

ECO-EFFICIENCY OF DIFFERENT LAND USE SCENARIOS BASED ON LIFE CYCLE ASSESSMENT

EFFICACITÉ ÉCOLOGIQUE DE DIFFÉRENTS SCÉNARIOS D'USAGES DES SOLS SUR LA BASE D'UNE ANALYSE DU CYCLE DE VIE

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ABSTRACT

Climate change is increasingly challenging water resource management, requiring decision-makers to balance mitigation of greenhouse gas (GHG) emissions with adaptation strategies. This study investigates whether the construction of an inter basin water transfer infrastructure constitutes an effective solution for securing regional water supply, using a Territorial Life Cycle Assessment (LCA) approach. The analysis is applied to a real case study in Provence (Southern France), covering approximately 15,000 ha with agricultural and potable water needs.

Three scenarios are compared: (1) continuation without any new water transfer infrastructure, relying on existing systems and groundwater supply when available; (2) development of a new inter-basin transfer system (mainly gravity fed) enabling expanded irrigation; and (3) the same infrastructure combined with agricultural diversification toward more food-oriented production.

The LCA integrates impacts from infrastructure construction and operation (materials, energy use) as well as agricultural practices (inputs, works...). A focus was made on GHG emissions and a Single Score indicator. Socio-economic and functional benefits are also assessed through gross margin, employment (FTE), and nutrient-based biomass production (NR9 score).

Results show that scenarios including new infrastructure (2 and 3) generate slightly higher environmental impacts than the baseline, but within the same order of magnitude. However, these scenarios significantly enhance agricultural productivity, economic returns, and employment. Scenario 3 yields the highest edible biomass due to diversification. Eco-efficiency analysis (relating service provision to environmental impact) indicates that scenarios 2 and 3 outperform the baseline, with scenario 3 emerging as the most efficient overall.

The study is an example of integrative approach combining environmental and socio-economic indicators through LCA, based on eco-efficiency ratios. Such an approach can help the decision-making process to determine whether a development project, despite its impact, brings real added value to a region.

Keywords: Climate change; water resource management; agricultural diversification; agricultural productivity; decision-making process.

RESUME

Le changement climatique rend la gestion des ressources en eau de plus en plus complexe, obligeant les preneurs de décision à rechercher un équilibre entre la réduction des émissions de gaz à effet de serre (GES) et les stratégies d'adaptation. Cette étude examine la manière dont la construction d'une infrastructure de transfert d'eau interbassin constitue une solution efficace pour sécuriser

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l'approvisionnement régional en eau, en utilisant une approche d'analyse du cycle de vie (LCA) territoriale. L'analyse porte sur une étude de cas réelle menée en Provence (sud de la France), couvrant environ 15 000 ha de terre ayant des besoins en eau agricole et potable.

Trois scénarios sont comparés : (1) le maintien de la situation actuelle sans nouvelle infrastructure de transfert d'eau, en s'appuyant sur les systèmes existants et l'approvisionnement en eaux souterraines lorsque celui-ci est disponible; (2) le développement d'un nouveau système de transfert interbassin (principalement gravitaire) permettant d'expansion de l'irrigation; et (3) la combinaison de même infrastructure avec une diversification agricole vers une production davantage axée sur l'alimentation.

Le LCA intègre les impacts liés à la construction et à l'exploitation des infrastructures (matériaux, consommation d'énergie) ainsi qu'aux pratiques agricoles (intrants, travaux...). L'accent a été mis sur les émissions de gaz à effet de serre et sur un indicateur de note unique. Les bénéfices socio-économiques et fonctionnels sont également évalués à travers la marge brute, l'emploi (équivalents temps pleins) et la production de biomasse basée sur les nutriments (score NR9).

Les résultats montrent que les scénarios incluant de nouvelles infrastructures (2 et 3) donnent lieu aux impacts environnementaux légèrement supérieurs à ceux du scénario de référence, tout en restant du même ordre de grandeur. Cependant, ces scénarios améliorent considérablement la productivité agricole, les retours économiques et l'emploi. Le scénario 3 produit la plus grande quantité de biomasse comestible grâce à la diversification. L'analyse d'efficacité écologique (qui met en relation le service rendu et l'impact environnemental) indique que les scénarios 2 et 3 surpassent le scénario de référence, le scénario 3 étant jugé comme le plus efficace dans l'ensemble.

Cette étude illustre une approche intégrée combinant des indicateurs environnementaux et socio-économiques par le biais du LCA, sur la base de taux de l'efficacité écologique. Une telle approche peut faciliter le processus de prise de décision visant à déterminer la manière dont un projet de développement, malgré son impact, apporte une valeur réelle ajoutée à une région.

Mots-clés : Changement climatique; Gestion des ressources en eau; Diversification agricole; Productivité agricole; Processus de prise de décision.

INTRODUCTION

The effects of climate change are forcing us to find the right balance between reducing greenhouse gas emissions and developing strategies to adapt to the impacts we are facing. At the regional level, decision-making tools are needed to answer the following question: 'Under what conditions can the construction of a water infrastructure be considered an effective option for securing water supplies in a region?'

The Life Cycle Assessment (LCA) approach can provide some answers. LCA is a standardized method for assessing multi-criteria environmental impacts. The results of an LCA can be presented in the form of different impacts: CO₂e emissions, resource depletion, water consumption, etc. This makes it possible to compare different agricultural and land use scenarios (e.g. irrigated vs. dry, or with different crops and practices), considering both the impact of creating infrastructure and the technical itineraries of crops.

The work carried out is inspired by the work of Rogy et al. (2022), who worked on a theoretical case study, comparing the environmental performance of an area with or without an irrigation infrastructure. For this, they used the Territorial-LCA (T-LCA) methodology, which is an adaptation of the LCA framework allowing the computation of the environmental performance of territory. Contrarily to the standard LCA methodology, T-LCA not only computes the potential environmental impacts of the territory, but also the quantity of services it provides. The latter can be for example linked to environmental, e.g. protection of natural area, economic, e.g. revenues, or social, e.g. job creation or food provision, considerations. Finally, in T-LCA, environmental performance is measured with eco-efficiency ratios, which are ratios of provided services by the territory with its potential environmental impacts (as defined by Seppälä et al., 2005). This ratio allows to answer the question: which scenario

is more efficient, given the same impact? As such, the higher the eco-efficiency ratio, the more services are provided by units of impacts, and the more the territory is performant from an environmental point of view. The aim of the study is to compare the environmental performances of three land-planning scenarios of a real territory including approximately 15,000 ha of agricultural land and urban water use. First, the different scenarios are described. Second, the input data and modelling methodology are explained. Finally, the eco-efficiency ratios of the three scenarios are compared.

STUDY AREA AND SCENARIO DESCRIPTION

The area (Figure 1) is located in Provence, Southern France, with low access to irrigation (low local surface water resources and some groundwater uptake). This area is already partially served by a water conveyance system from a wetter mountain storage zone. Land use is dominated by vineyards, with grassland and crops like olive trees and vegetables representing less than 20% of the cultivated area (Registre Parcellaire Graphique 2024). The area (15 000 ha approximately) is not benefiting from a proper irrigation infrastructure. Most of the crops are not irrigated, or benefit from punctual water supply from wells. An existing water infrastructure brings mainly raw water for potabilization (approximately 16Mm³).

Three possible irrigation development scenarios have been modelled.

SCENARIO 1: The territory evolves without any new inter-basin water transfer. Without new irrigated land, agricultural yields decrease in the occurrence of dry years. Potable water is provided through the existing pipeline by inter-basin transfer, needing energy for the pumping system.

SCENARIO 2: The same area evolves including a new inter basin water transfer via a water supply system, mainly gravity-fed. More irrigated crops can therefore be cultivated due to the adaptation to the effects of climate change that cause more crop water requirements and less local water resources available for irrigation. Potable water supply is provided by the same infrastructure to about 60 additional villages.

SCENARIO 3: This scenario includes the same inter basin water transfer as in scenario 2 but emphasizes agricultural diversification (i.e. towards more edible products instead of wine contrarily to scenario 2), to increase the territory's food independence.

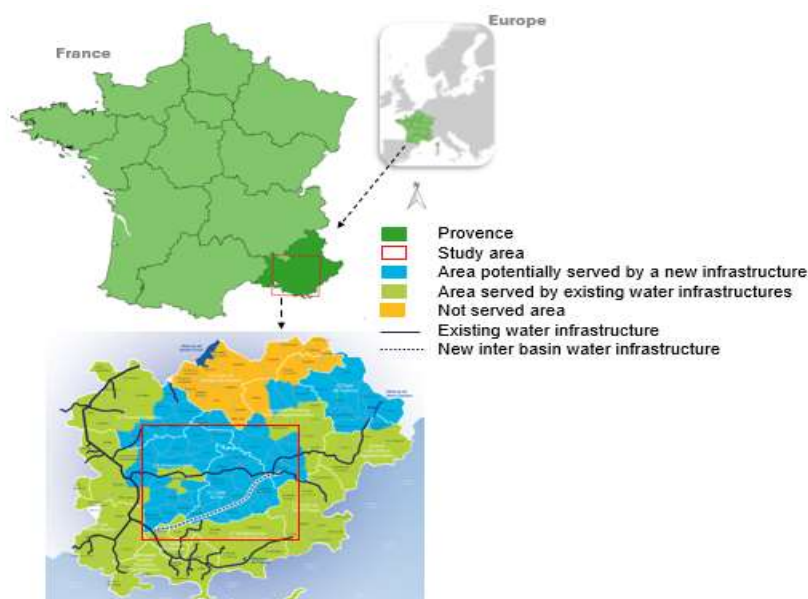


Figure 1. Map of the area and of existing and projected water infrastructures

INPUT DATA AND MODELLING METHODOLOGY

System boundaries include the inputs related to water infrastructure (materials for pipelines, works for their installation and energy to operate the system) and agriculture (fertilizers, pesticides, energy...), as well as the outputs of agriculture (fruits, grains etc...). To take into account the impacts coming from the water infrastructure the following input data are considered.

Table 1. Input data for infrastructure scenarios including water and energy needs

	Scenario 1	Scenario 2 or 3
New irrigation pipelines	-	Approx. 70 km of DN 500-1200 (metallic) Approx 200 km of DN 200-500 (plastic) Approx 42 000 km of small distribution network (plastic)
New reservoirs	-	2
New pumping stations	-	1
Annual water volume transferred by an existing infrastructure	3.6 Mm ³ /yr for crops 16.2 Mm ³ /yr for potabilization	5.1 Mm ³ /yr for crops 1.9 Mm ³ /yr for potabilization
Annual energy consumption for water transfer by existing infrastructure	9 230 MWh/yr	2 842 MWh/yr
Annual water volume transferred by the new infrastructure	-	9.9 Mm ³ /yr for crops 16.3 Mm ³ /yr for potabilization
Annual energy consumption for water transfer by the new infrastructure	-	840 MWh/yr
Annual groundwater volume uptake	0.8 Mm ³ /yr for crops 3 Mm ³ /yr for potabilization	-
Annual energy consumption for groundwater uptake	1900 MWh/yr	-
Total water used in the scenario	23.7 Mm³/yr	33.4 Mm³/yr
Total energy used in the scenario	11 130 MWh/yr	3 682 MWh/yr

The modelling is performed for an average year, based on the time horizon up to 2050. Based on the climate change effects over the Provence area (Météo-France, DRIAS/TRACC-2023) a decade is estimated to be composed of 5 average years, plus 3 dry years and 2 wet years. Therefore, in our modelling, one year has 50% of the characteristics of an average year, 30% of a dry year and 20% of a wet year.

Agriculture in the area evolves consequently to the irrigation and climatic conditions in each scenario. As for crops, only irrigable crops (Table 2) are affected by the 3 scenarios.

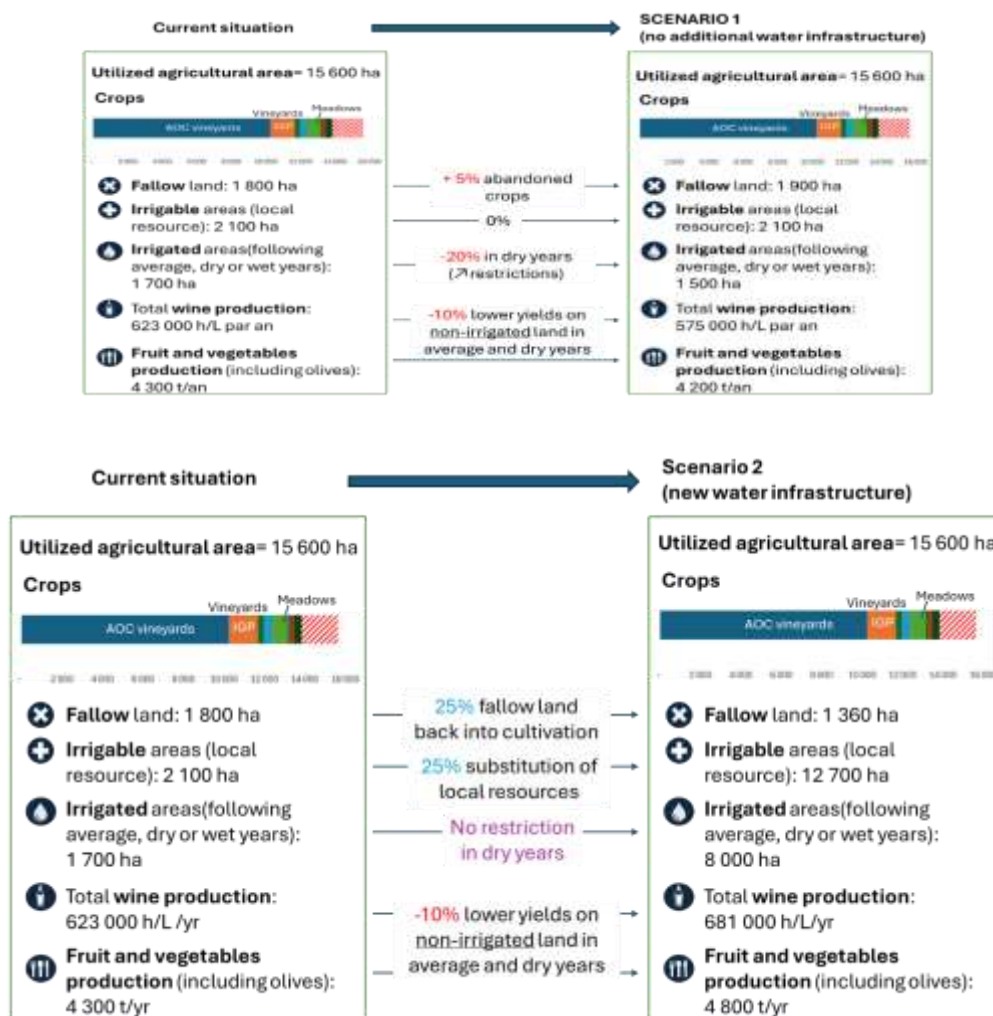
Table 2. Proportion of the different irrigable crops in the current baseline situation

Crop type	Percentage
Vineyards under "Appellation d'Origine Contrôlée (AOC)"	74 %
Non-AOC vineyards (e.g. IGP / PGI vineyards)	10%
Grasslands and forage crops	6%
Open field crops	5%
Olive trees	3%
Fruits and other permanent crops	2%
Greenhouse crops	0,5%
Field-grown vegetables	0,2%

As shown in Figure 2, different hypothesis characterizes the 3 scenarios:

1. Fallow land increases if there is no new water infrastructure, because landowners find it difficult to continue their work in conditions where the impact of climate change increases warming and occurrence of dry years. On the other hand, in the perspective of having a new water infrastructure available, some fallow lands are put back into cultivation.
2. Irrigated areas suffer in scenario 1 from lack of water during dry years (due to possible restrictions in the groundwater uptake), while crops needs are satisfied in the case of scenario 2 and 3.
3. In the case of the creation of a new water infrastructure (scenarios 2 and 3), the transferred water replaces the groundwater uptake. This implies less energy consumption (since no pumping by the wells is needed, and part of the water transfer is gravity fed).

Based on these hypotheses, crop yields vary accordingly in each scenario. The lack of water and the increased fallow land for example imply less production. On the contrary, scenarios 2 and 3 provide more products (wine and edible biomass in different proportions), but they also imply more impacts due to the creation of the infrastructure and the technical itinerary of each crop (increased cultivated area = increased use of intrants).



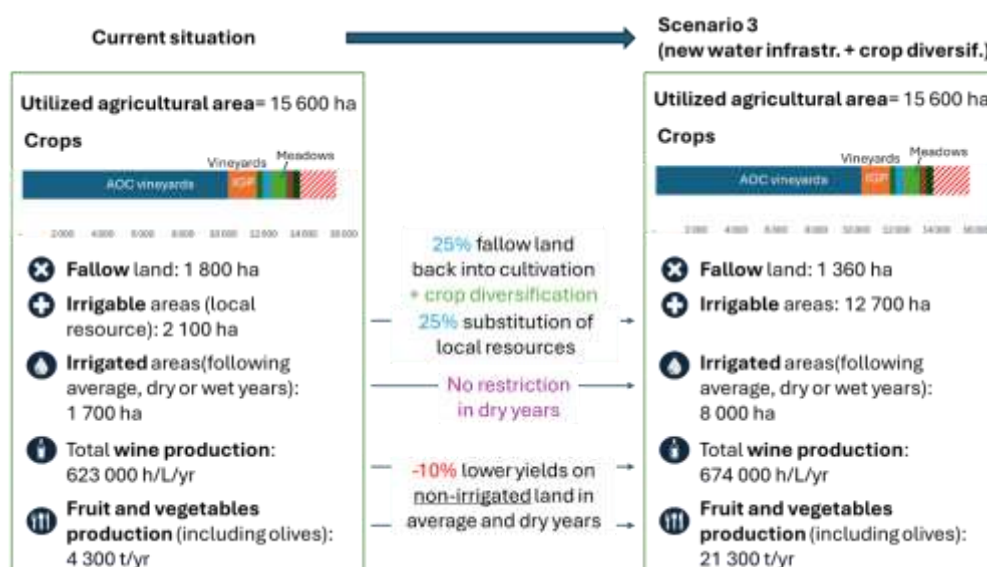


Figure 2. Main features of land evolution (2050 horizon) according to each scenario

The LCA methodology is used by modelling the technical itineraries of each crop and the impacts of energy consumption and infrastructure creation and operation, in order to assess the potential environmental impacts generated by each scenario. Figure 3 describes how the emission of chemicals and the extraction of natural resources linked to human activities (Life Cycle Inventory) are converted to potential environmental impacts (Impact Assessment).

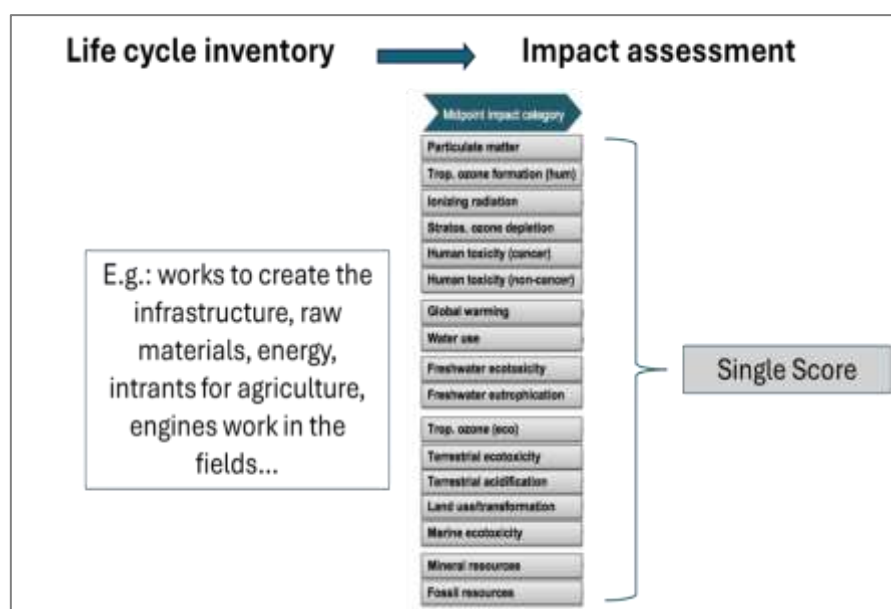


Figure 3. Schematic view of LCA midpoint impacts and Single Score

The software SIMAPRO was used for LCA modelling. Even though LCA allows to get potential impacts for several categories (land use change, eutrophication, GHG emissions, resources use etc.) the choice of two main impacts was made: GHG emissions (corresponding to the midpoint category "Global Warming") and Single Score (corresponding to a normalization and ponderation of all the midpoint impacts).

The services provided by the studied territory are 1. the economic profits, evaluated with the agricultural added value (gross margin), 2. the job creation, measured with the employment rate and 3. the provision of food, evaluated with the nutritional richness of agricultural products. These 3 services are calculated according to the following methodology.

Economic profit: The reference gross margin estimates are those available to economists for the region. Since crop rotation categories do not always correspond to the reference gross margin categories, an equivalence has been established. Fallow land is not included in the calculations.

Table 3. Gross margin for irrigated and non irrigated crops

Crop type	Non irrigated crop gross margin (€/ha)	Irrigated crop gross margin (€/ha)	Sources
Cereals and oilseeds (durum wheat, soft wheat, sunflower, rapeseed, etc.)	465 €	620 €	RICA2020
Temporary pasture	1 076 €	1 434 €	Expert hypothesis
Vegetables	- €	28 249 €	RICA PACA 2023
Flowers and horticultural products	- €	27 457 €	RICA PACA 2023
Vineyards	2 570 €	5 240 €	RICA PACA 2023
Fruits and other permanent crops	2 420 €	4 800 €	RICA PACA 2023
Olive trees	2 420 €	4 800 €	Expert hypothesis

Projections for increases or decreases in gross margins based on the type of year (wet or dry) were proposed by experts, based on observations in the Provence and other areas of southern France.

Table 4. Gross margin evolution rates depending on the climatic year type

Wet year		Average year		Dry year	
Evolution rate of gross margin for non irrigated crops	Evolution rate of gross margin for irrigated crops	Evolution rate of gross margin for non irrigated crops	Evolution rate of gross margin for irrigated crops	Evolution rate of gross margin for non irrigated crops	Evolution rate of gross margin for irrigated crops
110%	105%	100%	100%	70%	95%

Job creation: the number of full-time equivalents (FTE) per hectare in agriculture depends on whether crops are irrigated or not. Statistical data from the Agricultural Census have indeed shown that irrigated agriculture generates more jobs. The references used are as follows:

Table 5. Full-time equivalents per hectare depending on the crops

	FTE/ha in irrigated crops	FTE/ha in non-irrigated crops
Field crops	0,01	0,02
Mixed farming	0,02	0,06
Vegetables	0,07	0,29
Vineyards	0,06	0,07
Arboriculture	0,04	0,08

Provision of food: instead of the production weight or kcal provided, the NR9 nutrient score was preferred as an indicator of edible food production. The NR9 score is a nutritional quality index (Saarinen et al., 2017) that adds together the percentage daily values of 9 beneficial nutrients in a food. It is used to estimate how nutrient-dense a food is.

The nutrients commonly included are proteins, fibers, vitamins (A, C, D), calcium, iron, potassium and magnesium. Thus, a food rich in fiber, protein, vitamins, and minerals gets a high NR9 score.

RESULTS

The results of scenarios potential impacts (single score and GHG emissions) and territorial services (gross margin, employment, nutritional richness) are shown in table 6.

Table 6. Impact and benefits of each scenario

	IMPACTS		BENEFITS		
	Single Score Impact (kPt/yr)	GHG emissions (tCO ₂ e/yr)	Economic profit (M€/yr)	Job creation (FTE/yr)	Food provision (PtNR9/yr)
Scenario 1	3.9	18 444	36	824	444 317
Scenario 2	4.1	20 705	45	1 050	467 377
Scenario 3	4.7	24 000	51	1 132	3 453 668

It can be observed that single score or GHG emissions impacts among scenarios are higher in scenarios 2 and 3, but they have the same order of magnitude as scenario 1. On the other hand, scenarios 2 and 3 provide greater amount of services, especially scenario 3 as for nutritional richness.

The eco-efficiency ratios of the three scenarios are presented in Figure 4 for each territorial service and the single score impact (GHG emission would have a similar trend).



Figure 4. Eco-efficiency results for economic profit, job creation and food provision related to Single Score impact (% toward the best eco-efficiency)

Scenario 3 appears to be the most environmentally performant scenario for the provision of food, even though both scenarios 2 and 3 seem to be an eco-efficient good choice for the development of the area: they bring more benefits in terms of job creation and economic profit.

CONCLUSION

Such a study assists in the decision-making process to determine whether a development project, despite its impacts, brings real added value to a region. In fact, the higher potential impacts of Scenarios 2 and 3 compared to Scenario 1 (due to more agricultural practices and the construction of an irrigation infrastructure), are counterbalanced by the higher amount of service provided. As such, the irrigated scenarios have higher environmental performance than the baseline over the three territorial services. Scenario 3 being much more performant and having almost the same performance on economic profit and job creation as Scenario 2, Scenario 3 might be the most beneficial land-planning scenario for the future of the territory. Further research and public consultation would be required in order to understand which services the local community considers most important. In this way, environmental performance could be prioritized most effectively at the local level.

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