Assessing the eco-efficiency of irrigation scenarios using Territorial Life Cycle Assessment: Water, energy and infrastructure nexus of agricultural areas

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Introduction

Irrigation is one of the main strategies for adapting agriculture to climate change (El Chami & Daccache, 2015) as it allows sustaining yields in the face of drought and increasing temperature (Mbow et al., 2019). Large-scale planning projects can be implemented to secure agricultural area water supply such as Inter-Bassin Water Transfers (IBWT), based on imported water resources, or Agricultural Reservoirs (AR) that harvest local run-off water. These hydraulic infrastructures have a long lifetime, therefore an ex-ante environmental assessment is required to support local decision-making and support territorial planners for the selection of the least impactful alternative on the environment.

Several studies have used Life Cycle Assessment (LCA) to compare the environmental impact of hydraulic structures (Byrne et al., 2017). However, the boundaries stop at the water supply gate. Therefore, they do not grasp the entire range of services provided by irrigation, such as the territorial socio-economic benefits resulting from agricultural yield conservation. These limitations are inherent of the LCA framework which is a product-oriented method at a "microscale" and do not allow for the full integration of the territorial context, and multifunctionality (Loiseau et al., 2018).

These limitations can be overcome by using Territorial LCA (T-LCA), an adaptation of the conventional LCA framework, to assess the performance of a territory and an associated land planning scenario while considering its multifunctionality (e.g. economic, social or environmental land use functions) (Loiseau et al., 2013). The T-LCA outputs are eco-efficiency ratios, i.e. the ratios between services provided by the territory and its environmental impacts (Seppälä et al., 2005). This study aims at using the T-LCA framework to compare the eco-efficiency of land planning scenarios with or without hydraulic project implementation. In addition, trade-offs in the Water-Energy-Infrastructure nexus between projects were identified, and the design conditions under which one project performs better environmentally than another are discussed. Generic conclusions are drawn from a theoretical case study of an agricultural area occupying 700 ha located in a water-stressed area in the South of France.

Materials and methods

As shown in Figure 1, three land planning scenarios will be compared, i.e. one rainfed scenario (Scenario 0) and two irrigated scenarios (Scenario 1 – IBWT and Scenario 2 – AR). Since Scenario 0 does not have any irrigation infrastructure, the crops are rainfed. Three types of crops have been selected to be consistent with Mediterranean agriculture and to reflect a diversity of production both in terms of type of plants (perennial or not, cultivated or not), and in terms of valorization (food security or added value creation). Both scenarios 1 and 2 have the same crop occupation. Indeed, non-irrigated crops still occupy the cultivated area while irrigated crops occupy the remaining surface. With access to irrigation, it is assumed that yields could be increased and vines would no longer be registered as Controlled Designation of Origin (CDO) (yield limits) but would rather be classified within Protected Geographical Indications (PGI).

The IBWT imports water from an unstressed area whereas the AR uses water near the agricultural perimeter, in the same water stressed area. Unlike the AR, the IBWT allows for the irrigation of a large area, for which the studied territory only represents a small share (impact allocation based on a ratio between the annual quantity of irrigation water needed by the territory and the annual quantity of water circulating in the IBWT). The system boundaries rely on a cradle to territorial gate perspective, encompassing all upstream processes related to the water supply, the energy use, the irrigation infrastructure as well as all the inputs necessary to produce crops. To deal with multifunctionality, different territorial services are quantified, i.e. land management (ha) and food production (kg). Data collection is based on water and energy balances, and using existing processes in databases such as Agribalyse and World Food LCA Database. Environmental impacts are quantified at both the midpoint and the endpoint level with the Life Cycle Impact Assessment method IMPACT World+ (Bulle et al., 2019). Then according to T-LCA framework, eco-efficiency indicators are computed.

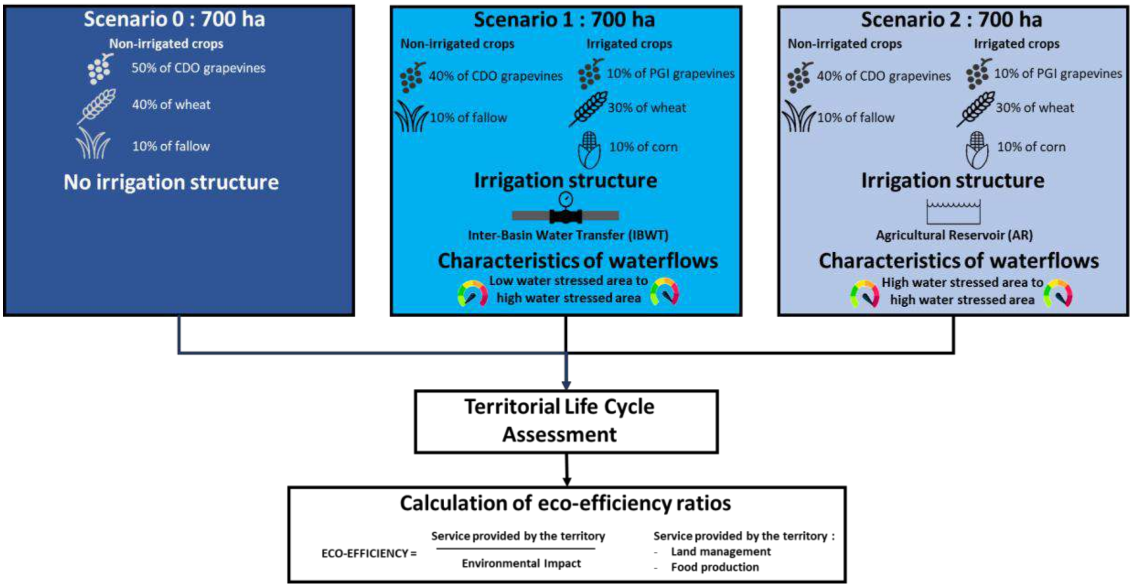
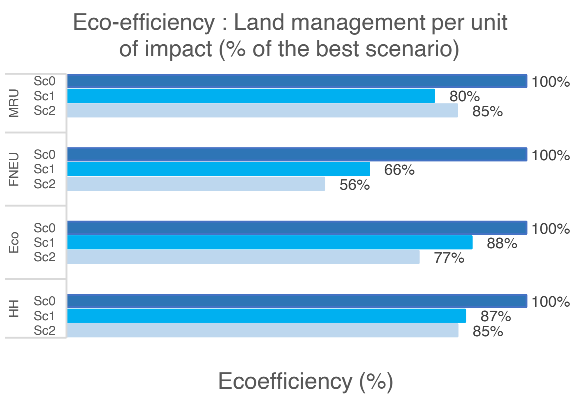


Figure 1 Description of the three land planning scenarios studied with the T-LCA framework

Results and discussion

The eco-efficiency ratios showed that the results for the environmental performance of a scenario depend on the investigated territorial function.



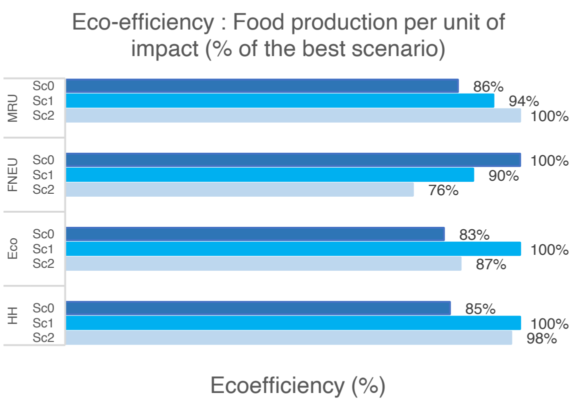


Figure 3 Eco-efficiency calculated for the agricultural area management HH: “Human Health”; Eco: “Ecosystems”; FNEU: “Fossil and Nuclear Energy Use”; MRU: “Mineral

Figure 2 Eco-efficiency calculated for the biomass production

For example, in Figure 2, when looking at "Land management", Scenario 0 (rainfed) is more performant than scenarios 1 and 2 (irrigated) for all impact categories. The results are more contrasted when looking at "Food Production", on Figure 3, where both irrigated scenarios perform worse than the rainfed scenario only on Fossil and Nuclear Energy Use (FNEU), because they both use the French electricity mix for irrigation, mainly based on nuclear energy.
Scenario 1 and Scenario 2 have the same crop occupation. Therefore, the difference of their eco-efficiencies resides in the impacts of water supply. The latter is presented in Figure 4.

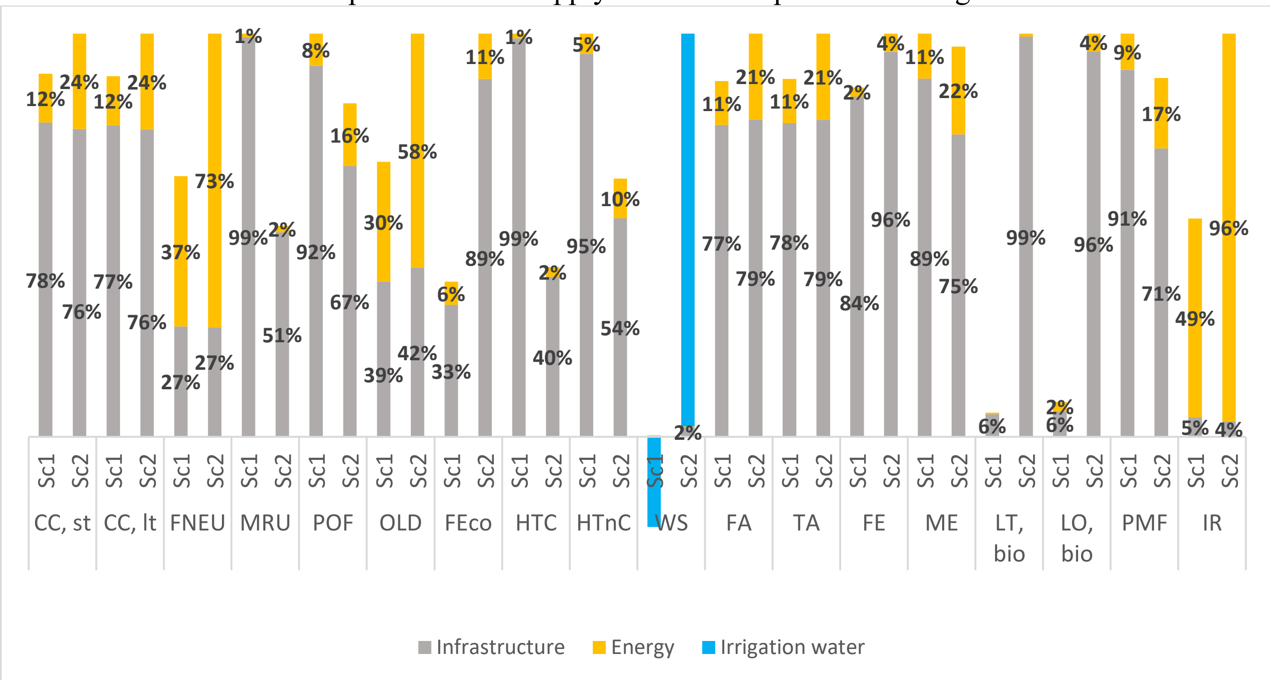


Figure 4 Environmental impacts at midpoint for Scenario 1 and 2 water supplies
CC, st: "Climate Change, short term"; CC, lt: "Climate Change, long term"; POF: "Photochemical Oxidant Formation"; OLD: "Ozone Layer Depletion"; FEco: "Freshwater Ecotoxicity"; HTc: "Human Toxicity cancer"; HTnc: "Human Toxicity non cancer"; WS: "Water scarcity"; FA: " Freshwater Acidification"; TA: "Terrestrial Acidification"; FE: "Freshwater Eutrophication"; ME: "Marine Eutrophication"; LT, bio: "Land Transformation, biodiversity"; LO, bio: "Land Occupation, biodiversity"; PMF: "Particular Matter Formation"; IR: "Ionizing Radiation";
PII: "Primary Irrigation Infrastructure"; SII: "Secondary Irrigation Infrastructure"; TII: "Tertiary Irrigation Infrastructure"

Scenario 2 performs worst that Scenario 1 on 12 of 18 impacts categories because of its Water-Energy-Infrastructure nexus. Concerning impacts due to water consumption, unlike the AR, the IBWT supplies water from a low water stress area with a low AWARE characterization factor (CF). Thus, for water scarcity (WS), this leads to an avoided impact for the Scenario 1. Concerning the energy use, the impacts of scenario 2 are about two-fold higher than scenario 1, because the energy use of the IBWT is approximately half that of the AR. For the "Infrastructure" part of the nexus, results are more mixed. For some of the midpoint indicators, the IBWT performs worse than the AR because of the high amount of cast-iron necessary in its infrastructure. On Freshwater Ecotoxicity (FEco) and Freshwater Eutrophication (FE), AR performs worse than IBWT because the amount of bronze and copper necessary for equipping the AR pumping station is fully allocated to the studied territory. The same applies to Land Transformation, biodiversity (LT, bio) and Land Occupation, biodiversity (LO, bio) because of the high amount of land occupied by AR, unlike the IBWT, which involves a buried pipeline. These results highlight the water, energy and infrastructure nexus induced by the two hydraulic projects. This nexus is determined by two main design parameters, i.e. i) the length of the IBWT pipeline (L_{IBWT}) and ii) the amount of water withdrawn at source for IBWT allocated to the agricultural area ($\%allocation_{IBWT}$).
Figure 5 presents the environmental break-even areas between the IBWT and AR bordered by tipping

lines according to different impact categories. The Ecosystems break-even area can only be achieved with unrealistic values of (L_{IBWT}, $\%allocation_{IBWT}$). Hence, IBWT always performs better than AR on Ecosystems damages as well as for water resources as it imports water from an unstressed area, to a water-stressed area. A project based on imported resources can perform better on all the endpoint indicators, if the parameters are located in Zone 5 (e.g. L_{IBWT} = 50 km and $\%allocation_{IBWT}$ = 1.0%). For other values of (L_{IBWT},$\%allocation_{IBWT}$), there is no better scenario for all the endpoint indicators.

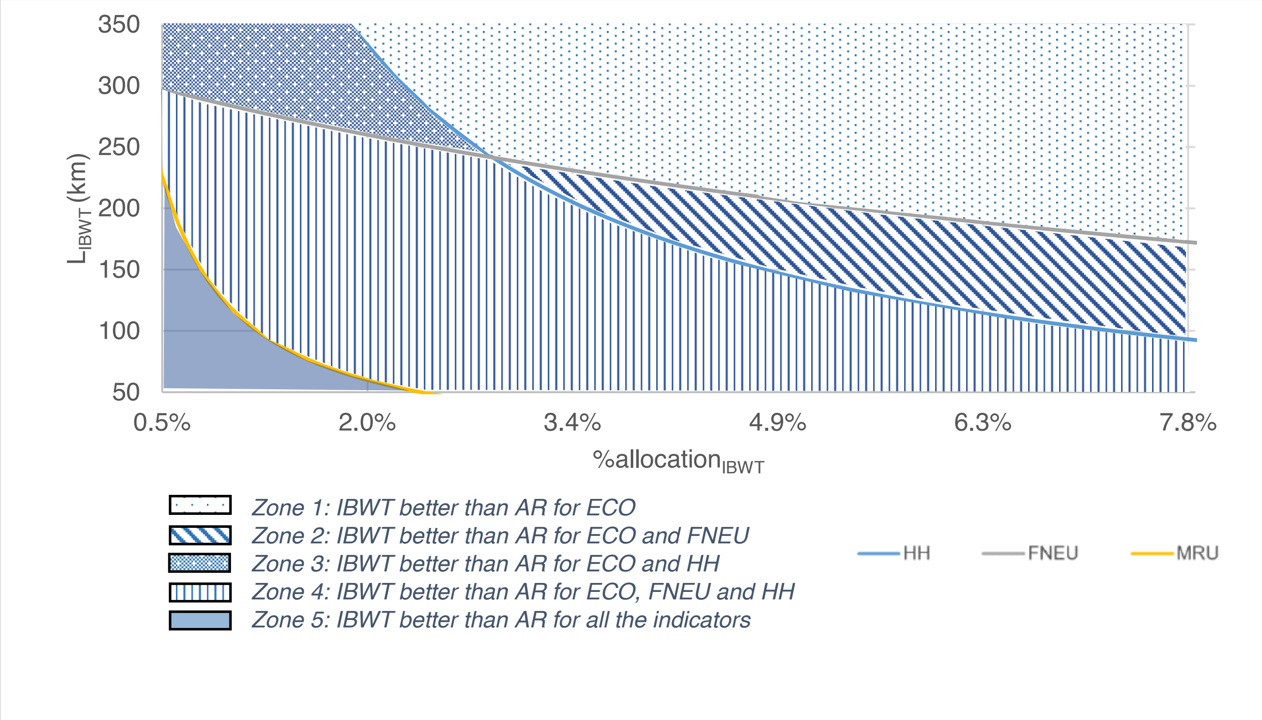


Figure 5 Environmental break-even area for which IBWT water supply is better than AR

Conclusion and perspectives

T-LCA was applied to a theoretical agricultural area to compare the eco-efficiency of three land planning scenarios with or without the implementation of hydraulic projects. These metrics provide exhaustive information about the environmental performance of land planning scenarios considering territorial multifunctionality. The environmental performance of the three land planning scenarios can vary depending on the selected territorial function. These outputs allow the identification of scenarios that limit trade-offs between different functions and impacts. T-LCA results also highlight trade-offs in the water-energy-infrastructure of hydraulic projects. These trade-offs depend on design parameters such as the size of the water pipeline or the water flow. One limitation of this study is the use of a static approach without considering prospective elements (e.g., climate, hydrology and soil) which are expected to further intensify during the lifespan of the hydraulic infrastructure, and affect their long-term environmental performance.

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