Science of the Total Environment 774 (2021) 145682

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Environmental impact assessment of agro-services symbiosis in semiarid urban frontier territories. Case study of Mendoza (Argentina)

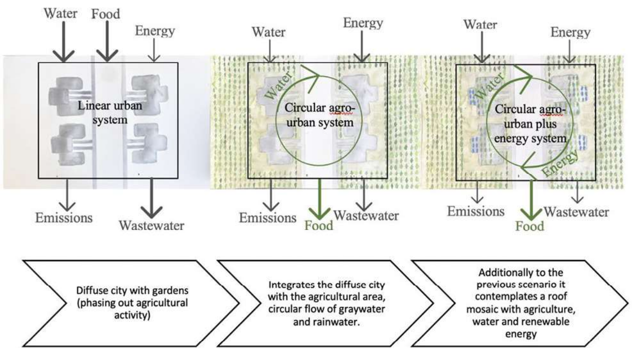
Natalia Bonilla-Gámez [a], Susana Toboso-Chavero [a,b], Felipe Parada [a], Bárbara Civit [c], Alejandro Pablo Arena [d], Joan Rieradevall [a,b], Xavier Gabarrell Durany [a,b,*]

[a] Sostenipra Research Group (2017SGR 1683), Institute of Environmental Sciences and Technology (ICTA-UAB), Unidad de Excelencia Maria de Maeztu (CEX2019-000940-M), Universitat Autònoma de Barcelona (UAB), 08193 Barcelona, Spain
[b] Department of Chemical, Biological Environmental Engineering, Universitat Autònoma de Barcelona (UAB), 08193 Barcelona, Spain
[c] Centro de Estudios para el Desarrollo Sustentable (UTN FRM), Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), 5500 Mendoza, Argentina
[d] Grupo CLIOPE, Energía, Ambiente y Desarrollo Sustentable (UTN FRM), Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), 5500 Mendoza, Argentina

HIGHLIGHTS

- Assessment of environmental impacts in linear and circular cities
- Resource symbiosis in agro-services systems in semiarid frontier territories
- Symbiosis of water and energy in agro-services systems
- Integration of mosaic roofs in households
- Mosaic roofs with photovoltaic panels, rain and graywater, and crops

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 21 November 2020
Received in revised form 16 January 2021
Accepted 3 February 2021
Available online 6 February 2021

Editor: Deyi Hou

Keywords:
Life cycle assessment (LCA)$_1$
Circular green cities$_2$
Water footprint$_3$
Frontier territories$_4$
Agro-urban planning$_5$
Vineyard$_6$

ABSTRACT

In the next 10 years, cities will house 60% of the world's population, where in agro-urban frontier territories, mainly in semiarid regions, problems associated with land use and water distribution will arise. Therefore, a model of growth that contemplates the lowest use of resources must be proposed. The aim of this study is to determine the environmental impact of the use of resources in agro-services frontier territories of semiarid regions in three urban growth scenarios, linear and circular systems. The study is focused on Luján de Cuyo in Mendoza, Argentina. Through a life cycle assessment, environmental performance was evaluated for the current scenario and the three proposed ones. In addition, an ecoefficiency analysis was performed in relation to climate change and water consumption and the cost of surface uses, as well as an assessment according to the multifunctionality of surface use. Scenario 1 is a linear diffuse urban system, scenario 2 a circular water agro-urban system, and scenario 2 green plus energy a circular water and energy agro-urban system. The outcomes illustrate that scenario 2 green plus energy has the least environmental impacts. Compared to the linear scenario, both circular scenarios show a substantial reduction in water consumption (38–40%) and marine eutrophication (32–47%) and curtail freshwater eutrophication impacts. Furthermore, household energy impacts are reduced by 39% in scenario 2 green plus energy with photovoltaic panel implementation, and maximum ecoefficiency in response to climate change is reached. Additionally, the impacts of scenario 2 green plus energy are more than 42% less than those of scenario 1 in terms of the multifunctionality of surface use. This study shows that it is possible to achieve more sustainable semiarid urban frontier territories with local water and regional energy circularity.

* Corresponding author at: Department of Chemical, Biological Environmental Engineering, Universitat Autònoma de Barcelona (UAB), 08193 Barcelona, Spain.
E-mail address: xavier.gabarrell@uab.cat (X. Gabarrell Durany).

https://doi.org/10.1016/j.scitotenv.2021.145682
0048-9697/

1. Introduction

The United Nations stated that approximately 55.3% of the world's population was concentrated in urban settlements in 2018 and that urban areas are projected to house 60% of the population (at least half a million inhabitants) globally by 2030 (UN, 2018). For this reason, in addition to the expansion of urban land; the exploitation of natural resources and new land for agricultural use; the loss of biodiversity and increased demand for food, water, and energy flows, cities have in recent years placed more pressure on global and local natural ecosystems (Cerón-Palma et al., 2012).

The most commonly used city model is that with linear input and output flows, characterized by the import and export of resources without closing cycles (Cerón-Palma et al., 2012). Since cities depend on water, energy and material resources, they play a vital role in the sustainable transition by, for example, managing urban metabolism with circular economy initiatives (circular cities) (Sánchez Levoso et al., 2020) and facilitating the exchange of flows between cities, the natural environment, and urban subsystems from an industrial and urban ecology perspective (Cerón-Palma et al., 2012).

Factors such as population growth, urbanization, water pollution, the use of fossil fuels and unsustainable development are increasing pressures on natural resources globally, which are further intensified by climate change (UN Environment, 2019). On the other hand, local communities depend on agriculture for employment and income generation, yet this cannot be developed further because of the pressures already placed on land and water resources, mainly in frontier/peri-urban areas of cities in semiarid regions where this loss of agricultural area occurs with greater intensity and where there is water scarcity (FAO, 2017). Worldwide, agriculture uses an average of 70% of all fresh water sources, so competition for water from cities and industry creates a need to improve agricultural water use efficiency while producing more food and using fewer and less harmful inputs (UN Environment, 2019). For this reason, the promotion of water-use efficiency, recycling and rainwater harvesting is becoming increasingly important to ensure water security and more equitable water allocation for different users and uses as well as the production and consumption of cleaner forms of energy (Corcelli et al., 2019; UN Environment, 2019). In addition, urban clusters (urban centers and their suburbs) have grown by a factor of approximately 2.5 since 1975, accounting for 7.6% of land worldwide in 2015 and creating urban heat islands due to effects on the hydrological cycle and soil functions (UN Environment, 2019). In this sense, sustainable land-use planning and management can protect high-quality, fertile agricultural soil from competing interests and maintain land-based ecosystem services (UN Environment, 2019).

In this sense, the developing region of Latin America and the Caribbean (LAC) has registered the fastest urbanization in the world, with its urban population increasing from 41% in 1950 to 80% in 2010 (IDB, 2011). This has resulted in an increase in vulnerability due to deficient urban planning processes and the abuse of environmental resources. In addition, 60 to 70% of the region's gross domestic product (GDP) is concentrated in urban centers (IDB, 2011).

Cities of LAC face common challenges and problems such as i) disjointed urban growth in the periphery, which causes scarce provisions of essential services in the peripheries of urban areas, ii) high rates of sociospatial segregation, iii) cities with monocentric development, and iv) an absence of clear and efficient urban development policies that allow for integral development (Nadal et al., 2019). In addition, the disorderly and unbalanced occupation of the territory promotes a low-density city model, resulting in the presence of incompatible land uses and excessive urban expansion on land with agricultural capacities, resulting in the loss of productive agricultural land and thus affecting future of food security in cities and cultural identity (Secretariat of Environment and Land Management, 2018).

Semiarid and arid regions cover approximately one-third of the world's land area, and in South America, there are four large semiarid areas (Moura De Moraes et al., 2011). These areas are more vulnerable to climate change due to fresh water resource scarcity and the consumption of fossil fuels for energy supply; therefore, the water footprint and greenhouse gas (GHG) emissions must be reduced. The problems associated with water resources are local and so are their solutions; for energy resources, the problems associated with their use are national but have local solutions. Therefore, in frontier territories, a vision of a local circular green city must be sought. Accordingly, the semiarid zone in Argentina is representative of this type of area.

Over the last four decades, the Metropolitan Area of Mendoza (AMM), similar to other Latin American cities, has experienced the effects of uncontrolled and unplanned urban growth (Secretariat of Environment and Land Management, 2018). AMM is considered a frontier territory, denoting the presence of urbanization over purely agricultural areas or green belts, and because it is located an arid zone with water scarcity issues, conflicts associated with the type of use and distribution of water resources have arisen.

One of the main territorial problems found in the North Oasis of Mendoza is related to the management of the urban-rural frontier because it is a geographic space that is affected by rapid and continuous transformation. A clear example of a frontier territory located between a diffuse city and vineyard, one of the main land uses in the area, is shown in Fig. 1.

Currently only independent studies of cities and agriculture exist and not integrated studies from an environmental perspective, that contemplate a vision of nexus water-energy-food, use of unused surfaces such as roofs, ornamental to productive green spaces and naturalization of cities. Under the premise of making AMM's economic and social development sustainable, given increasing populations and housing demands and the loss of agricultural areas, a model of agro-urban growth that contemplates the lowest use of resources must be proposed. In exploring such an approach, the following research questions arise. How can resources better more effectively used in the

Fig. 1. An example of an agro-urban frontier territory in Luján de Cuyo, Mendoza, Argentina.
Source: (Google, 2020).

Metropolitan Area of Mendoza, Argentina and how can we mitigate competition from agro-services in terms of the use of these resources and environmental impacts? How can agricultural production be maintained in ways that are compatible with urban development in frontier territories while also addressing climate change and water eutrophication issues, minimizing losses in the water distribution network and taking advantage of nutrients in domestic wastewater?

To answer these questions, we aim to determine environmental impacts of the use of resources in agro-services frontier territories of semiarid regions with conventional linear urban growth and of systems that integrate agro-urban symbiosis with circular flows of water and energy.

Our specific objectives are:

1. To identify all inputs and outputs that participate in conventional linear systems of diffuse cities, which do not integrate agriculture, at the frontier of semiarid urban regions in South America.
2. To propose future scenarios of circular green urban planning that integrate agriculture in frontier territories of semiarid regions.
3. To compare environmental impacts of the growth of conventional linear diffuse cities those that integrate a circular green city vision in frontier territories, determining the actions that have had the greatest impacts.
4. To quantify the minimization of resource consumption through the symbiosis of agro-urban systems in diffuse circular green cities.

2. Materials and methods

This section provides detailed information on the scenarios under study as well as stages of the life cycle assessment (LCA) methodology applied for the environmental impact assessment. The environmental impact assessment according to the surface multifunctionality and ecoefficiency assessment methods is presented.

2.1. Case study

The study is focused on AMM and local vineyard activity, specifically in the frontier territory of the department of Luján de Cuyo. The department of Luján de Cuyo is used as a reference because it experienced the greatest shift from rural or frontier land use to urban land use from 2001 to 2010. In other words, these areas were converted from rural areas with agricultural production to urban areas while maintaining irrigation water rights (Spotti, 2015). The Cabernet Sauvignon grape variety was used as a model because previous studies on water and carbon footprints were performed by the UTN FRM.

Three possible scenarios of urban growth were examined for the frontier territory of the semiarid region of Luján de Cuyo, Mendoza in addition to current conditions. Fig. 2 shows the scheme of each scenario as well as the associated area (in hectares). The current scenario (A) represents the frontier of Luján de Cuyo before urban growth, which includes conventional agriculture and a conventional urban diffuse system (households and green gardens). Regarding the proposed urban growth scenarios, scenario 1 (B) contemplates conventional linear urban planning diffuse city with gardens and green areas (phasing out agricultural activity). Scenario 2 (C) considers agro-urban planning, so it integrates the diffuse city with the agricultural area, and the green gardens become vineyard gardens (urban soil-based farming) with a circular flow of graywater and rainwater. For scenario 2 green plus energy (D), the diffuse city is integrated with the agricultural area, where the green gardens become vineyard gardens (urban soil-based farming), and a roof mosaic plan is employed with the combination of different systems by integrating urban rooftop farming (vineyard) with solar energy through the installation of photovoltaic (PV) panels on the remaining surfaces of roofs not colonized by the vineyard, with a surface ratio of 50% vineyard land use and 9% PV paneling. This scenario also considers a circular flow of graywater and rainwater.

2.2. Life cycle assessment

The evaluation was performed by applying the LCA methodological framework based on ISO standards 14040:2006 and 14044:2006 (ISO, 2006a, 2006b). The following steps were adopted to implement the LCA: i) goal and scope definition; ii) life-cycle inventory (LCI); iii) life-cycle impact assessment (LCIA) and iv) interpretation of results.

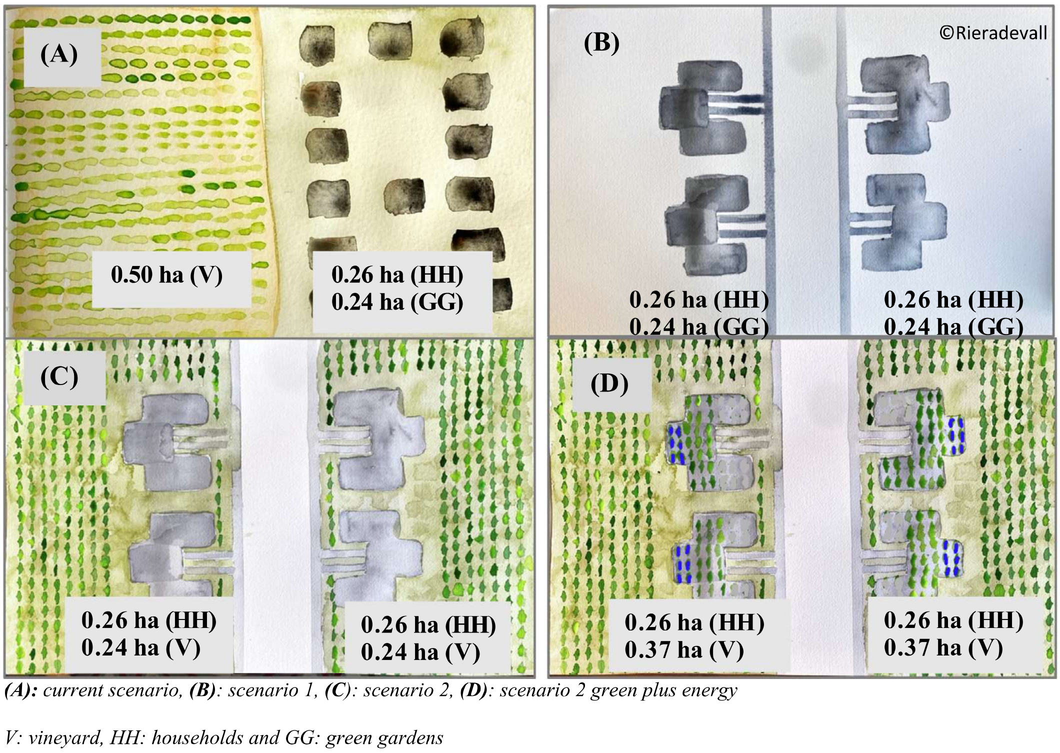


Fig. 2. Scheme of the scenarios under study and areas in hectares.

2.2.1. Goal and scope definition

This research aims to quantify the environmental impacts of three different scenarios of resource supply in agro-urban frontier territories of semiarid regions under urban growth. Each frontier territory scenario was divided into three subsystems: vineyards (V), households (HH) and green gardens (GG). Limits were set taking into account all input and output flows of water, resources, and energy levels of the scenario use phase; therefore, infrastructure and ornamental plants in the GG subsystem and vine plants in the V subsystem were excluded. For scenario 2 green plus energy, infrastructure associated with PV panel implementation in the HH subsystem is contemplated.

It should be noted that Luján de Cuyo is already applying policies and elements of sustainability in using little or no fertilizers in vineyards and green gardens; using water supplies that do require prior pumping or distribution energy due to the geography of the area; and managing a wastewater treatment plant, given the low cost of soil, with seminatural systems and low resource consumption. Additionally, in Mendoza, the recirculation of treated wastewater for agricultural irrigation is already implemented in some areas.

The functional unit (FU) of the study is to meet the average resource needs necessary to annually supply a use phase of 1 ha (ha) of an agro-services frontier territory in a semiarid region. This functional unit was selected in order to be able to compare agro-services (water, food and energy resources). The reference flows are equivalent to the average annual resource consumption per capita of a citizen in the case study area, which is equivalent to 2716.7 kWh of electricity, 174 m^3 of blue water, and an average annual consumption level of 1 kg of vid (*Vitis vinifera*), which translates into the need for 0.79 kWh of electricity and 1.55 m^3 of blue water for their production.

Fig. 3 shows a diagram with the system boundaries for the proposed urban growth scenarios, divided by linear system flows (for scenario 1), circular system flows (for scenario 2 and 2 green plus) and common system flows. The system boundaries of the current frontier scenario, an agro-urban linear system before urban growth, consider services or process stages of the local drinking water treatment plant (DWTP), diffuse city (HH and GG), and wastewater treatment plant (WWTP). Drinking water from the DWTP is used by households and gardens, and wastewater from households is treated in the WWTP. After treatment, a large portion of the water is sent to restricted crop areas (ACREs, by its Spanish acronym) for irrigation, and the remaining water is sent to the Mendoza River. Rainwater collected in the rainwater system is transported to the river. The DWTP employs 3 subprocesses: pretreatment with chlorine, treatment with active carbon and post-treatment with chlorine, where electricity is required for such treatment (Manau-Sifres, 2019). Active carbon in the DWTP is not taken into account in this study. The WWTP adopts a natural biological treatment process carried out in an aerobic, anaerobic, facultative and maturing lagoon. Cloacal liquid treatment takes approximately 35 days, and the process does not require electricity or reagents (Departamento General de Irrigación, 2017). The electricity used by households comes from the Mendoza electricity network. On the other side of the frontier territory is agricultural land, which includes a vineyard. Untreated surface water is used to irrigate the vineyard. The vineyard subsystem accounts for processes of cultivation and the manual harvesting of grapes, the tillage and maintenance of land, irrigation, the application of agrochemicals and fruit harvesting, and electricity and transport required for such processes. In general, the system does not use electricity to pump water into the network, as water is moved by gravity.

For the proposed urban growth scenarios, the process stages are the same on both sides of the frontier territory to evaluate a transition from the current frontier area to other more or less sustainable concepts. The boundaries of the first system, the linear diffuse urban system, are the DWTP, HH and GG and WWTP. Drinking water in the DWTP is used for both households and gardens, and wastewater from households is treated in the WWTP. After treatment, a large portion of the water is sent to ACRE farms for irrigation, and the remaining water is sent to the Mendoza River with collected rainwater. The processes of the DWTP and WWTP are the same as those in the current frontier scenario. The system does not use electricity to pump water into the network, as water is moved by gravity. The electricity used by households comes from the Mendoza electricity network. The second scenario, including the circular green agro-urban system and scenario 2 green plus energy: the circular green plus PV energy agro-urban system, contemplate the process stages of the DWTP, diffuse city and vineyard gardens (HH and V) and WWTP. Drinking water in the DWTP is used by households, black domestic wastewater is treated in the WWTP and sent to ACRE farms for irrigation, and the rest is sent to the Mendoza River. The gray domestic wastewater and collected rainwater from household roofs are stored in separate tanks and reused without treatment for the irrigation of vineyard gardens. Pumping this reused water requires electricity, unlike the rest of the processes. The processes of the DWTP and WWTP are the same as those of the current frontier scenario. For scenario 2 green, the energy used by households comes from Argentina's electricity network. For scenario 2 green plus energy, a percentage of the energy used by houses comes from solar energy by an installed capacity of 3 kWp of PV panels per house rooftop, and the rest comes from the electricity network (50% vineyard and 9% PV). This installed capacity is taken as a reference for this study since it represents the average amount of contracted power that homes in Mendoza use, taking into consideration what is established in the regulatory framework of Argentina. The tilt of the panels (4°) is equal to the average slope of the roofs of houses in Luján de Cuyo (7%), since through our preanalysis it was observed that if the optimal angle of the zone of 31° is used, a mounting system is required, which increases environmental impacts, economic costs, is not visually attractive and only produces 4.65% more electricity. It should be stressed that since there is a regulatory framework that allows for distributed generation, battery use was not considered.

The assumptions made in this study for Luján de Cuyo based on local data and previous research carried out by the UTN FRM are shown in Supplementary Information Table A1.

2.2.2. Life cycle inventory (LCI)

An inventory of input and output data of the studied scenarios per subsystem (V, HH, and GG) was carried out, involving the collection of data to meet the predefined goals. Inventories for meeting the needs of the subsystems covered energy (electricity and transport), water (blue, green, and reuse), resources (pesticides, reagents, PV panels, inverters, and electric installation components), and outputs (grapes, wastewater, collected rainwater, etc.) and are described in detail in Supplementary Information Table A2. In this study, local data were mainly collected from our own research done at the "Centro de Estudios para el Desarrollo Sustentable" of the UTN FRM and from other public sector entities in Argentina. For data from which no local information was available, regional or global data were used from various studies conducted at the Autonomous University of Barcelona (UAB). In the specific case of solar energy data, the SolarGis Prospect application was used. The source of each data point can be seen in Supplementary Information Table A1 of the inventory.

2.2.3. Life cycle impact assessment (LCIA)

An LCIA was performed using SimaPro 9.1.0.8 software developed by Pré Consultant (Pré Consultants, 2020). ReCiPe at a midpoint level (H) we used to calculate environmental impacts (RIVM, 2017). The Ecoinvent 3.6 database (Weidema et al., 2013) was used as our main source, followed by LCA Food DK (Nielsen et al., 2003). Seven impact categories were considered according to previous literature (Rufí-Salís et al., 2020) and the authors' expertise, including climate change (CC, kg CO_2 eq), terrestrial acidification (TAP, kg SO_2 eq), freshwater eutrophication (FET, kg P eq), marine eutrophication (MEP, kg N eq),

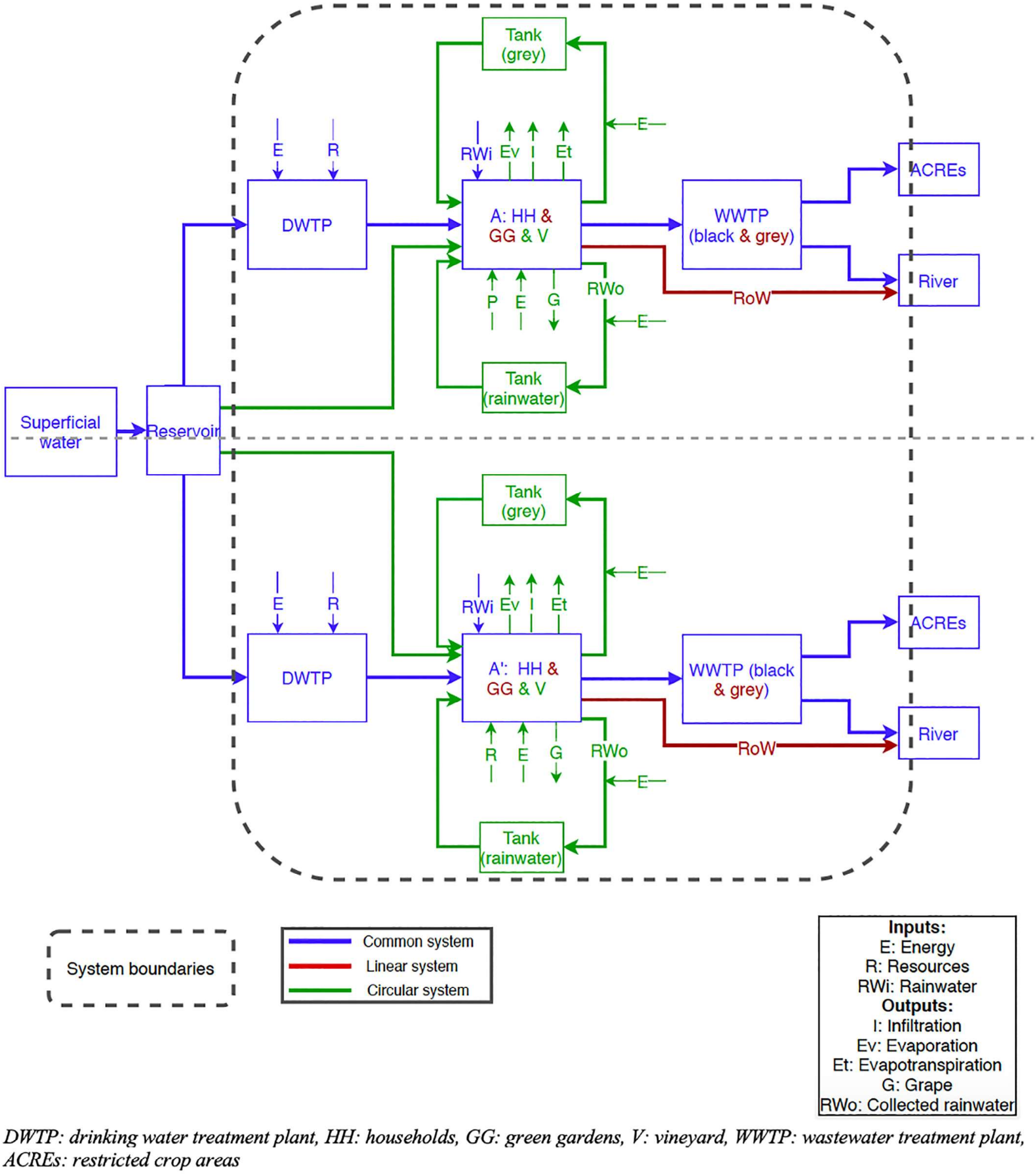


Fig. 3. Diagram of system boundaries.

freshwater ecotoxicity (FETP, kg 1.4 DCB to freshwater), land use (LOP, m^2a crop eq) and water consumption (WCP, m^3).

Impact categories of the proposed urban growth scenarios for which there is a difference of more than 10% are shown on a tricolored scale (red, yellow and green) where the color green denotes the lowest impact, and the color red denotes the greatest impact.

2.3. Sensitivity analysis of the LCA results

The results of a LCA study can be affected by different sources of uncertainty. The sensitivity analysis is one of the procedures of analysis used to estimate the uncertainty of LCA results, and it assesses the influence of a parameter (the independent variable) on the value of another (the dependent variable) (Cellura et al., 2011). The independent variables used in this study were the input data of grape productivity and green water (rainfall). The following sensitivity scenarios are then analyzed:

- A: minimum and maximum yearly data of grape productivity (Cabernet Sauvignon) in the province of Mendoza.
- B: minimum and maximum annual rainfall data in 10 years (from period 2008 to 2017) in the province of Mendoza.

The minimum and maximum yearly data of grape productivity (Cabernet Sauvignon) in the province of Mendoza was taken from the "Instituto Nacional de Vitivinicultura", while the minimum and maximum annual rainfall data in 10 years (from period 2008 to 2017) in the province of Mendoza from the "Dirección de Agricultura y Contingencias Climáticas". The values used were 2.43 t/ha and 10.67 t/ha, and 154.6 mm and 367.5 mm respectively.

2.4. Ecoefficiency assessment method

ISO 14045 (ISO, 2012) was applied to study the life-cycle environmental impacts of the frontier territory scenarios along with the value of services. Considering the bidimensional nature of ecoefficiency, the environmental performance of the scenarios was represented by indicators of climate change measured in kg CO_2 eq/ha and of water consumption measured in m^3/ha. Based on the types of system value defined in the ISO, a monetary perspective was applied. The value assessment was performed using the economic value of surface use (average price of grape production per year plus the average price of household rentals per year) in US$$\cdot$$ha^{-1}.

The relationship between both parameters was analyzed with an ecoefficiency chart to identify the most and least ecoefficient scenarios. It was assumed that high economic value and low environmental impacts are desired trends, as carbon emissions are then minimized while providing a service with high added value.

Additionally, the ReCiPe single score indicator, specifically the area of ecosystem quality, was analyzed because it provides an overall picture of the impacts generated to the ecosystem in a single score value. However, it is just to have another approach, since this methodology has a lot of uncertainty.

2.5. Environmental impact assessment according to the multifunctionality of surface use

To analyze environmental impacts obtained from the LCA from a multifunctionality perspective, agricultural and architectural services were considered. The equation is shown below. Eq. (1) denotes the total impact in relation to multifunctionality (I_s), where I represent the environmental impact per category, and SA and SU represent agricultural and urban surfaces in hectares, respectively, per scenario. It should be noted that gardens do not provide agricultural production services or protection or shelter from environmental conditions, so their area is not taken into consideration.

$$I_S = \frac{I}{(SA + SU)} \quad (1)$$

3. Results

The environmental performance levels of the case study scenarios are shown and described in the following section.

3.1. Life-cycle impact assessment (LCIA)

This subsection presents the results of the LCIA for each scenario, subsystem and inventory flow. The most important impacts are highlighted.

3.1.1. Analysis by scenario

Table 1 shows the environmental impacts of meeting the average resource needs necessary to annually supply 1 ha of an agro-service frontier territory in a semiarid region for each scenario as well as the relative impact of each subsystem per scenario and impact category. The results confirm that the current scenario for the frontier territory of Luján de Cuyo has low environmental impacts in almost all categories, since elements of sustainability are already incorporated and there is a nonintensive use of services, as only 26% of the system is occupied by housing and 50% is occupied by local agriculture. The results show significant differences (of more than 10%) between the linear growth scenario and the circular green scenarios, specifically in the CC, TAP, FET, MEP and WCP categories when comparing the impacts of scenario 1 and scenario 2 green plus energy, with scenario 2 green plus energy having the least impact, and when comparing scenario 1 to scenario 2 in the categories of FET, MEP and WCP, with scenario 2 being less impactful. However, in the FETP and LOP categories, the linear growth scenario has the fewest impacts, which are similar (less than 10% difference) to those of scenario 2 but 26% and 29% (respectively) lower than those of scenario 2 green plus energy. In the FET, MEP and WCP categories, the greatest difference between the linear growth scenario and the circular green scenarios is observed, as scenario 1 does not incorporate a circular vision of graywater and rainwater reuse. Avoided impacts are seen in scenarios 2 (−885.84 kg P eq) and 2 green plus energy (−3381.87 kg P eq) in FET) due to the reuse of the gray wastewater.

3.1.2. Analysis by subsystem

At the subsystem level, the household subsystem is the largest contributor to all impacts in the three proposed scenarios, where in the CC, TAP, FETP and LOP categories, it contributes more than 93.92%. In contrast, the vineyard subsystem contributes no more than 6.08% in the proposed scenarios and curtails impacts for both eutrophication categories (marine and freshwater) due to the reuse of gray wastewater (scenario 2: FET: −4081.23 kg P eq; MET: −0.31 kg N eq, scenario 2 green plus energy: FET: −5329.38 kg P eq; MET: −0.41 kg N eq).

3.1.3. Analysis by flows

Fig. 4 compiles the environmental impacts of the four frontier territory scenarios, including all subsystems and flows. When analyzing the household subsystem, it can be observed that energy is the most critical flow for the impact categories of CC, TAP, MEP, FETP and LOP due to electricity consumption. However, in scenario 2 green plus energy, there is a considerable reduction in the energy flow impacts of these categories (except LOP) of more than 39% due to the implementation of 3 kWp of solar panels per house, which cover 43.6% of the electricity demand of each home, reducing electricity consumption from the network and its respective impact. For the FETP and LOP categories, the impact of resources associated with photovoltaic installation (PV panels, inverts and electric installation components) is very high, reducing impacts due to solar electricity generation. Therefore, scenario 2 green plus energy has the greatest impact in these categories. For FET, the output flow is the most critical and is associated with domestic wastewater and its nitrite, nitrate and phosphate content discharged into the Mendoza River. For WCP, the water flow, associated with blue water extracted from the river for drinking or irrigation, is the most critical flow, responsible for more than 78% for all scenarios and subsystems, except for the vineyard subsystem under scenario 2 and scenario 2 green plus energy, which shows values equivalent to only 70.8% and 74.9%, respectively, since most of the vineyard is irrigated with reused water.

3.1.4. Water consumption

Since Luján de Cuyo is a frontier territory located in a semiarid region where water is a critical resource, we emphasize the category of water consumption and its importance. In the graph of water consumption shown in Fig. 4, the household subsystem is shown to consume the

Table 1
Environmental assessment of meeting the average water needs necessary to annually supply 1 ha of an agro-services frontier territory in a semiarid region.

	Current scenario				Scenario 1				Scenario 2				Scenario 2 green plus energy			
	V	**HH**	**GG**	**Total**	**V**	**HH**	**GG**	**Total**	**V**	**HH**	**GG**	**Total**	**V**	**HH**	**GG**	**Total**
CC	3.85E+03	1.21E+05	6.95E+02	1.25E+05	-	2.42E+05	1.39E+03	2.43E+05	3.76E+03	2.42E+05	-	2.46E+05	5.82E+03	1.42E+05	-	1.48E+05
	3.07%	**96.38%**	**0.55%**			**99.43%**	**0.57%**		**1.53%**	**98.47%**			**3.94%**	**96.06%**		
TAP	1.20E+01	3.73E+02	2.29E+00	3.87E+02	-	7.46E+02	4.59E+00	7.50E+02	1.17E+01	7.46E+02	-	7.57E+02	1.82E+01	4.51E+02	-	4.69E+02
	3.10%	**96.31%**	**0.59%**			**99.39%**	**0.61%**		**1.55%**	**98.45%**			**3.87%**	**96.13%**		
FET	4.18E-01	3.64E+03	1.27E-01	3.64E+03	-	7.28E+03	2.54E-01	7.28E+03	-4.08E+03	3.19E+03	-	-8.86E+02	-5.33E+03	1.95E+03	-	-3.38E+03
	0.01%	**99.99%**	**0.00%**			**100.00%**	**0.00%**		**-56.09%**	**43.91%**			**-73.24%**	**26.76%**		
MEP	7.14E-02	9.00E-01	1.32E-02	9.84E-01	-	1.80E+00	2.63E-02	1.83E+00	-2.43E-01	1.49E+00	-	1.24E+00	-3.01E-01	1.27E+00	-	9.67E-01
	7.26%	**91.40%**	**1.34%**			**98.56%**	**1.44%**		**-13.87%**	**86.13%**			**-19.11%**	**80.89%**		
FETP	9.26E+01	2.19E+03	2.37E+01	2.30E+03	-	4.38E+03	4.74E+01	4.42E+03	8.99E+01	4.38E+03	-	4.47E+03	1.39E+01	5.87E+03	-	6.01E+03
	4.02%	**95.95%**	**1.03%**			**98.93%**	**1.07%**		**2.01%**	**97.99%**			**2.32%**	**97.68%**		
LOP	2.63E+01	2.23E+02	5.36E+00	2.55E+02	-	4.46E+02	1.07E+01	4.57E+02	2.52E+01	4.44E+02	-	4.69E+02	3.91E+01	6.04E+02	-	6.43E+02
	10.33%	**87.57%**	**2.10%**			**97.65%**	**2.35%**		**5.37%**	**94.63%**			**6.08%**	**93.92%**		
WCP	1.01E+04	1.72E+04	1.07E+04	3.80E+04	-	3.43E+04	2.14E+04	5.57E+04	3.27E+02	3.43E+04	-	3.47E+04	2.02E+03	3.13E+04	-	3.33E+04
	26.70%	**45.17%**	**28.12%**			**61.63%**	**38.37%**		**0.94%**	**99.06%**			**6.06%**	**93.94%**		

Units: kgCO_2 eq (CC), kg SO_2 eq (TAP), kg P eq (FET), kg N eq (MEP), kg 1.4 DCB to fresh water (FETP), m^2a crop eq (LOP) and m^3 (WCP). Percentages express the relative contributions in each specific impact category. The impact categories of the proposed urban growth scenarios for which there is a difference of more than 10% are shown on a tricolored scale (red, yellow and green) where green denotes the least impact and red denotes the most.

greatest amount of water, mainly due to water flows (blue water) and to a lesser extent due to energy flows. Scenario 1 shows the highest consumption of blue water (55,716.81 $m^3 \cdot year^{-1}$), while scenario 2 green plus energy shows the lowest water consumption of 33,309.75 $m^3 \cdot year^{-1}$ followed by scenario 2 (34,665.31 $m^3 \cdot year^{-1}$). This denotes savings in scenario 2 green plus energy in relation to scenario 1 of approximately 40.2% for water and of approximately 37.8% for scenario 2. This reflects 14.1% less consumption than the current level in the frontier territory, where the population is 50% smaller. This minimization of blue water consumption is associated with the symbiosis of agro-services, the use of rainwater and graywater in the local reuse system, and the generation of 43.6% of electricity for houses with PV panels.

Currently (as shown in Fig. 5 and based on the inventory shown in **Table A2**) in the frontier territory of Luján de Cuyo, the vineyard is supplied 96% by blue water (from the Mendoza River), which is the same source used to meet the needs of the city, and only 4% by green water (rainwater). As mentioned above, since the territory is located in a semiarid region, it rains very little here. For this reason, scenarios 2 and 2 green plus energy propose a circular use of the water flow between the city and vineyard, creating agro-services symbiosis. Fig. 5 also shows the different water sources used for vineyard irrigation under these circular scenarios and the associated percentages according to their use. In scenario 2, there is no competition for blue water from the city to irrigate the vineyard, 96% of the vineyard is irrigated with reused gray wastewater, and the remaining 4% is irrigated with green water. On the other hand, under scenario 2 green plus energy, only 10% of the vineyard's water consumption comes from the river (blue water), 80% is composed of reused gray wastewater, 5% is composed of green water and 4% is composed of collected rainwater.

3.1.5. Sensitivity analysis

The results obtained from the sensitivity analysis of the LCA by varying the input data of rainfall and grape production in the province of Mendoza are shown in Supplementary Information Table A3. Grape production shows variations for all impact categories of both scenario 2 and scenario 2 green plus energy. The lower the grape production the lower the environmental impact, except for the FET and MEP categories where the lower the grape production the higher the impact. This is because less gray water would be reused, and therefore more would be sent to the river. For these two impact categories, the greatest influence is observed due to the variation in grape productivity.

On the other hand, in the case of rainfall, it has a very low level of impact. Only in scenario 2 green plus energy there is a variation in the WCP category, the rest of the categories for the three scenarios are not influenced. This is because, as shown in Fig. 5, only in scenario 2 green plus energy is rainwater reused to supply the vineyard, and in a very low amount (5%).

3.2. Ecoefficiency assessment

The relationship between the environmental impacts and the economic value of surface uses was analyzed with ecoefficiency chart (Fig. 6) to identify the best frontier territory scenario and desired trends. In terms of ecoefficiency in addressing climate change, scenario 2 green plus energy is shown in area A, and scenarios 1 and 2 are shown in area B. On the other hand, in terms of ecoefficiency for water consumption, all scenarios are shown in area B (scenario 2 and 2 green plus energy at the border with A). Fig. 6 also shows the variation in the economic value of surface uses (the average price of grape production per year plus the average price of household rentals per year) per scenario.

The graph of ecoefficiency assessment using the ReCiPe endpoint single score methodology follows a trend similar to that of the climate change indicator. For more information see Fig. A1 in the Supplementary Information.

3.3. Multifunctional analysis

In analyzing the environmental impacts of each scenario in relation to the multifunctionality (agricultural and architectural services) of

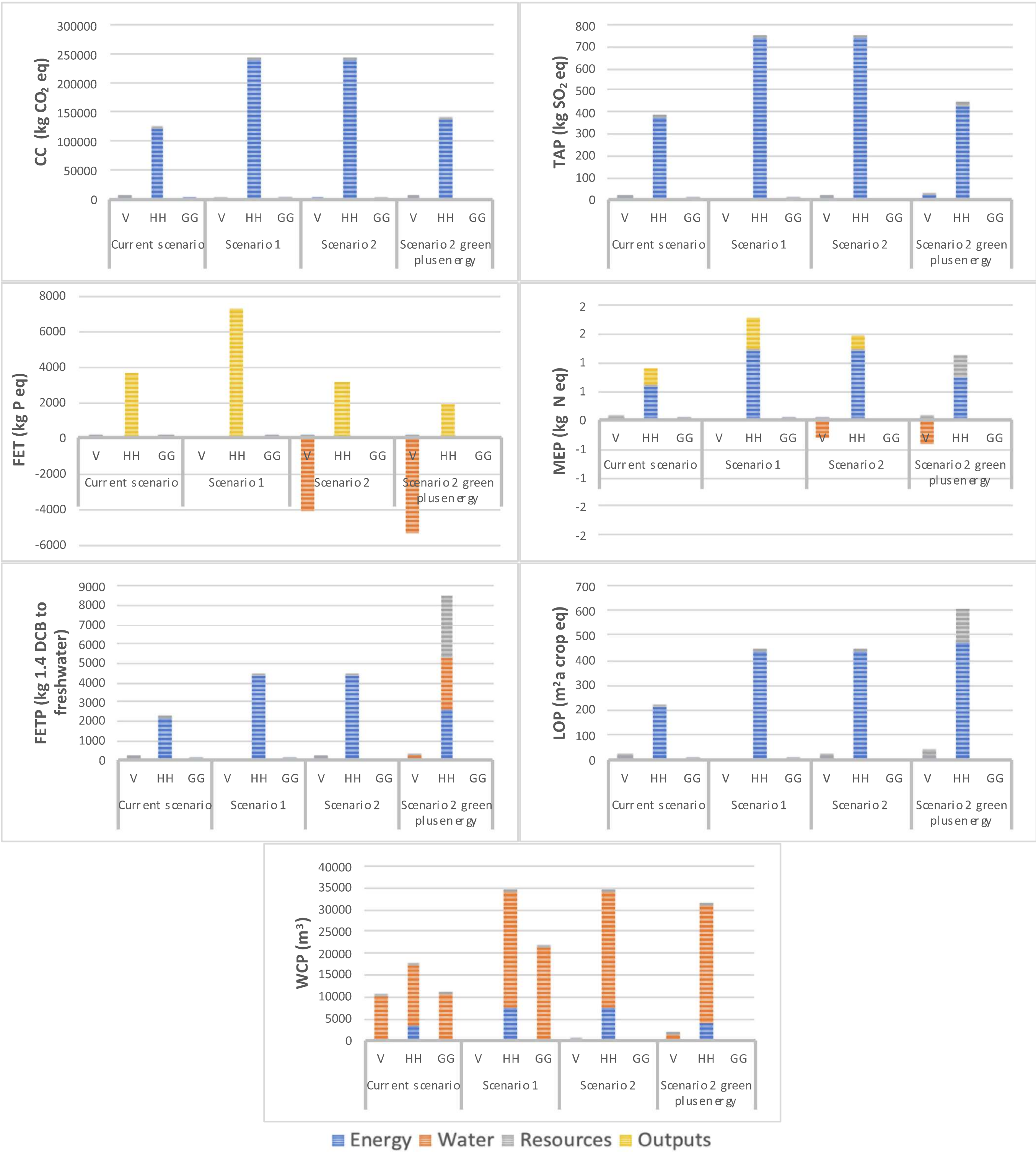


Fig. 4. Environmental impacts of the five scenarios for frontier territories according to each subsystem (V: vineyard, HH: households and GG: green gardens) and flow.

surfaces, the term multifunctionality is used to indicate that agriculture can produce various commodity and noncommodity outputs in addition to food. Table A1 shows the amount of local endogenous resources obtained per hectare (grape production, PV energy production and rainwater harvesting) for the three urban growth scenarios. The results of the proposed scenarios (see Table 2) show relevant differences of more than 10% for all impact categories. The impacts of scenario 2 green plus energy are more than 42% lower than those of scenario 1, and those of scenario 2 are more than 47% lower. As there are more forms of multifunctionality and services in the frontier scenario, the environmental impacts are reduced. For example, under scenario 2 green plus energy, for which there is more surface area for vineyard services, there is less environmental impact in all seven categories evaluated.

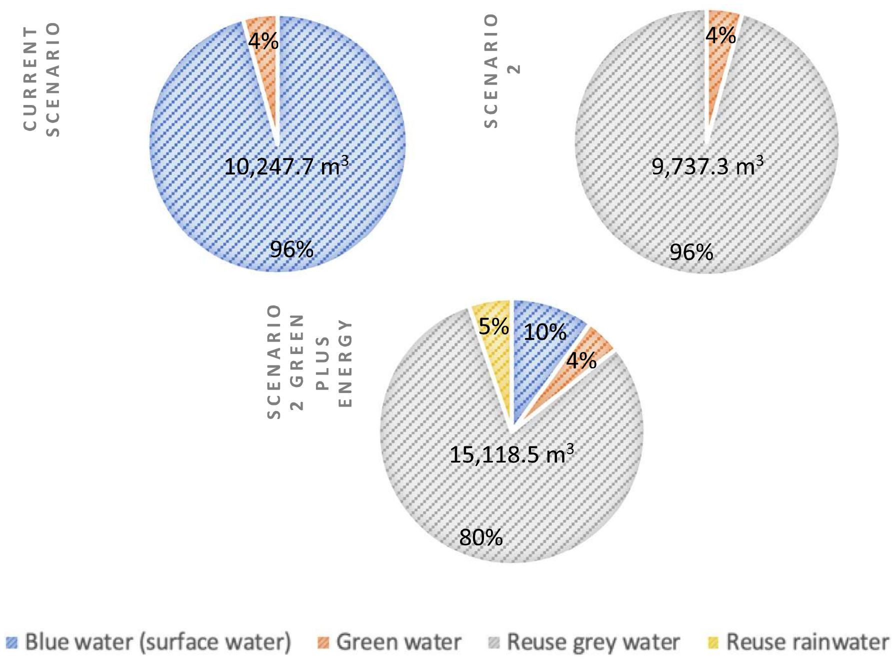


Fig. 5. Vineyard irrigation water sources for the current and proposed circular scenarios.

4. Discussion

4.1. Future circular frontier territories in semiarid regions

The frontier territory scenarios proposed in this study for a semiarid region simulate urban growth of approximately 50% of the population relative to the current situation scenario. When comparing these scenarios, materials and construction stages for the buildings and water infrastructure are similar and therefore not quantified in this LCA study, which instead focuses on the use phase.

As shown in Table 1, scenario 2 green plus energy has the lowest environmental impacts globally for the seven categories analyzed followed by scenario 2. This highlights the importance of a circular and symbiosis vision that integrates graywater and collected rainwater from the city into agriculture and clean energy through the use of photovoltaic panels. Under scenarios 1 and 2, impacts of the four categories (CC, TAP, FETP and LOP) are almost uniform (less than a 10% difference), but the functions of the frontier territory are very different. Under scenario 1, the frontier territory only provides one function, services, while under scenario 2, it is multifunctional, providing agro-services without this causing a significant increase in impacts. The household subsystem is the largest contributor in all impact categories. In the impact categories of CC, TAP, FETP and LOP, it contributes more than 93.92% and is associated with the critical flow of energy. This is the case because more than 60% of Argentina's electricity mix comes from fossil sources (mainly natural gas with 57%), unlike other countries in the region, such as Brazil, which draws more than 60% of its matrix from renewable sources (mainly hydro) (IEA, 2019a, 2019b). This significantly reduces carbon dioxide emissions and thus the impacts associated with climate change. For this reason, Fig. 4 shows a decrease of more than 39% in the impacts of energy flows (except for the LOP category) for scenario 2 green plus energy by generating 43.6% of the

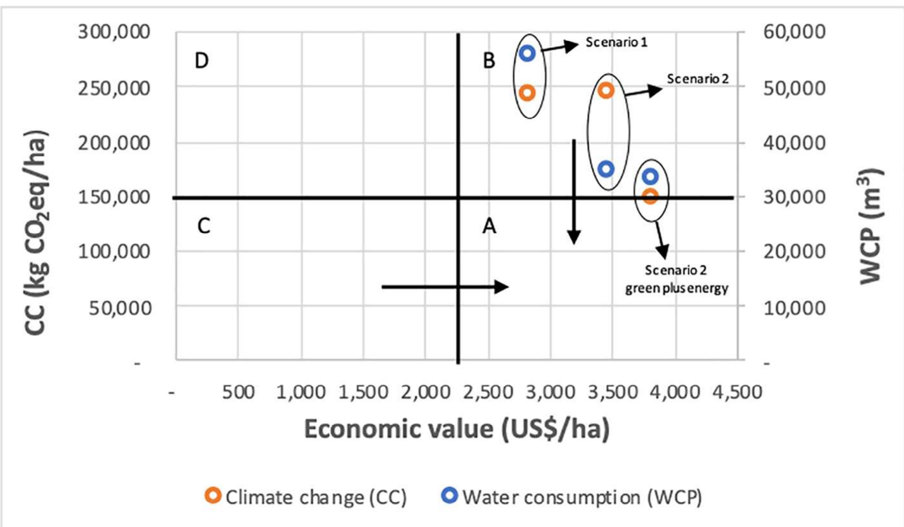


Fig. 6. Ecoefficiency of frontier territories for climate change (CC) and water consumption (WCP) against the economic value. Black arrows indicate desired trends.

Table 2
Environmental impact per scenario in relation to multifunctionality (I_s).

Impact/scenario	Current scenario	Scenario 1	Scenario 2	Scenario 2 green plus energy
CC (kg CO_2 eq)	1.65E+05	4.68E+05	2.46E+05	1.17E+05
TAP (kg SO_2 eq)	5.09E+02	1.44E+03	7.57E+02	3.72E+02
FET (kg P eq)	4.79E+03	1.40E+04	−8.86E+02	−2.68E+03
MEP (kg N eq)	1.30E+00	3.51E+00	1.24E+00	7.68E-01
FETP (kg 1,4-DCB)	3.03E+03	8.51E+03	4.47E+03	4.77E+03
LOP (m^2a crop eq)	3.35E+02	8.79E+02	4.69E+02	5.10E+02
WCP (m^3)	5.00E+04	1.07E+05	3.47E+04	2.64E+04

Agricultural and urban surface values: current scenario: SA = 0.50, SU = 0.26; scenario 1: SA = 0, SU = 0.50; scenario 2: SA = 0.48, SU = 0.50, scenario 2 green plus energy: SA = 0.74, SU = 0.52.

electricity demand of households with PV panels. It should be noted that this scenario is based on Argentine legislation on distributed generation, which establishes that the installed capacity cannot be greater than the power already contracted by a home. Under this premise, an installed capacity of 3 kWp only covers 10% of the roof of a house, leaving the remaining 40% in disuse. If this legislation were to be modified, up to 40% more PV panels could be installed, and more electricity could be generated than the demand of a house, achieving energy self-sufficiency and exporting the remaining energy.

In Luján de Cuyo, the energy impact is low because water is distributed by gravity and does not need to be pumped, and the local wastewater treatment system is atypical, does not require energy or reagents and already adopts a circular mode of treated wastewater use for the irrigation of ACREs, unlike those used in other areas of Latin America where there is no water treatment or wastewater reuse and where major differences are observed in some categories between scenarios 1 and 2. In other countries, the impact of rainwater and graywater recirculation in scenarios 2 and 2 green plus would be more relevant.

Water consumption savings observed for scenarios 2 and 2 green plus energy due to closing cycles using graywater and rainwater to irrigate vineyards and minimized losses in the distribution system in comparison to the current scenario and scenario 1 (linear systems) represent not only 37.8% or more less water extracted from the river but also a substantial improvement in the quality of water in the discharge river, since the system avoids sending contaminants in graywater generated by households, specifically nitrate, nitrite and phosphate, which contribute to eutrophication. In addition, blue water saved in the Mendoza River serves as an ecological flow or provides ecological services to the environment. Additionally, by eliminating garden irrigation, the consumption of blue water in a semiarid region and the impacts of making this water potable can be minimized. On the other hand, if infrastructure were taken into account in the LCA, by sending less wastewater to the WWTP in scenarios 2 and 2 green plus energy, the lifetime of the plant and of pipes and tanks of the water distribution network would be extended.

In scenario 2, gray wastewater generated by houses exceeds the demand required by the vineyard for irrigation, so the system does not require an additional use of collected rainwater to achieve a self-sufficient system in the use of water. However, in the case of scenario 2 green plus energy, domestic graywater used together with collected rainwater cannot supply vineyards, so a small amount of blue (surface) water is required. In semiarid regions where water scarcity poses problems for urban growth and where food security cannot be put at risk, both scenarios decrease competition for water resources between the city and agriculture by 90% (or more); in this case, the vineyard reaches agro-services symbiosis.

In the case of 50% urban growth in the frontier territory, a notable improvement in climate change impacts is seen, achieving ecoefficiency in scenario 2 green plus energy and providing a clear vision of the circular economy. Carbon dioxide equivalent emissions are mainly associated with energy, once again highlighting the critical point of electricity consumption in homes and the importance of generating clean energy. On the other hand, in terms of water consumption, no proposed scenario, either linear or circular, achieve maximum ecoefficiency in water consumption; however, scenarios 2 and 2 green plus energy are on the cusp of achieving ecoefficiency and make economic improvements in relation to scenario 1.

The above results of scenario multifunctionality in terms of surface use show that the scenarios with the largest agricultural and architectural surfaces, scenario 2 green plus energy followed by scenario 2, are those with the lowest environmental impacts across all categories.

4.2. Avenues for improvement

By making use of the roofs of houses for urban rooftop farming, more efficient land use can be achieved by taking advantage of existing space, as other studies have proven in the case of Europe (Toboso-Chavero et al., 2018). Under scenario 2 green plus energy, 35% more vines can be planted (0.26 ha more) than under scenario 2 by applying a roof mosaic cultivating in 50% of roof area and installing PV panels on 9% of the remaining roofs (equivalent to an installed capacity of 3 kWp). Almost half of household electricity can be generated with PV panels. As a complement to this study, architectural and engineering studies should be carried out based on crop weights to see if houses require any additional roof reinforcements when using soil substrate rather than hydroponics. Additionally, the positive impacts of urban rooftops, for example, on building insulation and energy efficiency through their contributions to building cooling and heating systems, should be considered in the future. Studies indicate that insulation effects can generate savings of 3 to 5% (Palma, 2012).

Since Mendoza is located in a semiarid region, we initially anticipated water to be a major obstacle, and this was thus the focus of the study. However, we found energy to be one of the flows with the greatest impact; therefore, it is necessary from a nexus perspective to improve efficiency levels. For this reason, modifying current legislation so that more photovoltaic panels can be installed per household is necessary. In addition, the minimization of energy impacts from the reductions that green roofs generate in terms of climate control should be quantified to reach full water, energy and food circularity, as well as quantifying the environmental impact of different local energy saving measures. Other means of minimizing the use of water in households and the use of pesticides in vineyards should also be analyzed.

In addition, other ways to integrate new landscape, ecosystem service, biodiversity, identity and ethnological indicators must be explored.

5. Conclusion

This investigation demonstrates the environmental impacts of the use of resources under different frontier territory scenarios in Luján de Cuyo, Argentina. Scenarios 2 and 2 green plus energy are designed to overcome the current frontier of agro-services by adopting a more circular vision to naturalize this barrier and achieve less aggressive urban growth. In addition, under scenarios 2 and 2 green plus energy, there are annual yields of local endogenous resources per hectare of 4275 kg and 6637 kg, respectively, for grape production, of 788 m^3 for rainwater harvesting and of 119,041 kWh for PV energy production for scenario 2 green plus energy. When comparing the environmental impact of scenario 1 with that of conventional urban growth, under scenarios 2 and 2 green plus energy, which integrate a green circular vision by maintaining agriculture and integrating it with gardens (and roofs for scenario 2 green plus energy), a substantial reduction in water consumption and marine eutrophication is observed and impacts on freshwater eutrophication are curtailed. Scenario 2 green plus energy has the least environmental impacts for the seven categories analyzed followed by scenario 2, showing that symbiosis in the use of rainwater and graywater from the local system in the integrated vineyard is effective as well as the implementation of PV panels to generate solar energy.

By integrating green plus energy systems between the vineyard and city in scenario 2 and replacing the gardens with vineyard gardens and incorporating a roof mosaic of 50% vineyard and 9% PV panels, there is a decrease in the impact of energy flows (except for the LOP category) and a minimization of blue water consumption relative to scenario 1. This minimization of water use occurs due to the reuse of rainwater and graywater, water savings in the irrigation of green gardens, reduced losses due to the distribution of irrigation water in a closed cycle, and reduced electricity use from the network.

An ecoefficiency analysis proved useful in demonstrating that in terms of the water consumption indicator, the circular green frontier territory scenarios (scenario 2 green plus energy followed by scenario 2) are almost ecoefficient, contrary to the linear urban growth scenario. We also found energy for houses to be one of the most critical aspects due to Argentina's electricity mix, with mainly fossil fuel sources. By installing PV panels on the rooftops of houses under scenario 2 green plus energy, ecoefficiency in response to climate change can be reached.

The findings of this study in relation to the impact of circular green cities to sustainable development could contribute to the international discussions and to local and national policies, and therefore be applied to other areas in Latin America, like the Guajira region in Venezuela and Colombia, the dry regions of Paraguay, Argentina, Peru, Chile and Bolivia and the semi-arid region of northeastern Brazil.

Our LCA has allowed us to highlight certain aspects; however, to visualize other positive impacts, such as ecosystem services (ES) and the multifunctionality of vineyard systems in scenarios 2 and 2 green plus energy, this study should be extended to topics such as the positive impacts of the landscape, ES, biodiversity, and ethnological and popular culture features. Vineyards shape important economic, cultural, and ecological systems. Wine production (growing, making, and selling) leads to the formation of vineyard landscapes, which are physical and cultural landscapes. Similar to other agricultural systems, they can serve as multifunctional landscapes that not only produce grapes but also serve as wildlife habitats, sequester carbon and support the rich traditions of those living among or visiting them (Winkler et al., 2017; Winkler and Nicholas, 2016).

With this study, we demonstrate that a more sustainable frontier can be promoted in Mendoza, Argentina in terms of water, food and energy use through a vision of circularity and symbiosis with the maintenance and integration of agriculture alongside urban growth.

CRediT authorship contribution statement

Natalia Bonilla Gámez: Writing – original draft, Investigation, Data curation. **Susana Toboso-Chavero:** Investigation, Methodology. **Felipe Parada:** Investigation, Resources. **Bárbara Civit:** Conceptualization, Project administration. **Alejandro Arena:** Resources, Validation. **Joan Rieradevall:** Conceptualization, Project administration. **Xavier Gabarrell Durany:** Supervision, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

The authors acknowledge the assistance of Lorena Corica, INAHE CONICET, for their collaboration in providing information and data of Luján de Cuyo, Claudio Rigoni, EPAS, for providing information on Mendoza's wastewater and Joan Muñoz, ICTA- UAB, for sharing access to Simapro for data analysis.

The authors are grateful to the National Commission for Scientific and Technological Research (Chile) for the grant awarded to F. Parada [grant number PFCHA-CONICYT 2017 – Folio 72180248]; and the Spanish Ministry of Education, Culture and Sports for the grant to Susana Toboso [FPU16/03238]. This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2021.145682.

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