] River flows were available on a daily basis from 1960 to 2008 from the measuring station Santo Domingo.[20] For the water balance the annual long-term mean of 16.1 m^3/s was used as inflow (I). The groundwater inflow into the area (GWI) and the groundwater recharge from the river within the lower valley (GWR$_S$) were estimated with Philip's formula.[21]

In 2010 more than 99% of the total irrigation water of 245 million m^3/a was withdrawn from the river;[22] the rest was abstracted from the aquifer. The area-specific amount of water applied to each crop was calculated as a share of the total irrigation water according to the middle crop coefficient (K_c) of each plant, i.e. plants with a higher K_c are allocated a larger amount of water per hectare than those with a lower K_c.

Table 1. Overview of the Scenarios, the Increased Crop Areas (in ha), and the Irrigation Water Sources (RW = river water, GW = groundwater)[a]

scenario name	increase asparagus	increase mandarin	increase strawberry	increase drip-irrigation	increase multicrop	increase mandarin, more GW	no irrigation
crops in 2010 (cultivated area, ha)	asparagus (161)	mandarin (3415)	strawberry (580)	avocado (1676) asparagus (161) mandarin (3415) strawberry (580)	avocado (1676) asparagus (161) mandarin (3415) strawberry (580) yellow maize(4660) potato (3212)	mandarin (3415)	no crops
crops in 2020 (cultivated area, ha)	asparagus (1612)	mandarin (5314)	strawberry (976)	avocado (2397) asparagus (1612) mandarin (5314) strawberry (976)	avocado (2090) asparagus (994) mandarin (4506) strawberry (807) yellow maize (6344) potato (5439)	mandarin (5314)	no crops
irrigation sources	RW (99%) GW (1%)	RW (99%) GW (1%)	RW (99%) GW (1%)	RW (99%) GW (1%)	RW (99%) GW (1%)	RW (75%) GW (25%)	no irrigation

[a]In the scenario "increase drip-irrigation", drip irrigation is assumed to be present on all areas with crop changes, while unchanged areas retain the original furrow irrigation system.

For livestock, 0.7×10^6 m^3 water/a were required, with a groundwater share of 98%.[22] Additional withdrawals for domestic, industrial, and mining purposes amounted to 4.7×10^6 m^3/a from the river and 0.6×10^6 m^3/a from groundwater.[22] Water withdrawals for livestock were assumed to be entirely lost from the system, since the largest part is used for drinking and cleaning the stables, ending up in the milk or being evaporated. We assumed that 20% of the amount withdrawn for mining, industrial and domestic purposes was lost, while 80% returned to the river (e.g., as sewage). This is based on information for return flows from domestic and industrial uses, which vary between 60%[23] and 90%[24] of total water withdrawal.

Evaporation and evapotranspiration (ET) take place from bare soil, water bodies, and vegetation in the lower valley, and all of them require adequate calculation procedures. The actual evaporation from bare, unproductive soil was calculated with the formula of Turc,[25] while the potential evaporation for the open water surface was estimated with the formula of Thornthwaite.[25] Evapotranspiration from the crops was calculated according to the FAO Penman−Monteith method.[26] For this, crop coefficients (K_c, indicating the difference in evapotranspiration between reference surface and respective crop)[26] and stress factors (K_s, accounting for water use efficiency and thus water losses, which will not reach the plant) were estimated. The following parameters are required for calculating evapotranspiration. The mean annual air temperature in Lima, used as proxy for Chancay-Huaral (about 60 km north of Lima), is 19.5 °C and varies between 14 and 28 °C.[27] The average precipitation in the lower valley is 34 mm/a.[17] Wind speed and dew point temperature were taken from METEOTEST.[27]

An important component in the water balance was the infiltration of excess irrigation water (GWR_I), which was estimated for each crop as the difference between the irrigation water applied and the crop evapotranspiration. Precipitation was assumed to be insignificant for groundwater recharge in the lower valley.

The groundwater flow to the sea (Ex) was estimated over the whole coastline by assuming a mean aquifer thickness of 25 m. For further details on parametrization and inputs to the water balance, see SI, sections S3−S9.

Relation between Water Level and Environmental Habitat Quality. The dominant plant species are *Schoenoplectus americanus*, *Typha dominguensis*, *Distichlis spicata*, *Paspalum vaginatum*, and *Sporobolus* species.[6,15] Thirty-seven species of the flora in Santa Rosa are terrestrial and 14 species are aquatic (floating, submerged).[6] The terrestrial species are assumed to grow from the edge of the wetland to a water depth of 1.5 m. The area from 1.5 to 3 m is considered as the aquatic plant species' habitat.

It is assumed that plants can be indicators for the suitability of an impacted wetland for birds. A change in vegetation diversity is likely to have an effect on birds as well, since "mobile" species like birds are generally dependent on vegetation and surface water bodies.[28] In contrast to the wetland, the river has a low biodiversity. Four phytoplankton species, one zooplankton species, and three benthic macroinvertebrates were registered, but not a single fish species.[29] However, the biodiversity of the river was assessed only once at one point in the lower valley and does not enter the calculation of any CF.

Scenario Development. Scenarios were developed for the year 2020 and compared to the base year 2010. The base year is 2010, since data for the crops, agricultural area, and water withdrawals were available for that year.

All proposed scenarios were developed and discussed in a workshop with local stakeholders, including farmers, biologists, hydrologists, and local authorities, held in Chancay in February 2011, which was crucial for the design of the scenarios.[30] It turned out that land is the limiting factor in the lower valley and a further expansion of agricultural area is not an option.[18] However, crops in existing areas may change at any time. During the workshop several crops that are likely to expand in cultivated areas during the next years were identified, as shown in Table 1. The changes projected in the scenarios are based on the development of the respective crops during the last 10 years, assuming past growth rates to continue until 2020. Changes in water use in the scenarios are thus not more pronounced than changes in the past. Mandarins are very important for the region and their production area has been rapidly increasing recently. This was not the case for asparagus and strawberries, but local stakeholders expect that the cultivation of these crops will increase as they are very cost-effective and demand for export is high. Since no further water rights will be allocated,[18] stakeholders try to increase the water use efficiency by adapting more water efficient irrigation techniques for perennial crops. Therefore, we considered in the "increase drip-irrigation" scenario a shift to more drip irrigation on areas with crop changes. Experiments with more water efficient irrigation techniques are undertaken at the INIA (Instituto Nacional de Investigación Agraria) and a shift to other techniques seems realistic. With rather strict water rights, the region seems able to prevent the depletion of water resources, which has, for example, occurred in Ica, the major asparagus producing region of Peru.[31] The calculated change in water use in the scenarios is incomplete because it only incorporates crop development and the water use of other sectors has not been varied. In the "multicrop" scenario, an unchanged continuation of the growing or decreasing trend of the last 10 years of the most common crops as well as of asparagus and strawberries, identified as crops with a high future potential due to economic reasons (53.3% of total crop area in 2010),[13] is considered. In order to investigate the importance of the water source for water-use related impacts, a hypothetical scenario for mandarin production with more groundwater irrigation was calculated.

Areal increases imply that areas of other crops need to be reduced. Crops that showed a decreasing trend over the last 10 years[13] are assumed to proportionally decrease further, in order to allow an expansion of other crops in the scenarios (Table 1). Since all crops have individual water requirements, the amount of irrigation water needed, and hence the water balance and groundwater level, all change. All nonconsumptively used groundwater is assumed to return to the aquifer and can be neglected. It was supposed that, except for the "increase drip-irrigation" scenario, the irrigation system will stay the same as in 2010. Crop water consumption of the scenarios presented are calculated with crop coefficient values (K_c) from the FAO,[26] since the majority of required K_c values were available from this source. For crops with no indicated K_c value, the value of a similar crop was used. Since the default K_s values ($K_{s,1}$), which are also used for calculating GWR_I, are widely varying, it was decided to apply a mean value of 0.5. Details about all crops are given in the SI (section S5) and results for scenarios with other K_c and K_s combinations are shown in the SI (section S13).

Calculation of Characterization Factors for the Scenarios. As commonly done in LCA, characterization factors (CF, eq 2) for each scenario x are calculated as the product of a fate factor (FF, eq 3) and an effect factor (EF, eqs 4 and 5).

$$\mathrm{CF}_{x,\mathrm{wetland}} = \mathrm{EF}_x \times \mathrm{FF} = (\mathrm{EF}_{x,\mathrm{terr}} + \mathrm{EF}_{x,\mathrm{aq}})\mathrm{FF} \tag{2}$$

$$\mathrm{FF} = \frac{\mathrm{ISR}_x - \mathrm{ISR}_{\mathrm{base\ year}}}{(\mathrm{ARWW}_x - \mathrm{ET}_{c,x}) - (\mathrm{ARWW}_{\mathrm{base\ year}} - \mathrm{ET}_{c,\mathrm{base\ year}})} \tag{3}$$

$$\mathrm{EF}_{x,\mathrm{terr}} = \frac{1 \times (A_{\mathrm{terr,base\ year}} - A_{\mathrm{terr},x}) + \left(1 - \frac{S_{\mathrm{terr},x}}{S_{\mathrm{terr,base\ year}}}\right)A_{\mathrm{terr},x}}{\mathrm{ISR}_x - \mathrm{ISR}_{\mathrm{base\ year}}} \tag{4}$$

$$\mathrm{EF}_{x,\mathrm{aq}} = \frac{1 \times (A_{\mathrm{aq,base\ year}} - A_{\mathrm{aq},x}) + \left(1 - \frac{S_{\mathrm{aq},x}}{S_{\mathrm{aq,base\ year}}}\right)A_{\mathrm{aq},x}}{\mathrm{ISR}_x - \mathrm{ISR}_{\mathrm{base\ year}}} \tag{5}$$

The agricultural river water withdrawal and evapotranspiration (consumptive water use) per kilogram of crop are collected in the inventory. Surface water (and groundwater) withdrawals are already today present in many life cycle inventory databases, such as ecoinvent.[32] Crop evapotranspiration can be estimated with a variety of formulas (e.g., Penman–Monteith) or tools (e.g., CropWat),[34] if necessary. For 160 crops this data is also available from Pfister et al.[33] The net balance of these inventory flows is then multiplied with the CF to arrive at impacts/benefits.

The fate factor (eq 3) reflects the relation between infiltration into the wetland (ISR) and the net groundwater flow, i.e., groundwater recharge from irrigation surplus water (inventory flow with positive sign) or groundwater consumption (negative sign). Water withdrawals from and recharge to an aquifer lead to changes in the groundwater table. Groundwater recharge is calculated as the difference of agricultural river water withdrawal (ARWW) and total crop evapotranspiration (ET_c). On the basis of infiltration rates and the corresponding infiltration area, the amount of water annually infiltrating into the wetland (ISR_x) is determined for each scenario x as a function of the groundwater level. Since the soil in the project region is sandy with high permeability, we assumed that the whole aquifer area is homogeneous and affected evenly. As Santa Rosa is exclusively groundwater-fed, the amount of infiltrating water determines the change in water level and surface area of the wetland (A_x). The resulting groundwater levels for the scenarios are then compared to the base year.

The effect factor (eqs 4 and 5) quantifies the potential disappearance of species (PDF) due to changes in wetland infiltration for the terrestrial (index terr) and aquatic (index aq) ecosystem, thus quantifying a change in biodiversity. The wetland is modeled as a circular cone with a maximum depth of 3 m. For the new wetland area the size of the aquatic and terrestrial plant zones and corresponding species numbers are calculated. $A_{\mathrm{terr},x}$ (m^2) and $A_{\mathrm{aq},x}$ (m^2) are in each scenario x the areas of the terrestrial and aquatic zone, respectively. The difference ($A_{\mathrm{base\ year}} - A_x$) is for both zones the area of wetland which is lost or gained in each scenario. $S_{\mathrm{base\ year}}$ is the original species number in Santa Rosa, and S_x is the number of species in the remaining area for both terrestrial and aquatic plants.[6] S_x is calculated with $S_{\mathrm{base\ year}}$ and the corresponding wetland areas (eq 6) for both ecosystems

$$S_x = S_{\mathrm{base\ year}}\left(\frac{A_x}{A_{\mathrm{base\ year}}}\right)^z \tag{6}$$

where z indicates the slope of the species–area relationship and is different for terrestrial and aquatic species (SI, section 10). The numerators of eqs 4 and 5 were inspired by the framework

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Table 2. Results for the Scenarios for Santa Rosa with $K_{s,1}$ and K_c Values from FAO with Both Base Case "2010" and "No Irrigation"[a]

base case "2010"	increase asparagus	increase mandarin	increase strawberry	increase drip-irrigation	increase multicrop	increase mandarin, more GW	no irrigation
total AWW (10^6 m^3/a)	246.1	239.5	244.9	217.4	241.6	239.5	0
change water level SR (mm)	0.06	−3	−0.4	−18	−5	−60	−70
area change Santa Rosa (%)	0.004	−0.2	−0.03	−1.21	−0.3	−4.1	−4.8
modeled impact (PDF·m^2·yr)	−19.7	785.5	117.7	5556.6	1372.2	18779.0	21797.2
$CF_{x,\mathrm{wetland}}$ (PDF·m^2·yr/m^3)	-3.19×10^{-4}	-3.19×10^{-4}	-3.19×10^{-4}	-4.45×10^{-4}	-3.18×10^{-4}	-3.11×10^{-4}	-3.10×10^{-4}
base case "no irrigation"	increase asparagus	increase mandarin	increase strawberry	increase drip-irrigation	increase multicrop	increase mandarin, more GW	2010
total AWW (10^6 m^3/a)	246.1	239.5	244.9	217.4	241.6	239.5	245.05
change water level SR (m)	0.077	0.074	0.077	0.070	0.072	0.011	0.077
area change Santa Rosa (%)	5.08	4.89	5.04	4.62	4.75	0.70	5.07
modeled impact (PDF·m^2·yr)	−24162.7	−23270.7	−24010.5	−22019.9	−22620.7	−3342.0	−24140.9
$CF_{x,\mathrm{wetland}}$ (PDF·m^2·yr/m^3)	-3.44×10^{-4}	-3.43×10^{-4}	-3.44×10^{-4}	-3.81×10^{-4}	-3.43×10^{-4}	-3.35×10^{-4}	-3.44×10^{-4}

[a]AWW stands for agricultural water withdrawal and SR for Santa Rosa. The modeled impact presented is the impact of both water withdrawal and consumption on the terrestrial and aquatic part of Santa Rosa. Note that the scenario in the last column is different for the two base cases.

set up by Eco-Indicator 99 for land use.[9] The left part of the numerator describes lost wetland area, where 100% of species disappear, i.e., PDF = 1. The right part targets potential loss of species in the remaining area, i.e. PDF = $1 - (S_x/S_{\text{base year}})$.

The CF for the wetland (eq 2) indicates the benefit of river water irrigation on Santa Rosa. Note that this does not include the impact on the river system, for which a separate CF, denoted CF_{river} here, is needed. The infiltration of surplus irrigation water from surface sources leads to groundwater recharge and a benefit for Santa Rosa. Consumptive groundwater use diminishes the water sources for Santa Rosa and has the opposite sign in the inventory analysis than groundwater recharge, hence resulting in an environmental damage. All groundwater withdrawals that are not consumptive infiltrate back into the aquifer in the case study region and are thus of no relevance to the impact (see example in Table 3).

Calculation of Total Environmental Impacts. Impacts on Santa Rosa can be calculated by multiplying the CF with the net infiltration into or consumption of the groundwater. In the inventory, the agricultural river water use (ARWW) and consumed amount of water per kilogram of crop (ET_c) should be reported. In order to calculate the net impact/benefit of river water use on Santa Rosa, the difference of the river water withdrawn and the consumed amount of water is multiplied with CF_{wetland}. For the impact of water withdrawal on the river's biodiversity CF_{river} according to Hanafiah et al.[35] is used, resulting in impacts in terms of water volume and not surface area. For calculating the impact of water consumption associated with groundwater use, $CF_{x,\text{wetland}}$ is multiplied with the consumptive fraction of groundwater withdrawal. Since we are assessing wetland area loss and not volume loss, the unit (PDF·m^2·yr) is directly comparable with the units used in land use assessment in LCA.[9] The calculation of these total environmental impacts is illustrated in Table 3 for the case of asparagus and mandarin production for different irrigation techniques and irrigation water sources.

Sensitivity Analysis. Crop coefficient (K_c) values given in the literature differ and we used additional K_c (denoted $K_{c,\text{ElRiego}}$, mostly from southern Spain[36]) for the sensitivity analysis. Additionally, the sensitivity of the results to an alternative stress factor ($K_{s,2}$) and the estimation of groundwater recharge was tested with an empirical formula from Turc.[37] Thus, each scenario has six subscenarios combining three different infiltration amounts and two alternative crop coefficients. For testing CF sensitivity to different base cases, a second base case, "no irrigation", was modeled, assuming an absence of irrigated agriculture. Additionally, we tested the sensitivity of the CF to the z-values.

RESULTS

Water Balance. The water balance is schematically shown in Figure 1 with results based on the mean $K_{s,1}$ value and K_c values from FAO.[26] The mean annual discharge to the sea is 382×10^6 m^3/a. This is the largest outflow of the system, followed by crop evapotranspiration.

Scenario Results. Except for "increase asparagus", all scenarios require less irrigation water and all scenarios lead to a decrease of wetland water level and area, because reduced river water withdrawal for irrigation decreases groundwater recharge (Table 2). Negative impacts and CF highlight a benefit for the wetland's area and biodiversity, as shown for all scenarios compared to base case "no irrigation". The additional water withdrawals for irrigation lead in these cases to advantages for Santa Rosa. The CF_xs for all scenarios are very similar in value (Table 2), showing that they are not very specific to the scenarios. Only the CF for "increase drip-irrigation" is different. Therefore, it is reasonable to use the median CF for all subsequent LCA studies for this region. This facilitates the assessment because it means that we can assign an impact to the amount (m^3) of water used, irrespective of the functional unit, without consideration of regional agricultural development (crop choice, irrigation development). The

Table 3. Example for the Production of 1 kg of Asparagus or Mandarin[a]

	asparagus		mandarin	
	furrow	drip	RW	GW
withdrawal surface water (ARWW)	1.9	0.9	0.4	0
withdrawal groundwater	0	0	0	0.4
net freshwater consumption (ET_c)	1.4	0.9	0.3	0.3
net flow into groundwater	0.5	**0**	0.1	−0.3
impacts on Santa Rosa[b] (PDF·m^2·yr/kg)	-1.59×10^{-4}	0	-3.19×10^{-5}	$+9.56 \times 10^{-5}$
impacts on the river[c] (PDF·m^3·yr/kg)	5.61×10^{-4} [d]	2.66×10^{-4} [d]	1.18×10^{-4} [d]	0.00[d]

[a]Asparagus is irrigated with river water, once with furrow irrigation and once with drip-irrigation. Mandarins are assumed to be irrigated traditionally with furrow irrigation, once with river water (RW) and once with groundwater (GW). The impact is calculated via the net balance between withdrawal and consumption (subtracting consumptive water use from withdrawals). Note that the impact on the river for the same volume shows a different impact for a different ecosystem, since it is focusing on fish species only and is calculated per m^3 and not per m^2. [b]negative = benefit for Santa Rosa, positive = damage for Santa Rosa. [c]On the basis of Hanafiah et al.[33] [d]Withdrawn from river → consumptive use for river.

generalized, median value for scenarios with base case "2010" for $CF_{wetland}$ is -3.19×10^{-4} PDF·m^2·yr/m^3.

Application of CFs in LCA (illustrating example). Table 3 shows an example for the production of 1 kg of asparagus and mandarins, illustrating the use of the developed CF. Mandarins are assumed to be irrigated with traditional furrow irrigation systems, once with river water (RW) and once with groundwater (GW). Asparagus is assumed to be always irrigated with river water, once with furrow irrigation and once with drip irrigation. It is assumed that with drip irrigation no water will infiltrate into the aquifer and thus everything will be consumed. In all examples except for "mandarin, GW" more water is abstracted from the river than consumed and hence groundwater is recharged (e.g., by 0.1 m^3 in "mandarin, RW"). In the "mandarin, GW" case, the same volume (0.4 m^3) is withdrawn from the groundwater of which 0.3 m^3 is lost through evapotranspiration. The 0.1 m^3 left reinfiltrates to the groundwater, without an effect on Santa Rosa. Hence, the complete groundwater withdrawal itself is not relevant. The mean $CF_{wetland}$ is negative, meaning that a net inflow into the groundwater (ARWW − ET_c), as calculated from the inventory flows, reveals benefits for Santa Rosa (impact with negative sign), while a negative net balance (i.e., groundwater consumption) leads to damage (impact with positive sign).

The impact on the river is calculated here for the amount of water withdrawn in each case. From the river's perspective, all of this volume is lost (i.e., consumptive), since principally none is returned to the river. The average potential impact on the river's fish biodiversity, estimated according to Hanafiah et al.,[35] is 2.95×10^{-4} PDF·m^3·yr/kg and should not be directly compared with $CF_{wetland}$ because of different units. Hence, it should be considered as a separate impact category in a full LCA.

We compared the water-related impacts for asparagus and mandarins, as presented in Table 3, with other impact categories adapted from Stoessel et al.,[38] in units of ReCiPe points.[11] ReCiPe is an established LCIA method quantifying environmental impacts for 16 different impact categories. Water-related impacts are only responsible for a relatively small share of the total ecosystem impact, which is dominated by climate change and agricultural land occupation. However, the irrigation system and the source of irrigation water have an influence on the total water-use-related impacts (SI, section S14).

Sensitivity Analysis. The streamflow to the sea varies between 11.4 and 14.1 m^3/s for all water balances with different K_c and K_s values. This variation is caused by differences in crop coefficients, leading to different evapotranspiration and groundwater recharge. The contribution of different K_s values to the changes of the water balances is larger than that of K_c values. Despite the sensitivity of the water balance to variations in both crop coefficients, the CFs sensitivities to changes in crop coefficients were generally small, except for changes in irrigation systems. Changes in the CFs for alterations in the z-values are small, considering the change of the z-value itself, namely, around 10% for increasing the original z-values to a maximal value of 0.34 and 16% for decreasing them to a minimal level of 0.03 (SI, sections S10, S11, S13).

DISCUSSION

Impacts. The modeled impact on the aquatic ecosystem in Santa Rosa was more pronounced than on the terrestrial ecosystem, since the area losses of open water body are relatively larger than that of terrestrial area. The different z-value of aquatic and terrestrial species also leads to stronger modeled impacts on aquatic species than on terrestrial ones.

The CF from the top-down approach of Pfister et al.[1] for the region investigated is 2.1 PDF·m^2·yr/m^3, constituting one of the highest values globally.[1] Commonly it is assumed that more water use always creates damage. However, the opposite is true for Santa Rosa when river water is used. Santa Rosa is special since it is exclusively fed by groundwater, which is enriched by surplus irrigation water as the soil is sandy, facilitating rapid infiltration. Less river water irrigation means less infiltration and thus creates ecological damage. The top-down results are not able to catch these local peculiarities, although they may be well-suited for a broader and large-scale assessment. If we broaden the view and include the river, we see conflicting results. There is an impact on the river from water withdrawals, and it would be beneficial for the river and potentially the coastal zone to decrease the amount of water withdrawn. However, extracting more groundwater would lead to larger impacts on the wetland. These conflicting results between ecosystems show the importance of distinguishing between the different sources and types of water use. It also shows the importance of balancing impacts between different ecosystems with different biodiversity. This is manageable on a small scale but becomes increasingly difficult at larger scales or when analyzing supply chains of products, thus accentuating the need for local studies alongside generalized top-down approaches.

The CF combines total species loss on the lost area and partial species loss on the remaining area, as commonly done in LCA according to the Eco-Indicator 99 framework. From an ecological perspective this is questionable. We adopted this

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concept nevertheless, taking into account the compatibility of our approach to other LCA methodologies.

A direct comparison of the CF derived in this paper with the CF for the river according to Hanafiah et al.[35] is not possible since the latter is based on fish species diversity, while the developed CF values for Santa Rosa refer to flora. CF_{river} was estimated according to Hanafiah et al.[35] although no fish species were recorded in the river.[29] Whether there used to be fish in the river and they disappeared, e.g., due to anthropogenic activities, is unknown. A direct comparison of our impacts with the complete LCA assessment of Stoessel et al.[38] faces similar drawbacks. The global value for agricultural land occupation is from central Europe[38] and thus hard to compare with coastal Peruvian conditions, which are naturally (in contrast to central Europe) desertlike. A direct comparison of impacts is often not meaningful because assessments that are able to reflect local conditions are still missing in various parts of LCIA, such as land and water use, or are applied outside of their regional scope (e.g., ReCiPe was developed for Europe).

Sensitivity and Uncertainties. Since there is no measuring station below Santo Domingo, it is not possible to assess the accuracy of the river flow estimate. However, the runoff seems to be in a realistic range according to local experts.[30]

The precipitation for the lower valley from METEOTEST,[27] based on mean monthly values from 1996 to 2005, is 37 mm/a and matches the value estimated from SENAMHI.[39] For the potential evapotranspiration, estimates range from around 1000[40] to 565 mm/a[41] for one station in the lower valley for two years in the 1960s and 1970s. The estimate with Thornthwaite (893 mm) lies between these two values and seems reasonable. Consumptive evaporation losses from the irrigation systems, as discussed in Faist et al.,[42] are only partially taken into account in the sensitivity analysis, as the application of different K_s values makes the estimated evapotranspiration vary by 29%.

Base cases and K_s and K_c values influence the water balance, the calculation of groundwater level, and impacts. The differences between the scenarios with different K_s and K_c values are small, except for the empirically derived Turc formula. However, this formula is questionable for groundwater recharge, since it neglects many factors influencing infiltration, such as soil properties. The difference between the median CFs with different base cases is only 8%, and the CFs are akin for the different scenarios indicating high linearity of the system. Consequently, the generalized values are applicable to the whole region and different crops with an acceptable uncertainty.

With the base case "no irrigation" and different K_s and K_c values, the increase in wetland area is predicted to be between 0.7% and 9.9%. This matches well with observations in the field that Santa Rosa has slowly, but constantly, been growing during the last decades. A comparison between aerial pictures from 1961 and 2006 revealed an area increase between 5.5% and 8.9% (SI, section S13).

An important question concerns the reference for an assessment of Santa Rosa. Since Santa Rosa has been growing, it has actually changed from its natural state (which is often suggested as reference) and the question remains which part of Santa Rosa deserves protection: only the natural part or the wetland as it is today with increased area due to irrigation. Similar discussions exist in land use assessments, where, for example, poor grassland is more biodiverse than forest, often taken as the potential natural vegetation.[43]

If birds were included in the impact calculation, the *z*-value would be different. However, especially migratory birds are difficult to consider in an impact assessment, since damages on one species (e.g., fewer individuals arriving) can be caused by different impacts elsewhere, showing that the ecological value of a region can be larger than the region itself.

An issue for the wetland today is also the water quality, since input of nutrients from agriculture and sewage lead to eutrophication, which is not examined in this work.

■ PRACTICAL IMPLICATIONS

Generic or top-down assessment methodologies like that of Pfister et al.[1] are good tools for a first screening assessment of a larger region. However, as our results have shown, the outcomes of these approaches may not be relevant at a local level. This highlights the importance and need for further regionalization in LCA and water footprinting, in order to improve the accuracy and applicability of LCA on local levels. It is suggested that the presented approach should be used for refinement of top-down results, in order to obtain locally valid figures and to capture the peculiarities and differences between surface water and groundwater of a region with a manageable procedure.

The relevance of proactive assessments is illustrated by the example of Ica, a nearby valley of Chancay-Huaral, where asparagus production contributed heavily to aquifer depletion and increased water scarcity.[31] In order to avoid such consequences, it is necessary to have a decision-support tool helping to assess management decisions. Our study provides generalized and scenario-specific CF factors for Chancay-Huaral which can be applied for evaluating different management options and crop choices. The drawn conclusions will be valuable for local decision-makers and international consumers in a North−South context. This involves the production of commodities in the "global South" (developing and emerging economies) while the consumption takes place in the "global North" (industrialized economies). Local decision-makers should be supported for planning future agricultural development and for the simultaneous protection of ecosystems such as wetlands, while international consumers should become aware of the aggregated impacts of their consumption. A classic example from Peru is the production of asparagus, which is mostly exported and not consumed locally.

■ OUTLOOK

The narrow geographical scope of the study prevents an application of the presented CFs on a worldwide level. However, the methodological approach is transferable to any other region due to the relative simplicity of the approach and low requirements for input data. Efforts are currently undertaken to provide characterization factors for the most important wetlands/watersheds on a global level in order to be able to consistently calculate impacts from water use on wetlands in a variety of geographical regions.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

Details on the agriculture, hydrologic parameters, methods applied, and sensitivities and further results. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

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REFERENCES

(1) Pfister, S.; Koehler, A.; Hellweg, S. Assessing the environmental impacts of freshwater consumption in LCA. *Environ. Sci. Technol.* **2009**, *43* (11), 4098−4104.

(2) *World water assessment programme. The United Nations world water development report 3: Water in a changing world*; UNESCO: Paris, 2009.

(3) OECD/IUCN. *Guidelines for aid agencies for improved conservation and sustainable use of tropical and sub-tropical wetlands*; OECD: Paris, 1996.

(4) International Organization for Standardization (ISO). *14040—Environmental management—Life cycle assessment—Principles and framework*; ISO: Geneva, 2006.

(5) van Zelm, R.; Schipper, A. M.; Rombouts, M.; Snepvangers, J.; Huijbregts, M. A. J. Implementing groundwater extraction in life cycle impact assessment: Characterization factors based on plant species richness for the Netherlands. *Environ. Sci. Technol.* **2011**, *45*, 629−635.

(6) Jiménez Vílchez, R.; Portocarrero Alcedo, O. M.;Alcántara Medrano, B. *Caracterización y evaluación de los principales factores biológicos del Humedal de Santa Rosa como base para su conservación, manejo y gestión, Lima and Chancay*; 2009.

(7) Gobierno Regional de Lima. Gerencia regional de recursos naturales y gestión de medio ambiente. Humedal Santa Rosa, nd.

(8) Ramirez, D. W.; Aponte, H.; Cano, A. Flora vascular y vegetación del humedal de Santa Rosa (Chancay, Lima). *Rev. Peru. Biol.* **2010**, *17* (1), 105−110.

(9) Goedkoop, M.; Spriensma, R. *The Eco-Indicator 99. A damage oriented method for life cycle impact assessment. Methodology report and annex*; Pré Consultants: Amersfoort, The Netherlands, 1999; http://www.pre.nl/eco-indicator99/.

(10) Falkenmark, M.; Rockstrom, J.*Balancing water for humans and nature. The new approach in ecohydrology*; Earthscan: London, 2004.

(11) Goedkoop, M.; Heijungs, R.; Huijbregts, M. A. J.; De Schryver, A.; Struijs, J.; van Zelm, R. *ReCiPe 2008: A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and endpoint levels. 1st edition. Report i: Characterization*; Ministerie van Volkshuisvesting, Ruimtelijke Ordening en Milieubeheer, 2009.

(12) Bernabé, D.; Torres, L.; Omar, R.; Silva, P.; Charles, J.; Chata, A. Evaluación y ordenamiento de los recursos hídricos de la cuenca Chancay-Huaral. Ministerio de Agricultura, Instituto de Recursos Naturales, Dirección general de Aguas y Suelos (DGAS): Huaral, 2001.

(13) Gobierno Regional de Lima. Personal communication (areas cultivos). 2011.

(14) Sanchez Vigo, J. Nutrición y fertilización del cultivo de Espárragos. In *Módulo Integrado de Espárragos y Alcachofas*; Facultad de Agronomía, UNALM: Lima, Peru, 2005.

(15) Alcántara Medrano, B.; Jiménez Vílchez, R. Estudio Base del Humedal de Santa Rosa, Chancay Cooperación, Proyecto Avina, IAF, Chancay, 2005.

(16) Martinez, A. Personal comunication (field visit wetland Santa Rosa, municipalidad de Chancay), February 2010.

(17) New, M.; Lister, D.; Hulme, M.; Makin, I. A high-resolution data set of surface climate over global land areas. *Climate Res.* **2002**, *21* (1), 1−25.

(18) León Luna, I. Personal communication (ALA, Administración local de Agua, Chancay-Huaral), March 2011.

(19) Bradley, R.; Vuille, M.; Diaz, H.; Vergara, W. Threats to water supplies in the tropical Andes. *Science* **2006**, *312*, 1755−1756.

(20) ALA (Administración local de Agua) Chancay-Huaral. *Registro de Descargas Diarias del Rio Chancay-Huaral (1960−2008)*, 2010.

(21) Jury, W.; Gardner, W.; Gardner, W. *Soil Physics*, 5th ed.; Wiley & Sons: New York, 1993.

(22) Gobierno regional de Lima, Agua Subterránea y Superficial 2010. Personal communication, 2011.

(23) Seckler, D.; Amarasinghe, U.; David, M.; de Silva, R.; Barker, R. *World water demand and supply, 1990 to 2025: Scenarios and issues. Research Report 19*; International Water Management Institute, Colombo, Sri Lanka, 1998.

(24) World Water Council. *The use of water today* (accessed January 24, 2012); http://www.worldwatercouncil.org/fileadmin/wwc/Library/WWVision/Chapter2.pdf.

(25) Koch, M. Vorlesungsskript Ingenieurhydrologie I (Chapter 5). Sommersemester 2003, Universität Kassel.

(26) Allen, R. G.; Pereira, L. S.; Raes, D.; Smith, M. *Crop evapotranspiration. Guidelines for computing crop water requirements. FAO irrigation and drainage paper No. 56*, FAO: Rome, 1998.

(27) METEOTEST. *meteonorm*; 2011.

(28) Hatton, T.; Evans, R. *Dependence of ecosystems on groundwater and its significance to Australia. Occasional paper no. 12/98*; Land and Water Resources Research and Development Corp. (LWRRDC): Australia, 1998.

(29) CESEL Ingenieros. *Estudio de impacto ambiental del proyecto "reforzamiento de la línea de transmisión centro norte medio en 500 kV" (Línea de transmisión eléctrica zapallal—trujillo y subestaciones asociadas)*; MINEM (Ministerio de Energia y Minas): Lima. 2010.

(30) Workshop in Chancay with local stakeholders: Balance hídrico de la parte baja de Chancay-Huaral e identificación de escenarios futuros; February 2, 2011, Chancay.

(31) Hepworth, P.; Postigo, N. D.; Güemes Delgado, B.;Kjell, P. *Drop by drop. Understanding the impacts of the UK's water footprint through a case study of Peruvian asparagus*; Progressio, CEPES, and Water Witness International: London, Lima, Edinburgh, 2010.

(32) Ecoinvent Centre. Ecoinvent data v.2.2. (accessed February 17, 2012); www.ecoinvent.org.

(33) Pfister, S.; Bayer, P.; Koehler, A.; Hellweg, S. Environmental impacts of water use in global crop production: Hotspots and trade-offs with land use. *Environ. Sci. Technol.* **2011**, *45* (13), 5761−5768.

(34) FAO (Food and Agricultural Organization of the United Nations). *CropWat* (accessed February 17, 2012); http://www.fao.org/nr/water/infores_databases_cropwat.html.

(35) Hanafiah, M. M.; Xenopoulos, M. A.; Pfister, S.; Leuven, R. S.; Huijbregts, M. A. J. Characterization factors for water consumption and greenhouse gas emissions based on freshwater fish species extinction. *Environ. Sci. Technol.* **2011**, *45* (12), 5572−5278.

(36) elRiego.com. Necesidades de agua de los cultivos (accessed April 18, 2011); http://www.elriego.com/informa_te/riego_agricola/fundamentos_riego/programacion_riegos/necesidades_agua.htm.

(37) Turc, L. Le bilan d'eau des sols: Relations entre les précipitations, l'évaporation et l'écoulement. *Ann. Agron.* **1954**, *5*, 491−596.

(38) Stoessel, F.; Juraske, R.; Pfister, S.; Hellweg, S. Life cycle inventory and carbon and water foodprint of fruits and vegetables: Application to a Swiss retailer. *Environ. Sci. Technol.* **2012**, *46*, 3253−3262.

(39) SENAMHI (Servicio Nacional de Meteorología e Hidrología del Perú). *Datos históricos-ultimos datos estación Huayan* (accessed July 6, 2011); http://www.senamhi.gob.pe/include_mapas/_dat_esta_tipo.php?estaciones=000539.
(40) Gutierrez Pusoni, J. Field visit, Chancay, INIA (Instituo Nacional Deinvestigación Agraria), February 2010, Chancay-Huaral.
(41) INRENA (Instituto Nacional De Recursos Naturales). *Proyecto de habilitación de terrenos eriazos comunidad campesina de Aucallama, Huaral-Aucallama*; INRENA: Lima, 1999.
(42) Faist Emmenegger, M.; Pfister, S.; Koehler, A.; de Giovanetti, L.; Arena, A. P.; Zah, R. Taking into account water use impacts in the LCA of biofuels: An Argentinean case study. *Int. J. Life Cycle Assess.* **2011**, *16* (9), 869−877.
(43) Koellner, T.; de Baan, L.; Beck, T.; Brandão, M.;Civit, B.; Margni, M.; Milà i Canals, L.; Saad, R.; Maia de Souza, D.; Müller-Wenk, R. UNEP-SETAC guideline on global land use impact assessment on biodiversity and ecosystem services in LCA. *Int. J. Life Cycle Assess.* In press.

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