

## An increased dependence on agricultural policies led European grazing agroecosystems to an unsustainability trap

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As all production processes, the agrifood system is driven by energy and materials. The origin and relative contribution of these resources to the system's functioning determines its sustainability. Here we analyse the evolution of the sustainability of mountain grazing agroecosystems, which are often perceived as a better alternative for animal food production than industrial systems. Specifically, we use Emergy Accounting to assess the dependency of livestock farming on materials and energy in the Spanish Pyrenees along the last three decades, using data collected through face-to-face surveys in 1990, 2004 and 2018. We observe an increase of farm dependence on non-renewable resources, despite longer grazing periods and reduced use of off-farm animal feeds. The increasing inflow of public economic support and services from the socio-economic system (mainly driven by non-renewable sources) transfers its unsustainability to mountain grazing agroecosystems.

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The agrifood system has become increasingly dependent on non-renewable energy and material resources<sup>1–3</sup>. Energy efficiency has sometimes increased, but the net use of fossil fuels has escalated in parallel with agricultural industrialisation and expansion of livestock numbers to feed an increasing population, but also due to overconsumption in some regions<sup>4</sup>. Despite food security remains elusive at the global scale<sup>5</sup>, the agrifood system is a major driver of transgressing a number of key planetary boundaries<sup>6</sup>. The multiple environmental impacts caused by the abovementioned trend is raising many calls to transform the agrifood system<sup>7–11</sup>. The role that livestock systems should play in this transformation process is a central matter of debate. There is agreement on the need to reduce fuel-dependent inputs, the use of non-arable areas for livestock production and a better distribution of animal source foods across populations<sup>12–15</sup>.

Grazing agroecosystems emerge as a potential alternative to alleviate those drawbacks<sup>16,17</sup>. Grazing livestock has been a common practice in marginal areas contributing to tackle food insecurity in many regions globally, particularly in the global south<sup>18,19</sup>. Likewise, they generate job opportunities in rural areas, mitigating rural depopulation<sup>20</sup>. Moreover, grazing agroecosystems make use of local renewable resources when properly managed (e.g., avoiding overgrazing). The high use of local renewable resources reduces the environmental impact associated with the acquisition of purchased inputs, the accumulation of nitrogen residues and the occurrence of wildfires<sup>21,22</sup>, while minimising the dependence on non-renewable resources.

Nowadays, grazing agroecosystems in developed countries are increasingly absorbed in the global agrifood system<sup>23–25</sup>. As a result, most of them have become economically unprofitable due to their impossibility to compete against highly productive industrial livestock enterprises<sup>23</sup>. To offset this economic competitive disadvantage, the Common Agricultural Policy (CAP) aimed to promote rural areas in the European Union through its First (Direct payments to farmers) and Second (Rural development policy) Pillars. CAP payments have allowed European grazing agroecosystems to maintain a constant level of

profitability, but also conditioned their evolution in the last decades<sup>26,27</sup>. Despite economic dependency on public policies being consistently contemplated in socio-economic analysis of grazing agroecosystems<sup>27–30</sup>, it still remains poorly explored in environmental assessments (Muñoz-Ulecia, Bernués, Briones-Hidrovo, Casasús and Martín-Collado, under review). Assessing the effect of public policies on grazing agroecosystems' sustainability from an environmental support perspective can provide useful information that contributes to the debate of the necessary transformations of the agrifood system.

In this study, we assess how the sustainability of grazing agroecosystem has evolved within a systems ecology and thermodynamic perspective. To do so, we analysed mountain grazing agroecosystems by applying the Emergy Accounting approach<sup>31,32</sup>. The Emergy method allows to consider all the available energy (i.e., ability to do work or drive a process) that has been previously required directly or indirectly to produce each input entering the system under study, differentiating between renewable/non-renewable and local/imported sources. Emergy Accounting takes into consideration that resources are generated by natural processes through hierarchical transformations where larger amounts of low-quality resources (low ability to drive a process) are converted into smaller volumes of higher-quality items, with input resources degraded in each transformation (being the food chain the most familiar example). Products requiring more emergy per unit occupy a higher position in the supply chain hierarchy<sup>32</sup>. A product's position in the energy transformation hierarchy can be calculated as the emergy required to produce it divided by its available energy content, yielding a conversion factor named transformity (solar emergy joules per Joule— $sej/J$  –, product expressed as joule) or Unit Emergy Value (UEV), if the product is expressed in terms of mass ( $sej/kg$ ), currency ( $sej/\$, \text{€}, \text{¥}$ , etc), information ( $sej/bit$ ), etc., as further clarified in Methods, Table 1. A transformity or UEV size depends on the number and size of intermediate transformations required to yield the product<sup>32</sup>. As such, primary producers like grasslands support a grazing livestock system; however, due to the low-quality of photosynthetic biomass (low transformity or

**Table 1** Emergy indicators definition and formula.

Emergy indicator	Definition	Formula
Transformity (Tr)	The ratio between the total emergy yield (U) and the total output yield (Y) measured as joules of output. It represents the emergy efficiency. If the output is measured through other units (e.g., kg), the ratio is denominated UEV (Unit Emergy Value).	$\frac{U}{Y}$
Renewability (%R)	The ratio between natural renewable local inputs (R) and the total emergy of the system. Represents renewability.	$\frac{R}{U}$
Emergy Yield Ratio (EYR)	The ratio between the emergy yield (U) and the emergy from purchased inputs (F) and services (S). Represents net contribution to the socio-economic system.	$\frac{U}{F+S}$
Emergy Investment Ratio (EIR)	The ratio between the emergy from purchased inputs (F) and services (S) and the emergy from natural local (renewable or not) inputs (R and N). Represents market dependency.	$\frac{F+S}{R+N}$
Emergy Exchange Ratio (EER)	The ratio between the emergy yield (U) and the money paid for a product or service. Represents market trade status.	$\frac{U}{e \cdot [\frac{U}{e}]}$
Environmental Loading Ratio (ELR)	The ratio between non-renewable natural (N) or purchased (F and S) emergy inputs divided by natural renewable (R) ones. Represents environmental load, i.e., increasing distance from environmental equilibrium.	$\frac{N+F+S}{R}$
Emergy Sustainability Index (ESI global)	The ratio between EYR and ELR. Represents sustainability at global level.	$\frac{U}{\frac{F_n+S_n}{R+F_r+S_r}}$
Source Diversity Index (SDI) <sup>a</sup>	Summation of the proportional contribution of each input ( $U_i$ ) to total emergy yield (U) multiplied by its logarithm. Represents inputs redundancy, an attribute of resilience.	$-\sum_i (EIVS_i) \cdot \log EIVS_i$ , where $EIVS_i = -\left(\frac{U_i}{U}\right)$

$F_r$  and  $S_r$  are the renewable fraction of the purchased resources and services, while  $F_n$  and  $S_n$  are the non-renewable fraction of the purchased resources and services.

<sup>a</sup> $U_i$  is the amount of the emergy of  $i$ th flow.

UEV), it takes a large amount of biomass (available energy) to generate a small amount of high-quality unit of livestock. On the contrary, highly processed flows that require many intermediate transformations, complex processes and know-how, like fertilisers and pesticides, carry high amounts of energy associated to low amounts of available energy with high UEV. Therefore, the energy contribution of a resource flow to a system is calculated as the amount of that flow entering the system (usually as Joules, grams or money) multiplied by its hierarchy position factor (i.e., its UEV). The sum of all energy resource inflows translates into the total energy supporting the final product of the process or the survival of the system (a tree, a person, an economy). Therefore, we might describe energy as a multi-dimensional environmental footprint, much more comprehensive than land, carbon or water footprints. The perspective offered by the Energy Accounting approach allows to consider interconnections between farming systems, the environment and the socio-economic system, following the flows of energy, materials and information among them<sup>31</sup> without disregarding their cumulative available energy due to the biosphere's support.

Previous studies related to agroecosystems' research have commonly used national or regional datasets to assess the evolution of agricultural systems' sustainability from the middle of 20th century to the first decade of the 21<sup>st</sup> century<sup>33–35</sup>. In general, these authors found an increase of agricultural efficiency (i.e., less resources required per product unit), but also a higher use of non-renewable resources, resulting in a stagnation or decrease in the sustainability of agricultural processes. Since dynamics at global levels can mask changes at lower levels (e.g., local and farm levels)<sup>27</sup> where, ultimately, farmers decide which agricultural practices to implement, here we assess the sustainability of 50 mountain grazing farms over a 30-year period. These farms are located in three valleys of the Spanish Pyrenees, each one characterised by presenting a different farming trajectory of evolution<sup>27</sup>.

Specifically, using Energy Accounting we aimed to (i) assess the global evolution of mountain grazing agroecosystem's environmental sustainability (energy indicators) from 1990 to 2018; (ii) explore if different evolution pathways followed by farming systems in the last three decades<sup>27</sup> translated into a varying evolution of their environmental sustainability, and; (iii) finally discuss the role of the CAP to enhance or diminish agricultural sustainability over time and its implications. We found an increase in farm dependence on non-renewable resources, despite longer grazing periods and reduced use of off-farm animal feeds. The increasing inflow of public economic support from the CAP and services from the socio-economic system (mainly driven by non-renewable sources) transfers its unsustainability to mountain grazing agroecosystems.

## Results

Figure 1 shows the systems diagram of the investigated process, with main components and mutual interactions, different energy, material and money resources flowing into and out of the farming systems: local renewable inputs, purchased inputs and monetary flows, labour and services, as well as system's product outputs: milk, weaned calves or fattened calves. The system diagram in Fig. 1 shows the dependence of components from outside sources as well as from each other: components within the Agricultural farm and Animal farm components are connected to each other via complex feedbacks and supports that are not shown in the diagram for space reason (just think of the topsoil organic matter regulation by appropriate crop rotation and management).

**General evolution of grazing agroecosystems—heading towards lower sustainability.** The proportion of energy

(cumulative resources from economy and nature) flowing into the farming systems from animal feeds, crop inputs and labour halved from 1990 to 2004, coinciding with a switch from dairy to beef production in the region, and then suffered limited changes from 2004 to 2018 (Fig. 2). On the contrary, the relative contribution of CAP payments, services and others (i.e., machinery, buildings and energy) multiplied from 1990 to 2004 and remained more or less constant from 2004 to 2018. Due to this increase, the relative contribution of local natural resources (topsoil and rain, among others) decreased over time and the contribution of natural pastures stagnated (Fig. 2).

These shifts in the relative contribution of input flows to farms' functioning were assessed using energy indicators that captured different aspects of sustainability (Table 1). These indicators account for the proportion of renewable resources used (Fig. 3a); the system's contribution to (Fig. 3b) and dependence on (Fig. 3c) the socio-economic system; the market trade relation (Fig. 3d); the environmental load as the ratio of non-renewable and purchased inputs by local renewable inputs (Fig. 3e); and, finally, the sustainability as the ratio between the contribution to the socio-economic system and the environmental load generated (Fig. 3f). Main changes occurred from 1990 to 2004 and then farms remained relatively stable (Fig. 3; Numerical values and statistical tests in Supplementary Table 5).

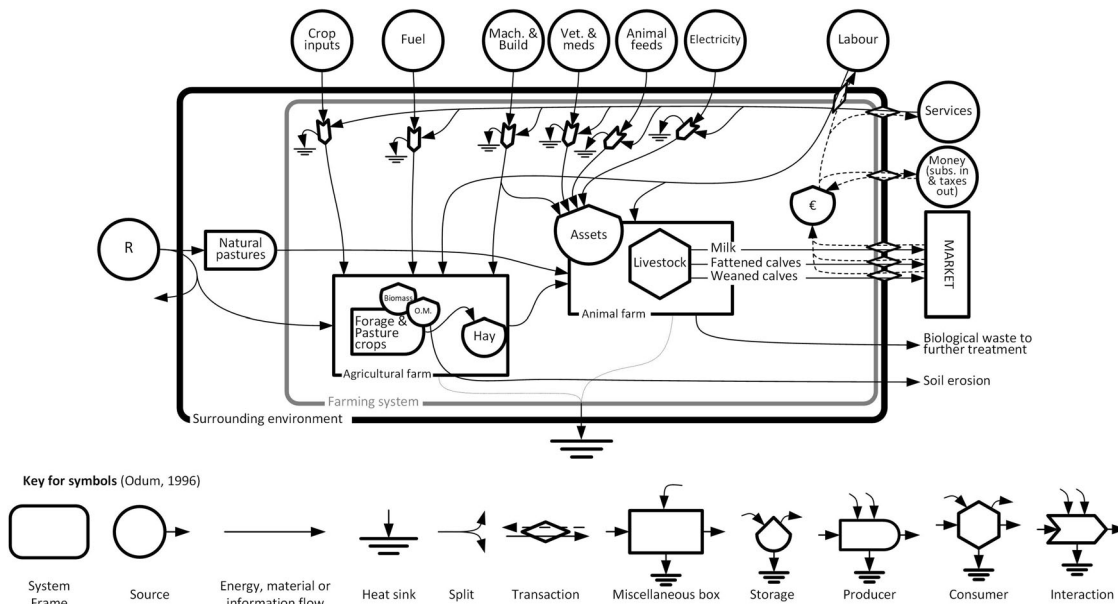
Figure 3 shows that from 1990 to 2004, on average, farms decreased the incorporation of inputs from renewable sources, decreased their contribution to the socio-economic system and halved their sustainability performance remaining with a non-sustainable functioning throughout the investigated 30-year period. Likewise, farming systems increased their dependence on market inputs and their environmental load. Lastly, market trade status showed uneven exchange between farms and the market, but the increasing incorporation of CAP payments starting in the second period placed farms closer to market fair trade (defined as farms being paid the same amount of energy that they provide, which would be a Market trade status = 1). Moreover, variability across farms decreased in most indicators.

**Different farming trajectories of evolution but similar environmental performance.** We tested that despite farms followed different trajectories of evolution in structural, technical and socio-economic terms<sup>27</sup>, all of them followed the general trend observed in Fig. 3 and presented sustainability outcomes between the same thresholds, except for minor differences (Fig. 4; Numerical values and statistical tests in Supplementary Table 6).

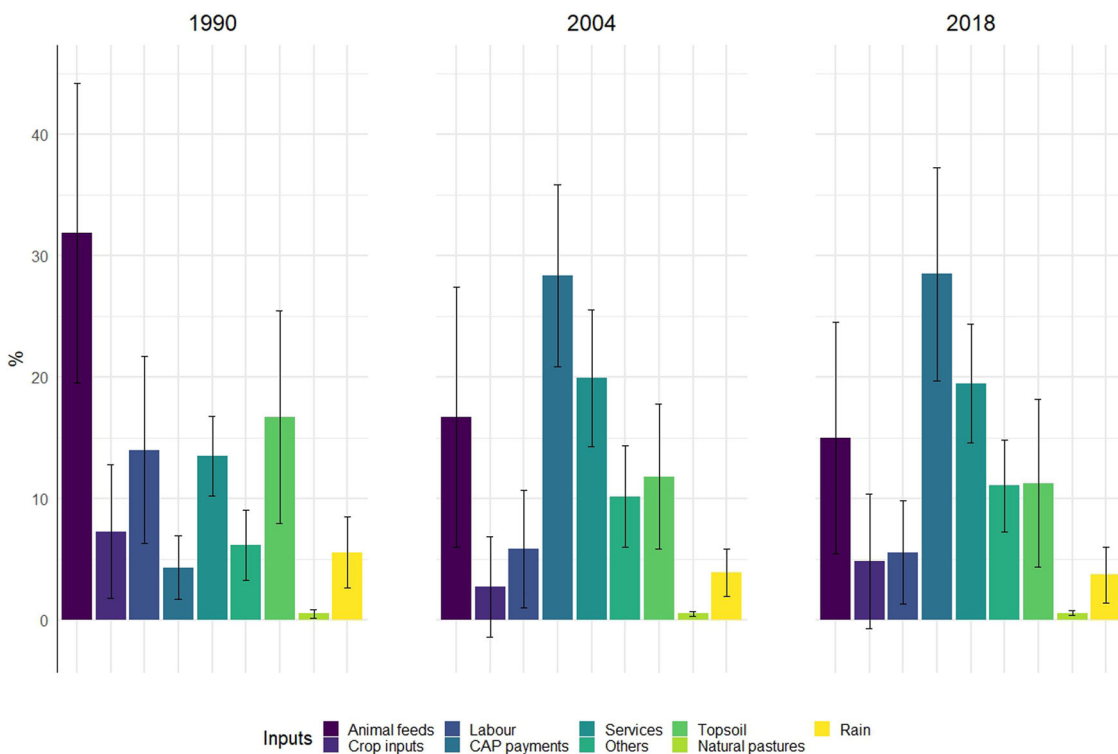
**Farming systems' evolution of inputs' sources diversity.** We assessed the diversity of inputs' sources as an attribute of farming systems' resilience and how it evolved in the studied period (Table 2). Farming systems have decreased the diversity of inputs sources in the last 30 years ( $p < 0.01$ ), mainly from 1990 to 2004. This period was marked by the strong increase in CAP payments dependence, hired labour decrease and herd feeding simplification due to the transition from dairy to beef production. Farms from all trajectories of evolution followed the general trend decreasing their diversity of inputs from 1990 to 2004. Broto trajectory, whose limited availability natural resources implied a wider range of input sources<sup>27</sup>, stands out as the trajectory with higher values in each time-point.

## Discussion

Farming systems evolved differently in the last thirty years<sup>27</sup>, however, our results show that the increasing dependence on CAP payments determined their overall sustainability, despite minor regional differences. Grazing agroecosystems in the Pyrenees, like in other European mountains, have decreased the



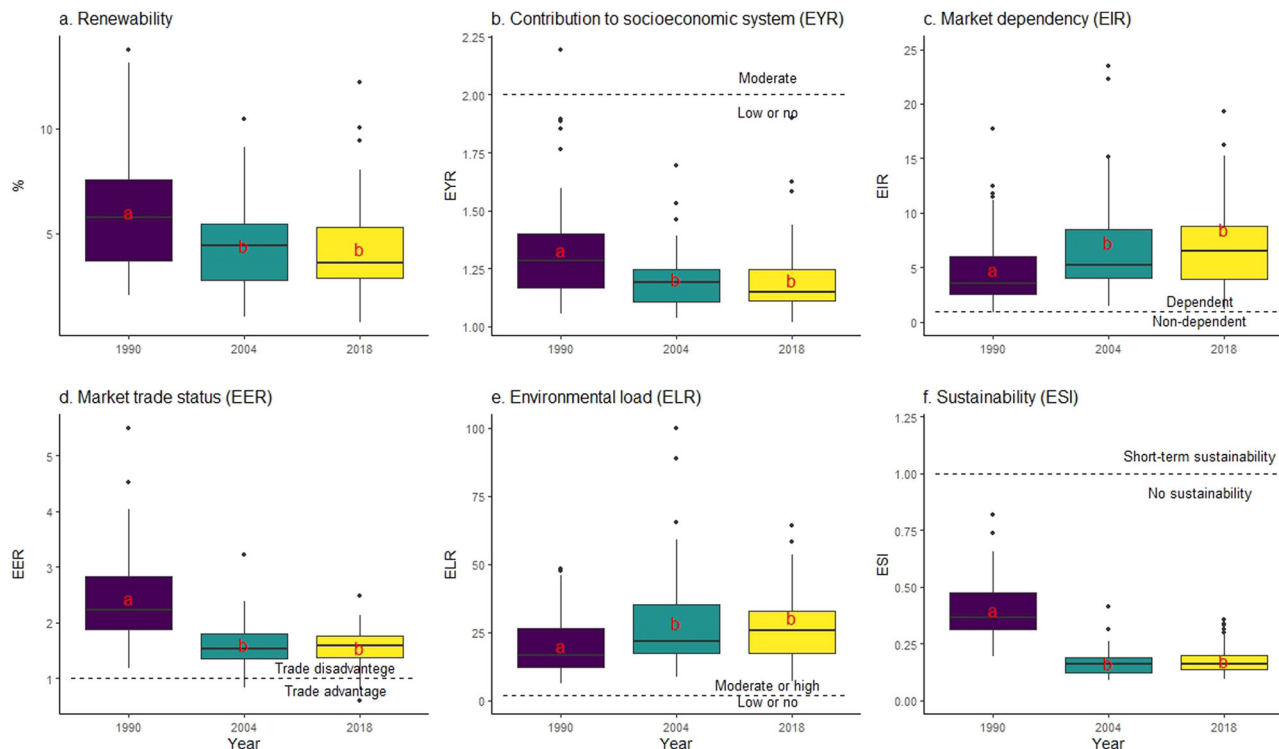
**Fig. 1 Diagram representing the functioning of the studied grazing agroecosystems.** R refers to local renewable sources (Sun, Deep heat, Rain, and Wind). O.M. refers to organic matter in topsoil. Crop inputs includes seeds, fertilisers and phytochemicals. Mach. & Build includes machinery, buildings and small equipment. Animal feeds include straw, corn, forage, vitamin-mineral supplements and concentrates. Services are the indirect labour to produce all purchased inputs. Subs. & taxes are the taxes paid and public economic support received by farmers.



**Fig. 2 Evolution of resources proportional contribution to total farms' energy.** Figures are the average of the 50 farming systems. Vertical lines represent standard deviation. Animal feeds include straw, forage, vitamin-mineral supplements and concentrates. Crop input includes seeds, fertiliser and phytochemicals. Others include machinery, buildings, small equipment, veterinary and medicines, electricity and fuel. Numerical raw values are available in Supplementary Tables 1–3 and calculations in Supplementary Table 4.

purchase of animal feeds due to their shift in product orientation (from dairy to cattle) and the increased grazing season length<sup>27,29</sup>. These changes meant higher use of local renewable resources and a reduction of external feed inputs. This farming pattern usually reduces productivity<sup>23</sup>, forcing farms to adapt their management to comply with the requirements of public policies in order to

maintain economic viability<sup>36</sup>. Consequently, farms dependence on the socio-economic system has increased. These monetary inflows, usually disregarded in environmental assessments, represent the work of nature and society entering farming systems and allowing them to maintain their functioning and, therefore, it is of critical importance to account for them<sup>31</sup>.



**Fig. 3** Energy indicators by year. **a** Represents the proportion of renewable resources; **b** the contribution of farms to the socio-economic system; **c** represents farms dependence on resources from the market; **d** the equity of the market trade; **e** the environmental load of farms; and **f** the environmental sustainability of farms. Each boxplot represents the 50 farms analysed. Boxplots represent the farms (points), mean (letters), median (solid horizontal lines), first and third quartiles (boxes) and dispersion (vertical lines). Letters refer to statistical differences ( $p < 0.01$ ) between years using Kruskal-Wallis's test. Thresholds of energy indicators were set by refs. 31,54.

Changes that aim at simplifying the farming system by decreasing the internal links and the dependence on local natural inflows, while at the same time making it dependent on outside economic support in terms of inputs and monetary compensations (and therefore non-renewable imports) may pave the way to unsustainable patterns with gradual intensification of the agricultural production processes and loss of diversity and resilience. The performance indicators provided by the Emergy method have allowed a multi-dimensional evaluation of systems' evolution in the investigated period, in so highlighting crucial aspects for sustainable policies.

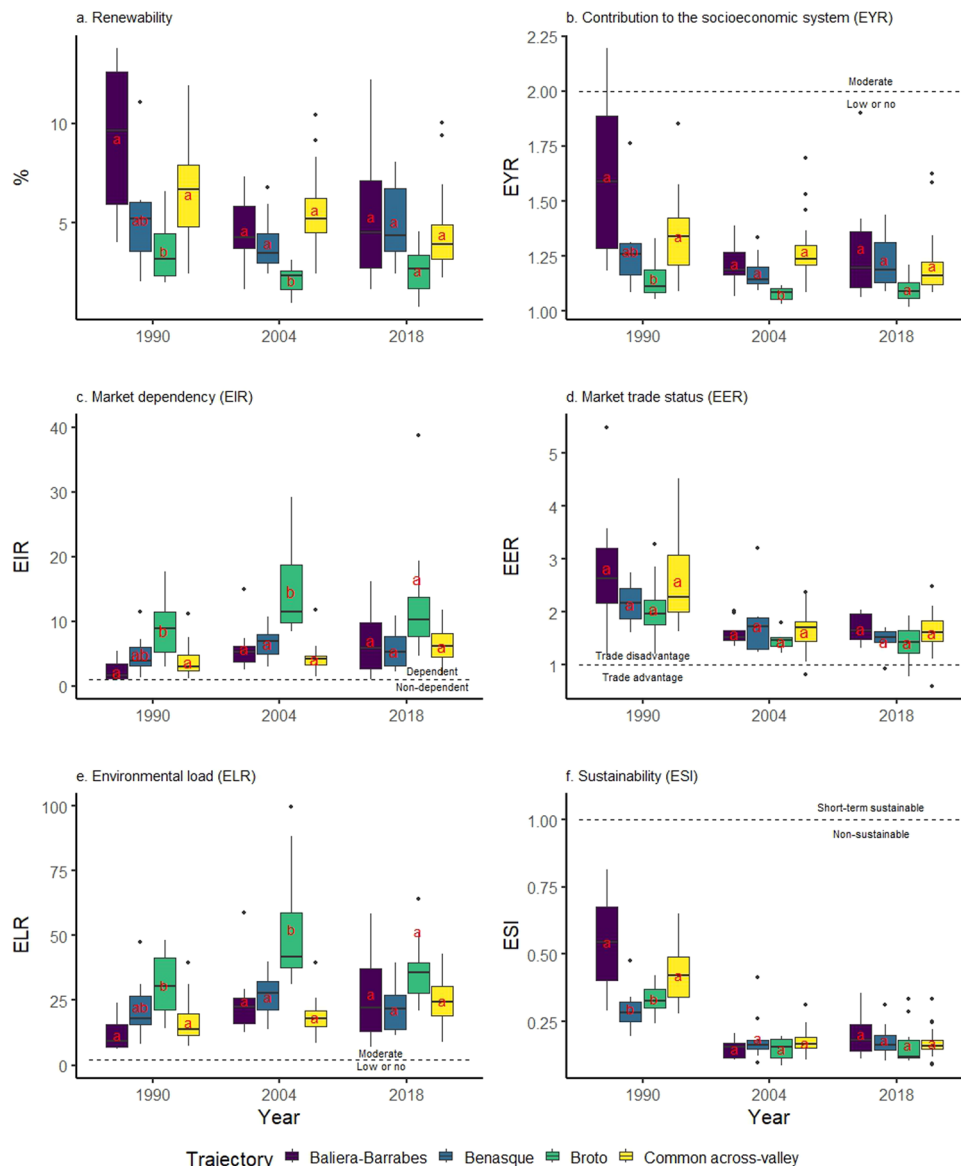
Our results reveal a double trend of evolution with contrasting outcomes at the local and global level (i.e., direct versus indirect processes). At the local level, farming systems have increased their (direct) use of local renewable sources through increasing grazing season length and agricultural areas. They have also reduced the (direct) purchase of animal feeds and crop inputs (which are partly non-renewable). These changes, that imply increasing renewable and decreasing non-renewable inflows of direct energy and materials, would be expected to improve farming systems' sustainability<sup>13</sup>. Indeed, they go in the direction of maximising the use of natural resources. However, global level (indirect) dynamics outperform these potential improvements.

At the global level, fossil fuels account for around 80% of primary energy use (BP, 2021. Available at <https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html>). In emergy terms, the proportion of non-renewable sources maintaining the functioning of the socio-economic system from 2001 to 2015 in Spain has ranged from 86% to 95% (Available at <http://www.emergy-nead.com/country/data>). Therefore, the increasing inflow of monetary inputs into farming systems (through CAP payments and services) bring with them the long shadow of

non-renewable resources that are used to produce them (i.e., societal infrastructures, information, mobility, etc., which affect the functioning of the farm itself and its relation with markets).

The agrifood system is at the core of the conflict between the socio-economic system and the environment<sup>37</sup>. These are interconnected systems with a complex net of direct and indirect interactions, where a positive (or negative) change may not result in the a priori expected outcomes<sup>38,39</sup>. From a systems perspective, it is known that there are hierarchies and that components at lower levels build the higher levels, which in turn exert a top-down control<sup>40,41</sup>. We can draw two consequences from here. First, since the farming systems analysed are at a lower hierarchical level than the socio-economic system, they are constrained by it. Our study shows the high impact of agricultural policies on overall farm sustainability, which is translated into limited management options to improve the environmental sustainability of farms at the agroecosystem level (Muñoz-Ulecia, Bernués, Briones-Hidrovo, Casasús and Martín-Collado, under review). Second, the farming systems under study are embedded in the socio-economic system and, therefore, they have the potential to influence it to some extent. The changes towards a more sustainable management at the farm level are an essential (yet insufficient) step in the long way to achieve sustainability of grazing agroecosystems. This means that the environmental sustainability of a local process cannot be achieved only by using local renewable energy and resources, but also by making more sustainable the whole surrounding society.

What is the future of grazing agroecosystems then? The climate, ecological and energy crises have raised urgent calls to cut down the use of fossil fuels in all economic sectors<sup>42,43</sup>. Are grazing agroecosystems better positioned for a future with lower availability of fossil energy? From the resilience perspective,



**Fig. 4 Evolution of energy indicators in the different trajectories of evolution.** **a** Represents the proportion of renewable resources; **b** the contribution of farms to the socio-economic system; **c** represents farms dependence on resources from the market; **d** the equity of the market trade; **e** the environmental load of farms; and **f** the environmental sustainability of farms. Trajectories sample size: Baliera-Barrabés = 8 farms, Benasque = 9, Broto = 11 and Common across-valley = 22. Boxplots represent the farms (points), mean (letters), median (solid horizontal lines), first and third quartiles (boxes) and dispersion (vertical lines). Letters refer to statistical difference ( $p < 0.01$ ) between trajectories within years using Kruskal-Wallis's test. Thresholds of energy indicators were set by refs. 31,54.

agroecosystems ability to face exogenous changes (i.e., energy scarcity) is determined by their robustness, adaptability and transformability capabilities<sup>44,45</sup>. More specifically, the different components of a system and the relations between them affect its resilience<sup>46,47</sup>. This fact has given rise to indexes like the Shannon biodiversity index for ecosystems, or the inputs diversity and redundancy attributes analysed in social-ecological systems<sup>45,48</sup>. In our study, the trend to reduce the diversity of inputs with the concentration of high number of embedded resources in a few of them (i.e., services and CAP payments) could negatively impact farms' resilience. However, despite grazing agroecosystems being indirectly increasing their dependence on non-renewable resources, their use at the global level is negligible compared to other agricultural systems covering most agricultural land<sup>13,49</sup>. Therefore, a transition of the livestock sector towards grazing appears as a promising strategy to reduce non-renewable energy

consumption (and their associated release of fossil carbon), increase preparedness for a less-fossil-energy future, and improve food security and sovereignty in marginal regions. However, this transition should come together with many behavioural and societal changes, since neither the current nor the expected future demand for livestock products can be met from grazing agroecosystems<sup>50</sup>.

In summary, the integration of biophysical and economic fluxes to analyse the evolution of farming sustainability offers a privileged view to frame grazing agroecosystems as social-ecological systems. Through this holistic framework we found that the product orientation transition from dairy to beef cattle farming, driven by past agricultural policies, have favoured the adoption of more sustainable farming practices in grazing agroecosystems at the local level. However, these gains in sustainability at the local level are outperformed due to the global

**Table 2 Farms' sources diversity over time and across trajectories of evolution.**

Year	Trajectory	SDI/SDI <sub>max</sub> (%)	SD
1990		77.32 <sup>A</sup>	6.8
	Baliera-Barrabés trajectory	79.48 <sup>ab</sup>	4.5
	Benasque trajectory	72.95 <sup>a</sup>	4.4
	Broto trajectory	81.80 <sup>b</sup>	5.9
	Common across-valley trajectory	76.06 <sup>ab</sup>	7.4
2004		71.14 <sup>B</sup>	6.4
	Baliera-Barrabés trajectory	72.68 <sup>ab</sup>	5.1
	Benasque trajectory	67.65 <sup>a</sup>	4.0
	Broto trajectory	75.57 <sup>b</sup>	5.8
	Common across-valley trajectory	69.78 <sup>ab</sup>	6.7
2018		71.76 <sup>B</sup>	6.4
	Baliera-Barrabés trajectory	73.15 <sup>a</sup>	4.4
	Benasque trajectory	68.48 <sup>a</sup>	7.7
	Broto trajectory	74.06 <sup>a</sup>	4.3
	Common across-valley trajectory	71.35 <sup>a</sup>	7.1

Mean and standard deviation (SD). Capital letters represent statistical differences between years. Lowercase letters represent statistical differences between trajectories in each year. Differences were calculated using Kruskal-Wallis's test, available in Supplementary Table 5. SDI = Source Diversity Index. SDI<sub>max</sub> = Maximum theoretical SDI.

overuse of non-renewable resources which enter the system, mainly through payments of the CAP. In the context of the social and institutional demand for sustainable agrifood systems our results point to a clear message: grazing agroecosystems may play a key role in the sustainability of farming at the local scale due to their low direct use of non-renewable energy and resources and their contribution to tackle food insecurity in some world regions (especially in the global south). However, as long as the global socio-economic system remain fossil fuel-driven, there is limited space for developing sustainable agricultural systems at the global scale since the unsustainability of the global economy enters local systems through CAP payments and external inputs.

## Methods

**Study area.** This study focused on the valleys of Broto, Benasque and Baliera-Barrabés, in the Spanish central Pyrenees. The study area was chosen because of the availability of previous information that allowed analysing a constant sample of farms over a 30-year period. The valleys were originally selected to represent diverse livestock farming systems as well as different biophysical and socio-economic contexts, enabling to compare how regions with different development opportunities and constraints evolved under common global pressures<sup>27,30,51,52</sup>. Moreover, these valleys have already been proved as a paradigmatic example of European grazing agroecosystems<sup>27</sup>. This study focused on the farming system level and resulted from the monitoring of 50 cattle farms that have been surveyed through and in-depth face-to-face questionnaire at three dates (1990, 2004 and 2018). Everything was performed in accordance with the guidelines and approval of the Ethics Committee of the Agrifood Research and Technology Centre of Aragón, Spain (no. CESIH\_2022\_3). Data anonymity was granted to the participants, who expressed their oral informed consent to provide the information contained in the questionnaire.

**Description of farming systems evolution.** The technical and structural evolution of the mountain grazing agroecosystems under study in the last three decades can be summarised as follows.

Over the 1990–2004 period, mountain grazing farms experienced an average one-month increase of the grazing season and an increase of agricultural land and herd managed per work unit (WU), coinciding with a switch from dairy to beef production with on-farm fattening. Over the 2004–2018 period, agriculture land stabilised but the increase of herd managed per WU process went on, while farms reduced their feeding costs per livestock unit (LU), in parallel to a decreasing

importance of fattening, with farms selling weaned calves to be fattened in specialised feedlots located outside the studied valleys.

At a regional scale, four trajectories of evolution were identified, three of them specific to each valley under study (we named each of these trajectories by the name of the valley) and a common across-valleys trajectory. *Broto trajectory* was characterised by a small agricultural area and large herd growth. *Benasque trajectory* strongly reduced labour input due to increasing tourism in the region. *Baliera-Barrabés trajectory* was characterised by the largest agricultural area and lowest stocking rate. The *Common across-valley trajectory* was compounded by small farms that made slight changes. These trajectories resulted from the interaction between global and regional drivers and household particularities. The CAP played a major role at the global level (representing on average a 70% of farm gross margin in 2004 and 2018), while tourism development and household internal characteristics were the main drivers at the regional level. Many farms responded by maximising their output related to the most limiting production factor in each valley (i.e., agricultural land or labour). However, 44% of farms showed limited changes during the studied period. See ref. <sup>27</sup> for further details.

**Emergy accounting.** Emergy is defined as the sum of all the available energy inflows of one kind (generally solar) invested directly or indirectly into a process per unit of product or service, measured as solar energy joule (sej) or emjoule. The available energy (or exergy in thermodynamics, see<sup>31</sup> page 33, Table 1.1) is a measure of the work potential of each inflow, that is, its ability to drive a transformation process. The strength of the emergy approach relies in its ability to account for the entire supply chain in the biosphere's trial and error dynamics, most often named donor side perspective. We have followed all the steps to perform an emergy accounting as described in<sup>31</sup> using the Global Emergy Baseline (the sum of the primary energies driving all the processes of the geobiosphere) of 12.0E + 24 sej/yr established by<sup>53</sup>. In particular, the emergy approach requires the following steps:

- (i) To draw an emergy diagram defining the system boundaries and correlations among components and sources.
- (ii) To classify all inputs and outputs and to transform them to emergy units.
- (iii) To calculate emergy ratios and indices (Table 1).

We also applied the Source Diversity Index (SDI) proposed by<sup>47</sup> to assess system's stability or redundancy of input sources, which is an attribute of the system's resilience. The value of SDI is maximum (SDI<sub>max</sub>) when all input flows have the same Emergy Importance Value of Sources (EIVS<sub>i</sub>) (which does not mean that the same raw amount of each flow is provided to the process, but instead that there is a balance among low-quality and high-quality inflows). As described by<sup>47</sup> and previously by<sup>46</sup> for ecosystems functioning, the ratio between SDI and SDI<sub>max</sub> measures the difference between the current and the theoretical optimal functioning. The evolution of this ratio over time provides insightful information to assess if a system is increasing or decreasing this attribute of resilience.

Here, emergy accounting is applied to evaluate a constant sample of 50 farms in 1990, 2004 and 2018 to analyse how they evolved in their sustainability performance and resilience over the last thirty years. The procedure for the calculation of each flow is available in Supplementary Table 4. To analyse differences between trajectories of evolution and time periods we have used ANOVA and Kruskal-Wallis tests depending on sample size, data normality and heteroscedasticity. R Studio (version 4.2.2) was used for all statistical analysis and graphics.

## Data availability

Data are available at <http://hdl.handle.net/10532/6446>. Data used to display figures is available at: <https://doi.org/10.6084/m9.figshare.23585292.v1>.

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E.M.U.: conceptualisation, data curation, formal analysis, investigation, methodology, visualisation, writing—original draft. A.B.: supervision, writing—review & editing. A.B.H.: Writing—review & editing. P.P.F.: methodology, writing—review & editing. E.B.: methodology, writing—review & editing. R.S.: methodology, writing—review & editing. S.U.: methodology, writing—review & editing. D.M.C.: conceptualisation, supervision, writing—review & editing.

## Competing interests

The authors declare no competing interests.



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