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A Societal Metabolism Approach to Effectively Analyze the Water–Energy–Food Nexus in an Agricultural Transboundary River Basin

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Abstract: We implemented the semantically open conceptual framework 'Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism' (MuSIASEM) to deal with nexus challenges in agricultural production systems in transboundary river basins, using the Iranian Aras River Basin as a case study. The performance of the agricultural sector was characterized for relevant typologies of crop production using metabolic profiles, i.e., inputs and outputs per ton of crop produced, per hectare of land use, and per hour of labor. This analysis was contextualized across hierarchical levels of analysis, including the agronomic context at the regional level (rainfed versus irrigated cultivation), the socio-economic and political context at the national level (food sovereignty; urbanization), and the hydro-ecological context of the larger transboundary river basin (water constraints, GHG emissions). We found that the simultaneous use of two different interrelated logics of aggregation—the productivity of land and labor (relevant for the agronomic and socio-economic dimension) and the density of flows under different land uses (relevant for the hydrological and ecological dimension)—allowed for the identification of trade-offs in policy deliberations. In the case of Iran, it showed that striving for strategic autonomy will exacerbate the current water crisis; with the current cropping patterns, agronomic improvements will not suffice to avert a water crisis. It was concluded that the proposed approach fills an important gap in nexus research, but to effectively guide nexus governance in the region, a co-production of the analysis with social actors as well as more complete data sets at the river basin level would be essential.

Keywords: water–energy–food nexus; food security; social-ecological system; societal metabolism; agricultural policy; Aras River Basin; Iran

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1. Introduction

As early as the 1970–1980s, several scientists drew the attention of the scientific community and policy makers to the potential detrimental impact of agriculture on our natural environment and emphasized the importance of linking the analyses of food, energy, water, soil, biodiversity, and population size [1–3]. However, it was not until the 2011 Bonn Nexus Conference [4] that the key importance of the nexus between water, energy, food, and environment for sustainability policies was first openly discussed by the scientific community. In the years following, the 'nexus' quickly gained traction in the scientific literature dealing with sustainability policy challenges, although it was predominantly with regard to water policies [5–16]. Indeed, despite the impressive body of literature, the governance of the sustainability of food security has remained largely organized in silos. This strategy is inept for dealing with the challenges of the nexus [17–20]. One of the possible explanations for the persistence of silo governance is the inadequacy of the current scientific paradigm for addressing complex problems, especially when it comes to quantitative analysis [21].

Indeed, several exhaustive reviews of nexus models [22–26] have shown that few new tools or methods have been developed purposefully to address the transdisciplinary water–energy–food (WEF) nexus linkages. Most nexus models focus on analyzing two-sector linkages within WEF systems by combining closely-related existing disciplinary techniques (e.g., [5,27,28]). However, the assessment metrics and approaches designed for individual nexus components may no longer be valid for the nexus system as a whole. Integrated assessment models feeding a deterministic (economic) framework of analysis with ad hoc modules for "water", "energy", and "food", i.e., the so-called 'Frankenstein models' [29], no matter how complicated, cannot capture the underlying biophysical entanglement characteristic of the nexus between water, energy, food, environment, and population across different levels of analysis [30]. This challenge requires the ability of handling the unavoidable presence of non-equivalent descriptive domains (associated with different scales) and, therefore, quantitative assessments generated within non-equivalent modeling assumptions [31]. To get out of this impasse, sustainability science needs a more holistic and critical approach that recognizes the complex nature of the social–ecological system. This is especially true for transboundary river basins, where political and economic factors impinge on policies aimed at governing the biophysical resource nexus in different national contexts [32–35].

In relation to this challenge, the above-quoted reviews and particularly Albrecht et al. [22] identified the following key knowledge needs: (1) to better define system boundaries and consider the multi-scalar relationships of water, energy, and food systems; (2) to improve the quantification and modeling of underlying complex nexus linkages; (3) to consider the local context (how the resource nexus affects, and is affected by, socio-political systems). Albrecht et al. [22] also pointed to "flexibility" as a key attribute of nexus assessments, "particularly to tailor methods to various geographic regions and spatial and temporal dynamics, to allow for transferable principles across scales, and to incorporate new knowledge". However, what if the system (the levels and the dimensions) of interest can only be observed by adopting different boundaries at the same time?

Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM) is a semantically-open accounting scheme purposefully developed to fill this research gap by handling the above-mentioned epistemological predicaments associated with the resource nexus [36]. MuSIASEM aims to identify the factors that determine the feasibility, viability, and desirability of metabolic patterns for a defined social–ecological system characterized in terms of inputs and outputs associated with different types of human activity. It recognizes the impredicative nature of the relations among resource flows and the need to contextualize non-equivalent representations of the system under analysis (e.g., economic, social, technical, and ecological performance). Indeed, each social–ecological system—be it a village, an agricultural region, a country, or a transboundary river basin—is 'special' because of its specific location and biophysical context, its history, its economic organization, and the culture of its inhabitants. Nonetheless, the concept of metabolic pattern allows the analyst to define *expected* relations between the characteristics of its functional and structural elements across hierarchical levels [36].

Earlier applications of MuSIASEM have focused on the national and pan-European level (e.g., [37,38]). The novelty of this work is that it explored the potential of MuSIASEM for resource nexus analysis at the river basin level. To this purpose, we conducted a multi-scale analysis of the metabolic pattern (energy, water, food, land uses, labor) of the Aras River Basin (ARB) in northwestern Iran, an important agricultural production region, for the period of 2006 to 2016. Our research question was how to generate a coherent information space that can be used by different social actors that have different but legitimate concerns and goals to carry out an informed deliberation about how to use agricultural resources at the river basin level. Such information space should be useful for characterizing the trade-offs that can be expected when considering different nexus-related policies formulated within different contexts. The selected region for our case was of particular interest because the ARB is a transboundary basin characterized by geopolitical concerns over nexus security [35,39]. In the ARB, as in many other hydrological river basins, land and water are being overexploited by agricultural activities, mainly because of an excessive intensity of production and inefficient irrigation systems in relation to population growth and the thirst for economic growth [35,40–43].

The rest of the text is organized as follows. Section 2 describes the selected study area and its socio-economic and ecological context. Section 3 describes the conceptual framework (MuSIASEM), its formalization for a transboundary river basin, and the data sources. Section 4 illustrates a diagnostic analysis of the metabolic pattern for the selected regional agricultural production system in Iran, considering several flows and funds and hierarchical levels (scales) of analysis, and contextualizes these results considering several different boundaries. Section 5 discusses the strength and shortcoming of the social metabolism approach for nexus analysis. Section 6 concludes.

2. Study Area and Contextualization

2.1. The Iranian Aras River Basin

The Aras River Basin is a trans-boundary basin. The Aras originates in the Binaguldaq Mountains in Erzurum province in eastern Turkey. It flows along the Turkey-Armenia border, the Iran-Armenia border, and the Iran-Azerbaijan border, before joining the Kura River in Azerbaijan and draining into the Caspian Sea (see Figure 1). The Aras drains the south side of the Lesser Caucasus Mountains, while the Kura drains the north side. The Aras has a total length of 1072 km, and the Aras watershed encompasses a total area of 102 thousand km^2.

Figure 1. The Kura-Aras River Basin.

In Iran, the ARB covers 37,071 km^2 of northern west lands (2.24% of the country's total land), of which 71.5% consists of mountainous area and 28.5% of plains [44,45]. The Iranian ARB, hereafter abbreviated as IARB, extends over three provinces, West Azerbaijan, East Azerbaijan, and Ardabil. In the period 2001–2016, the IARB registered an average temperature within the interval of 11.7–13.5 °C, an average precipitation of 151–300 mm/y, and an average evapotranspiration of 151–300 mm/y [46].

The IARB mainly encompasses lands with climatological patterns typical of the Mediterranean with spring rains [47] that allow the coexistence of both irrigated and rainfed cultivation systems. The agricultural production in the area, notably the rainfed production, is significant and makes an important contribution to the national goal of food self-sufficiency [40]. Over the last decade, the IARB provided about 21% and 11% of the Iranian annual crop production in rainfed and irrigated agriculture, respectively [48,49]. The main crops cultivated in the area are cereals and, to a lesser extent, alfalfa, legumes, fruits, and sugar beets.

As in many other areas of Iran, water resources are critical in the IARB. Total (surface and ground) water storage change in the IARB has been on average negative over the period 1986–2016, with a mean annual decrease rate in the interval (−30––20) mm/y in the period 1986–2000 and (−20––10) mm/y in the period 2001–2016, implying a significant (but slightly slowing) decline in water resource availability [46]. In addition, the rapidly exacerbating water scarcity in the nearby Urmia Lake Basin (a drying saline lake) threatens the ARB because of the potential water transfer and restoration plans from the ARB to the Urmia watershed [50,51].

2.2. Agriculture in Its National Context

While Iran has an abundant endowment of fossil energy resources, water and land represent important biophysical constraints. About 92% of available freshwater resources in Iran are used by the agricultural sector [52,53], compared to an average global rate of 70% [54,55]. Water resources are being used beyond both scarcity and renewable threshold by 80% and 8%, respectively [56]. Not surprisingly, the country has experienced a reduction of 70% of renewable water per capita over the past 50 years [57]. As a result, groundwater depletion amounted to 100 billion m^3 over the past 50 years [58].

Given the availability and the quality of the land, the option space of agriculture in Iran is severely constrained. During the period studied (2006 to 2016), about 28–29% of the total land area was classified as agricultural land, and about 10–11% of the total land area was considered cropland (FAOSTAT). Based on soil quality, more than 50% of Iran's croplands are classified as either poor, very poor, or unsuitable land for agriculture [52]. Nonetheless, Iranian croplands have seen a significant increase in their output over the last 40 years, from 15 to more than 45 million tons of produce per year, with only a minor variation (about 10%) in the number of hectares cultivated [59] (see Figures A1 and A2 in Appendix A). Given the persistence of outdated irrigation techniques, the continual increase in annual yields has therefore been realized through more intensive cultivation and more irrigation on the same amount of land. This situation has contributed to severe crises of water resource sustainability in many watersheds in Iran [60,61].

At the same time, the import of agricultural commodities also increased considerably (almost doubled) to sustain food security [59]. These changes in domestic agricultural production and imports have been driven by population growth and an increase in per capita crop consumption due to a higher standard of living. Indeed, Iran saw an important increase in population over the period studied, from 70.5 million in 2006 to 79.9 million in 2016 (and from 36.4 in 1978 to 84 million in 2020). Despite trade embargoes, income from fossil energy exports has sustained the ongoing demographic transition toward a predominantly urban economy; the urbanization rate increased from 69% in 2006 to 74% in 2016 [62]. Given that one of the strategic priorities of Iran is food self-sufficiency [63,64], these demographic changes have had a profound impact on its agricultural sector. Indeed, in specialized areas, such as the IARB, where relatively fertile land and water is (still) available, agriculture is no longer aimed at feeding the rural communities by sustainably exploiting the terrestrial agroecosystems, but it has increasingly become an economic activity aimed at producing an adequate supply of food commodities for the growing urban population within the regulations imposed by the government market (e.g., prices set by the government [59] determining the economic return on the investment). This has entailed an important change in the crop mix and the techniques of production in the

Iranian agricultural sector. In most rural areas, a mix of small-holder farmers predominantly cultivating crops for subsistence and entrepreneurs entirely dedicated to cash-crop farming now co-exist.

Energy use in agriculture accounts for only 2% of the total energy use in the country (see Table A1 in the Appendix A). Given its abundant oil reserves, Iran almost completely relies on fossil fuels, with only 0.59% being 'sustainable energy' [65]. Although the energy metabolic rate of agriculture is low compared to the other economic sectors, it has steadily increased during the period observed. This is indicative of the increasing capitalization (mechanization) of the agricultural sector and/or the shift to the cultivation of more energy-intensive crops.

2.3. The Ecological Context: The Transboundary Aras River Basin

During the past decades, the construction of small and medium sized dams and the redirection of tributaries for supplying water for expanding agricultural lands, as well as urban and industrial areas in the upstream of the Aras River Basin in Turkey, have negatively affected the quantity and quality of water flowing downstream to Iran [66]. Similar trends in anthropogenic impacts on land cover have been observed in the ARB in upstream Armenia and the bordering Nakhchivan Autonomous Republic of Azerbaijan [45]. These developments have important implications for the agricultural production in the Iranian part of the ARB. Similarly, increased anthropogenic water consumption in Iran will affect the downstream irrigated lands of the Kura–Aras Lowland, the main agricultural zone of Azerbaijan [67]. Azerbaijan's dependence on surface water resources is particularly high, making upstream water abstraction in the Aras sub-basin a highly sensitive issue from a transboundary perspective [39].

Transboundary environmental problems are not limited to the variation and reduction of the hydrological flow of the Aras. Other important problems include the deterioration of water quality in the river basin (anthropogenic water pollution from industrial and mining sites, agricultural lands, and rural and urban households), ecosystem degradation and declining bio-resources (deforestation, land degradation, loss of biodiversity), and increased flooding and bank erosion due to anthropogenic interventions and climate change [39].

Underlying causes of these transboundary environmental problems include inadequate land use planning and management (e.g., agricultural expansion, urbanization), poor law enforcement and compliance, undeveloped civil society and public awareness, and inadequate policies [35,39]. While there is an urgent need for dealing with the transboundary nexus resource governance and water geopolitics [35], the contextualized knowledge of societal metabolism dynamics is needed to provide alternative solutions, and more importantly to secure food and livelihoods.

3. Methodology: Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism

3.1. The Semantic Framing of the Metabolic Pattern of Social-Ecological Systems

MuSIASEM was first put forward by Giampietro and Mayumi [68,69] to advance the sustainability discussion with a non-reductionistic conceptual framework. In an analogy with the metabolism of a living organism, MuSIASEM studies the metabolism of human society. Indeed, society is a complex social–ecological system with a hierarchical structure of functional and structural elements (made up of fund elements) that metabolize inputs (flows) for expressing expected functions and disposing wastes [36]. In this perception, the study of biophysical, social, economic, and cultural context is not only relevant but essential. The local biophysical environment determines the *feasibility* of the metabolism, i.e., its compatibility with natural processes taking place in the biosphere (beyond human control). The local socio-economic context determines the *viability* of the metabolism, i.e., its compatibility with processes taking place inside the technosphere (under human control). The international biophysical and socio-economic context determines the *level of openness* of the system through imports and exports, i.e., the externalization of technosphere and/or biosphere processes *outside* the geographic borders of the system under analysis. Lastly, but importantly, the institutional setting and the culture, religion, and normative values of the population (the history and the identity of the society) determine the *desirability* of the metabolic pattern for the society in question.

Thus, in MuSIASEM, the term *metabolic pattern* is understood to be a complex hierarchical set of the processes of production and consumption of multiple types of flows carried out by an integrated set of functional and structural elements made up by funds.

3.2. Formalization: The Accounting Framework

MuSIASEM's accounting framework is based on Georgescu-Roegen's flow-fund model [70] and relational biology [71,72]. According to convention, flows are defined as elements that either disappear ('enter into a process'—inputs) or appear ('come out of it'—outputs, useful products and wastes) in the timeframe of the analytical representation. Fund elements, on the other hand, are elements that enable the metabolic conversion; they preserve their identity throughout the selected time period [70,73]. Thus, the funds define the size of the elements by describing "what the system is made of", whereas the pattern of flow-fund relations defines the level of metabolic activity by describing "what the system does". Funds as well as flows that are aggregated over a defined period are categorized as *extensive* variables; they reflect societal features related to the *size* of the metabolic process. On the other hand, flow-fund ratios are intensive variables (benchmarks) and represent qualitative characteristics of metabolic elements, i.e., the metabolic rate in time (e.g., J of the energy carrier consumed per h of human activity) and metabolic density in space (e.g., kg of crops produced per ha of land).

Note that the resource nexus in MuSIASEM is interpreted in a broad sense. It not only includes *water* and *energy* inputs and *food* outputs, but it also includes a broader set of primary and secondary inputs essential for food production, such as required land uses, ecological services, labor, and fertilizers. The *metabolic profile* of a crop typology (see Figure 2) considers all these nexus attributes, together with the useful output itself (food and useful byproducts), as well as the environmental pressures in terms of primary resource extraction (in relation to supply capacity) and primary flows dumped into the environment (in relation to the sink capacity). The *metabolic processor* is the tool (data processor) that quantifies the entanglement among the nexus elements and the resulting pressures exerted on the environment. As shown in Figure 2, three types of inputs and outputs are linked by the metabolic processor:

1. Secondary inputs derived from the technosphere. These include flows, such as blue water for irrigation, energy inputs, fertilizers, pesticides, and funds, such as land use, labor, and technical capital (machinery).
2. Secondary outputs going into the technosphere. This concerns the produced crop (food supply) and eventual by-products. The supply of this output is the reason (the function) that justifies the existence of the process of production in the first place.
3. Primary inputs and primary outputs exchanged with the biosphere. These define the feasibility of agricultural production in relation to natural constraints (supply and sink capacity) and include both funds, such as green water (derived from rain but made available by the soil) and other 'soil services' (nutrients), and flows, such as the abstraction of blue water from aquifers (this quantity is larger than that used as the input for irrigation because of the losses in distribution), GHG emissions (generated by activities in the technosphere and with land-use changes), and the leakage of nutrients (NPK) and pesticides.

Once the metabolic profiles of relevant crop typologies are defined, the analysis of the agricultural production process can be refined or contextualized across different hierarchical levels of analysis, for instance by considering rainfed versus irrigated cultivation. An example of the system of (dis)aggregation based on relational analysis is shown in Figure 3 and is elaborated on in Section 4. Note that the metabolic processors describing typologies of production (crop typologies) only provide information on the forced relations among inputs and outputs associated with the technical coefficients and characteristics of the crops at the local scale (the identity of the metabolic processors). To be relevant for policy, this information must be scaled up. In the calculation of the overall metabolic profile of the supply system at the regional level (e.g., IARB), we must also include information on other factors, such as the relative share of crop types (e.g., in relation to internal food demand or export revenues), the relative share of typologies of land uses (rainfed versus irrigation), and the economic viability of farming. Obviously, the more we enlarge the scale of analysis (adopting non-equivalent definitions of boundary for the system) the more numerous are the factors relevant to describe the metabolic profile of the agricultural system. With an enlargement of scale, the relevant factors are no longer only of a technical nature but also of a socio-economic (including trade-related issues), demographic, environmental (biophysical constraints prevalent in the transboundary basin), and political nature (e.g., desire for food self-sufficiency). In relation to this challenge, the dual nature of the metabolic processor, describing both the interactions within the technosphere (the upper profile of inputs and outputs) and those with the biosphere (the lower profile of inputs and outputs), permits the simultaneous use of different logics of aggregation in the description of the metabolic profile of a supply system across levels and dimensions.

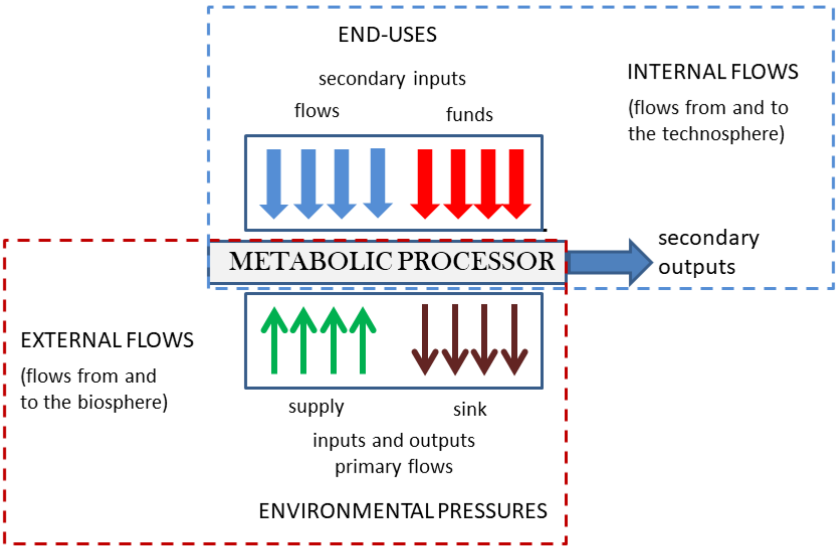

Figure 2. The metabolic processor connecting resource inputs, useful output, and environmental pressures into a metabolic profile.

Indeed, the originality of the present implementation of MuSIASEM lies in the generation of indicators that refer to different boundary definitions of the social–ecological system (several subsystems) while still preserving the coherence of the quantitative representation. This is an important contribution to the metabolic analysis of social-ecological systems. As pointed out by [74]: "a defining feature of system regimes is the relationship between its subsystems, including its social and ecological subsystems at different scales and in different locations". We therefore considered (i) the natural definition of boundaries: the river basin; (ii) the administrative and socio-political definitions of boundaries: Iran and, at the same time at lower levels of analysis, its administrative units and its socio-economic sectors; (iii) several functional (notional) definitions of boundaries: the local agricultural system, typologies of crop production, and rain fed versus irrigated agriculture. As we will explain in the next section (Section 3.3), these different boundary definitions permitted the generation of different indicators of performance in relation to different contexts and that are relevant for the different concerns of the diverse community of stakeholders.

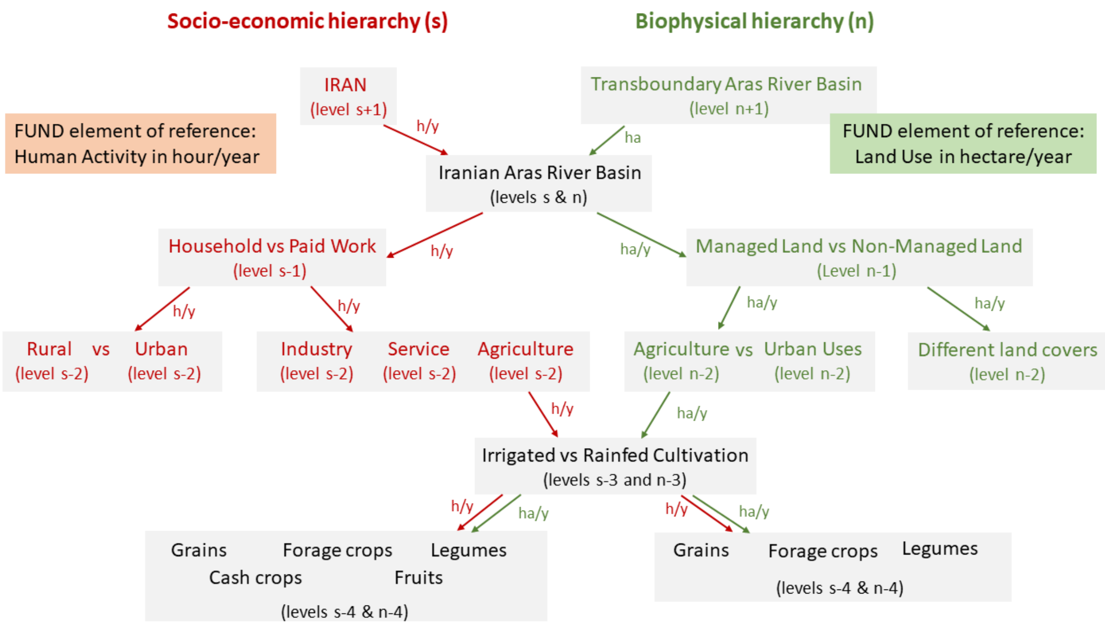

Figure 3. Socio-economic and biophysical (hydro-ecological) contextualization of a river basin in MuSIASEM.

3.3. Formalization of the Set of Relations Used in the Accounting

In semi-arid countries such as Iran, with an actual water usage (96 billion cubic meters (BCM) per year) that exceeds the renewable water and water scarcity thresholds by, respectively, 8% and 80% [56,75], it is important to evaluate nexus security at the river basin scale [76,77]. Hence, in the present study, the focal level was the Iranian ARB region: level *s* within the socio-economic sphere, and level *n* within the biophysical sphere, see Figure 3. These two non-equivalent spheres (*s* and *n* in Figure 3) provided the contexts for evaluating the findings of the analysis carried out at the lower levels. Within the socio-economic sphere, our quantitative analysis was based on flow-fund benchmarks per hour of human activity (considering the secondary inputs and outputs to study attributes relevant for socio-economic analysis), whereas, within the biophysical sphere, the quantitative analysis was based on flow-fund benchmarks per hectare of land use (considering primary inputs and outputs to study attributes relevant for ecological and hydrological analysis).

Within the socio-economic sphere, at level $s - 1$, we distinguished between the subsystem household (residential) and paid work sector, the sizes of which were defined in terms of hours of human activity per year (proportional to population size). Remaining in the socio-economic sphere, we then went down the hierarchy by further subdividing the paid work sector into the agricultural sector, industry, and services and government (level $s - 2$), while the household sector was sub-divided into rural and urban (level $s - 2$).

Moving down to even lower levels within the agricultural sector (and remaining in the sphere of socio-economic analysis), as required for an effective analysis of agricultural production techniques, we considered specific localized processes of crop production, i.e., rainfed versus irrigated cultivation (at levels $n - 3/s - 3$) and crop typologies (at levels $n - 4/s - 4$). We selected the five main crop types cultivated in the region to characterize the agricultural production:

1. Grains (wheat and barley)
2. Legumes
3. Forage crops or 'fodder' (alfalfa)
4. Cash crops (sugar beet)
5. Fruits (apple, grape, and cherry)

In 2006, these crops together occupied 88% of croplands, produced 85% of the overall agricultural added value, and consumed over 85% of the agricultural water flows in the ARB (with grains being the most dominant crop). The distinction between rainfed and irrigated land-use is extremely important in the IARB because the ecological water balance showed that, in 2011, the total water inflow was 13,817 million m^3, while the total consumption was 13,881, indicating a 63.4 million m^3 yearly depletion rate from aquifers [44]. Other factors could be considered in the analysis depending on the interests of the stakeholders. This flexibility in the analysis is a strength of our approach.

At these lower levels (from levels $n - 3/s - 3$ downward), the socio-economic and ecological definitions of levels coincided, and we simultaneously used two sets of benchmarks. That is, we defined for the same set of human activities benchmarks per hour of work and per hectare of land. In this way, we could contextualize the representation of the metabolic pattern in relation to both the socio-economic dimension (the organization of flows per hour in a dendrogram of human activities, relevant for socio-economic analysis) and the hydro-ecological dimension (the organization of flows per hectare in a dendrogram of land uses, relevant for studying environmental constraints) (see Figure 3).

Note that, in principle, the accounting in MuSIASEM must be closed to obtain the sudoku effect, which means that the sum of the extensive variables at any one hierarchical level (i) of the dendrogram must equal the value at the upper level ($I + 1$). In the present study, the accounting was closed to level ($n - 2$). At the lowest levels ($n - 3$ and $n - 4$), we only illustrated the forced relations for the most important crops. In general, to scale the analysis up and maintain closure, the relative contribution of crop types to the total agricultural output of the social-ecological system must be considered.

In line with the conceptual work of [77], we further considered the entire country and the entire transboundary ARB as upper levels for, respectively, socio-economic and hydro-ecological contextualization. As shown in Figure 3, these two types of contextualization operate with a different logic in the definition of the hierarchical levels. Providing closure at the level of the transboundary ARB would require an extension of the analysis (using the logic based on land-use) to also include the parts of the river basin located in Turkey, Armenia, and Azerbaijan (which is beyond the scope of this analysis). In the same way, socio-economic closure at the national level would require including all of Iran in the analysis (using the logic based on human activity), which is ideally conducted based on administrative units. This double logic is required because, in practice, the boundaries of river basins hardly ever coincide with administrative boundaries [77]. Hence, our approach would require a joint and coordinated effort of the different countries that form part of the transboundary river basin.

As mentioned earlier, in MuSIASEM, the selection of funds and flows for inclusion in the accounting is dependent on the scope of the analysis. In this study, we considered the funds land and population and the flows energy, blue water, and agriculture produce (water–energy–food nexus). At the lowest level ($n - 4$), that of crop types, we also considered added value, measured in Iranian rial (IRR), and greenhouse gas emissions (GHG).

Note that the fund population is expressed as available (or allocated/invested) human activity (HA) on a year basis and is measured in h/y (one person has available 8760 h/y). Against this fund element, we assessed *the pace (or rate)* of the metabolism of the flows in relation to the profile of time allocation to the various functional compartments of the society. The fund land is expressed as available or allocated land area on a year basis and is measured in ha. Against this fund, we assessed the *density* of the metabolism of the flows and the resulting impact on hydro-ecological processes.

3.4. Data Sources

Data were derived from multiple sources. Demographic data (2006, 2011, 2016) were from the detailed analyses of the yearly national censuses of Iran [62]. Energy statistics were from the energy balance datasheets (2006, 2011, 2016) issued by the Iranian Ministry of Energy [78]. Water usage statistics were collected from the Iran Water Resource Management company, from the provincial water companies that are directly controlled by the Iran Water and Wastewater Engineering Company, and from the Aras Water sustainability studies 2005, Micro-Irrigation Feasibility study 2003, and the National updating on the Iran Water Holistic Plan [44,79–82].

Energy consumption and GHG for crop types were from life cycle analysis studies conducted either in the IARB or other areas of Iran with similar climatological conditions and cultivation practices [wheat: [83]; barley: [84,85]; alfalfa: [86]; legumes: [87]; fruits: [88,89]. Data on irrigation water, land-uses, hours of labor, and the economic return of crop types were from the 2012 and 2015 series of the Updating Studies on Holistic Plan for Water Management of Iran for the IARB [81,82].

4. Results: The Metabolic Pattern of Agriculture across Hierarchical Levels

To assess the overall metabolic profile of agricultural production in the IARB, we considered: (i) the metabolic profiles of the individual local cultivations (specific crops, specific production techniques); (ii) the relative mix of rainfed and irrigated land uses in the production of the various crops; (iii) the relative contribution of the various crops to the total local production. In addition, we contextualized the observed metabolic pattern of the agricultural production system in the ARB in relation to the socio-economic concerns of the country as a whole (Iran) over the period 2006–2016 and the evolution of environmental constraints in the transboundary river basin.

4.1. The Metabolic Profile of Agriculture in the IARB

We started our analysis bottom up, at the levels $n - 3$ and $n - 4$, by observing the metabolic profiles of the structural elements, i.e., specific local processes of agricultural production in the Iranian ARB, for both irrigated and rainfed farming. Note that grains, legumes, and fodder were cultivated on both irrigated and rainfed land, while cash crops and fruits only on irrigated lands.

In Figure 4, we provided a multi-criteria characterization of the metabolic profiles of these crops per unit of crop output. It was obtained by normalizing the average values of the selected inputs and outputs for each crop, calculated as unitary metabolic processors per ton of crop produced. (The scale in the graph is from -1 to 3, in which 0 is equal to the average of all crops.) The metabolic profiles per hectare of land-use are shown in Figure 5, employing an alternative type of visualization (bar graph). The values of the corresponding unitary metabolic processors are reported in Table 1 (per ton of produce) and Table 2 (per ha of land cultivated). Extensive variables and the relative contribution of these crop types to the total crop mix considered are detailed in Figure 6.

Comparing the irrigated and rainfed cultivation of cereals (wheat, barley), alfalfa, and legumes, we see that dry-land agriculture required significantly more land per ton produced than irrigated agriculture (about three times more for all the crops considered, see Tables 1 and 2 and Figure 4). Expectedly, as rainfed agriculture does not rely on blue water (translating into less pressure on the aquifer) and hence does not require irrigation infrastructure and operation, energy and water input per hectare was significantly lower compared to irrigated land (Figure 5, Table 2). Nonetheless, most of the irrigated crops (cereals, legumes) produced the same amount of added value with less or equal energy use compared to their rainfed counterparts, except for alfalfa. Differences in labor requirements per ton of crop produced between rainfed and irrigated cultivation varied considerably among crop types, with rainfed cereals requiring more labor input per ton, rainfed alfalfa less labor input per ton, and no difference for the legumes (Table 1). Labor requirements per ha were consistently lower for rainfed agriculture compared to irrigated agriculture (Table 2). The nexus trade-offs were clear. The lower consumption of water and energy inputs in rainfed cultivation translated into a lower environmental impact but also a smaller food supply and less economic value of production. The opposite was true for irrigated crop production.

Comparing the cultivation of fruits with that of the other irrigated crops considered (the current mix of cereals, alfalfa, sugar beets, and legumes), we found that (per ton of produce) the fruits cultivated in the IARB (current mix of apple, grapes, and cherry) consumed on average 53% less water and 47% less energy, occupied 52% less land, but generated two times more net added value than the mix of other irrigated crops. Irrigated legumes (mostly lentils) in particular required 14 times more land, 6 times more energy, 10 times more water, and 8 times more labor hours per ton of produce compared to apples (the most important fruit in terms of land use and output), while producing only 50% more added value. Despite their relatively small share to the overall agricultural output in the IARB (0.22% for irrigated legumes and 0.88% for rainfed legumes), these data are nonetheless important to keep in mind, as legumes are an important staple food in Iran, being linked to its cultural identity.

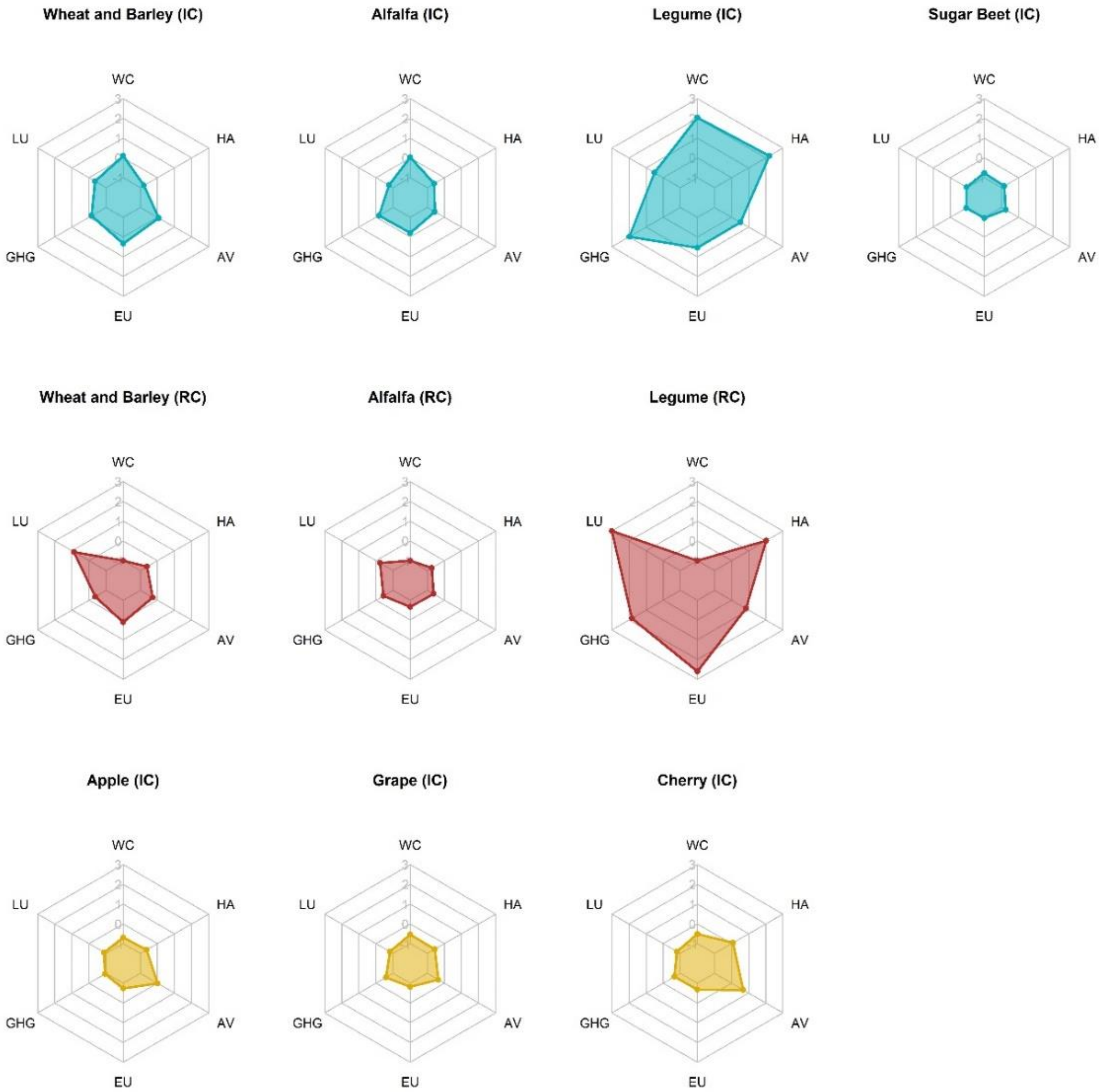

Figure 4. Multi-criteria characterization of the performance (per ton crop output) of the main crop typologies in the IARB. The abbreviations IC and RC in the graph titles stand for irrigated and rainfed cultivation, respectively. The abbreviations WC, HA, AV, EU, GHG, and LU on the spider diagram axes stand for, respectively, water consumption, human activity, added value, energy use, GHG emission, and land use. Data refer to 2006 (data source: IWWA [80]).

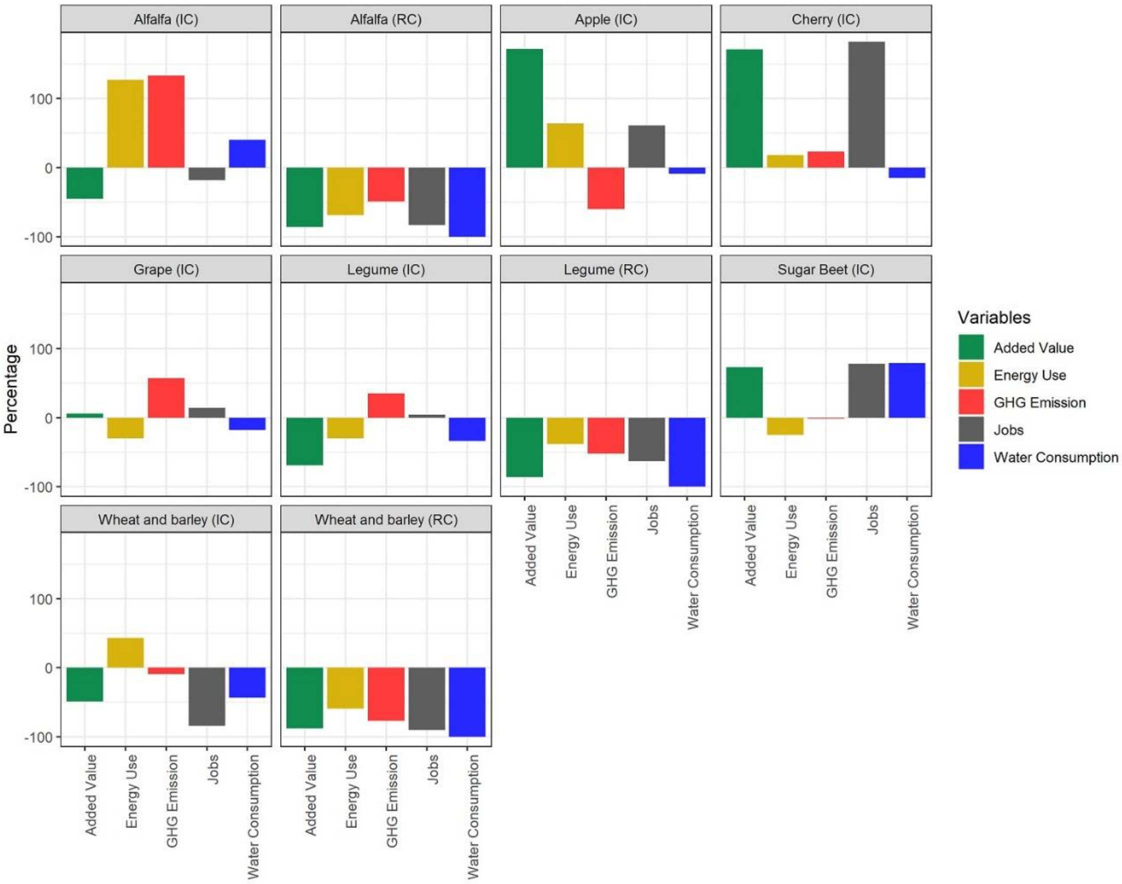

Figure 5. Multi-criteria characterization of the performance (per hectare of cultivation) of the main crop typologies in the Iranian Aras River Basin. The abbreviations IC and RC in the graph titles stand for irrigated and rainfed cultivation, respectively. Data refer to the year 2006. Data source: [80].

Table 1. Metabolic characteristics per unit of crop output (ton) for the selected crop types (irrigated and rainfed).

	Irrigated							Rainfed		
	Cereals	**Alfalfa**	**Sugar Beet**	**Legume**	**Apple**	**Grape**	**Cherry**	**Cereals**	**Alfalfa**	**Legumes**
Water use (m^3/t)	1533	1429	327	4210	431	642	679	0	0	0
Land use (m^2/t)	3786	1424	256	8926	664	1090	1116	11,139	4515	23,718
GHG emission (kg CO_2eq/t)	1023	988	76	3594	79	509	410	769	682	3414
Energy use (GJ/t)	25.45	15.20	0.90	29.43	5.11	3.60	6.16	21.31	6.51	68.81
Added value (10^6 IRR/t)	1.56	0.63	0.36	2.20	1.45	0.93	2.43	1.05	0.52	2.66
Added value (US$/t) *	169.25	68.87	38.74	239.15	158.01	100.75	264.45	114.18	56.45	289.57
Labor (h/t)	9.5	18.0	7.0	142.7	16.5	19.1	48.4	17.6	11.7	135.0

* Based on the exchange rate for the reference year 2006 [90].

Table 2. Metabolic characteristics per unit of land use (ha) as well as labor productivity (IRR/h) for the selected crop types (irrigated and rainfed).

	Irrigated							Rainfed		
	Cereals	**Alfalfa**	**Sugar Beet**	**Legume**	**Apple**	**Grape**	**Cherry**	**Cereals**	**Alfalfa**	**Legume**
Yield (t/ha)	2.64	7.02	39.10	1.12	15.06	9.18	8.96	0.90	2.21	0.42
Water use (10^3 m^3/ha)	4.05	10.04	12.78	4.72	6.49	5.89	6.09	0	0	0
Energy use (GJ/ha)	67.22	106.7	35.03	32.97	77.00	33.00	55.21	19.13	14.42	29.01
GHG (kg CO_2eq/ha)	2.70	6.94	2.96	4.03	1.20	4.67	3.68	0.69	1.51	1.44
Added value (10^6 IRR/ha)	4.11	4.45	13.93	2.46	21.90	8.50	21.80	0.94	1.15	1.12
Added value (US$/ha) *	446	483	1514	267	2381	924	2370	102	125	122
Labor (h/ha)	25.1	126.2	273.5	159.9	247.8	174.8	434.0	15.8	25.9	56.9
Labor productivity (10^3 IRR/h)	164	35	51	15	88	49	50	60	44	20
Labor productivity (US$/h) *	17.79	3.83	5.54	1.68	9.61	5.29	5.46	6.49	4.83	2.14

* Based on the exchange rate for the reference year 2006 [90].

Sugar beets (only irrigated cultivation in the area) require less inputs (land, energy water) per ton produced than any of the other crops cultivated in the area (see Figure 4 and Table 1). However, given the high yield, on a per hectare basis, the input requirements of sugar beets were less favorable, notably for water and labor (Figure 5, Table 2). Sugar beets have a relatively low added value per ton produced (Table 1) but not per hectare cultivated or per hour of labor (Table 2) and hence are an important cash crop in the area. Indeed, given the favorably climatological conditions (relatively cold), the West Azerbaijan Province has seen an important increase in sugar beet production in recent years and is currently among the biggest producers of the crop in Iran.

These are examples of the type of trade-off analysis among nexus attributes that can be conducted with "what if" scenarios for the mix of crop production in agricultural sectors operating with a given river basin. It is also possible to scale up this analysis of trade-offs to the national level by considering the metabolic processors of other river basins in Iran and tailoring the analysis to national concerns.

4.2. The Nexus across Scales: Visualization of Water–Energy–Food Linkages

For the information in Figures 4 and 5 (and Tables 1 and 2) to be useful to inform policy, it is essential to organize all these inputs in a multi-level and multi-dimensional information space in a way that allows the simultaneous use of qualitative (intensive variables) and quantitative (extensive variables) information. Indeed, the question of how to handle the analysis of different concerns and different dimensions of performance (different nexus attributes) of the agricultural sector is a major problem for the multi-level governance of the nexus. In Figure 6, we show a way to solve this problem. In this dendrogram, we used top-down data from available statistics combined with the bottom-up data on the metabolic profiles of crop and cultivation typologies to generate a multilevel integrated analysis of the metabolic pattern of the agricultural sector in the IARB.

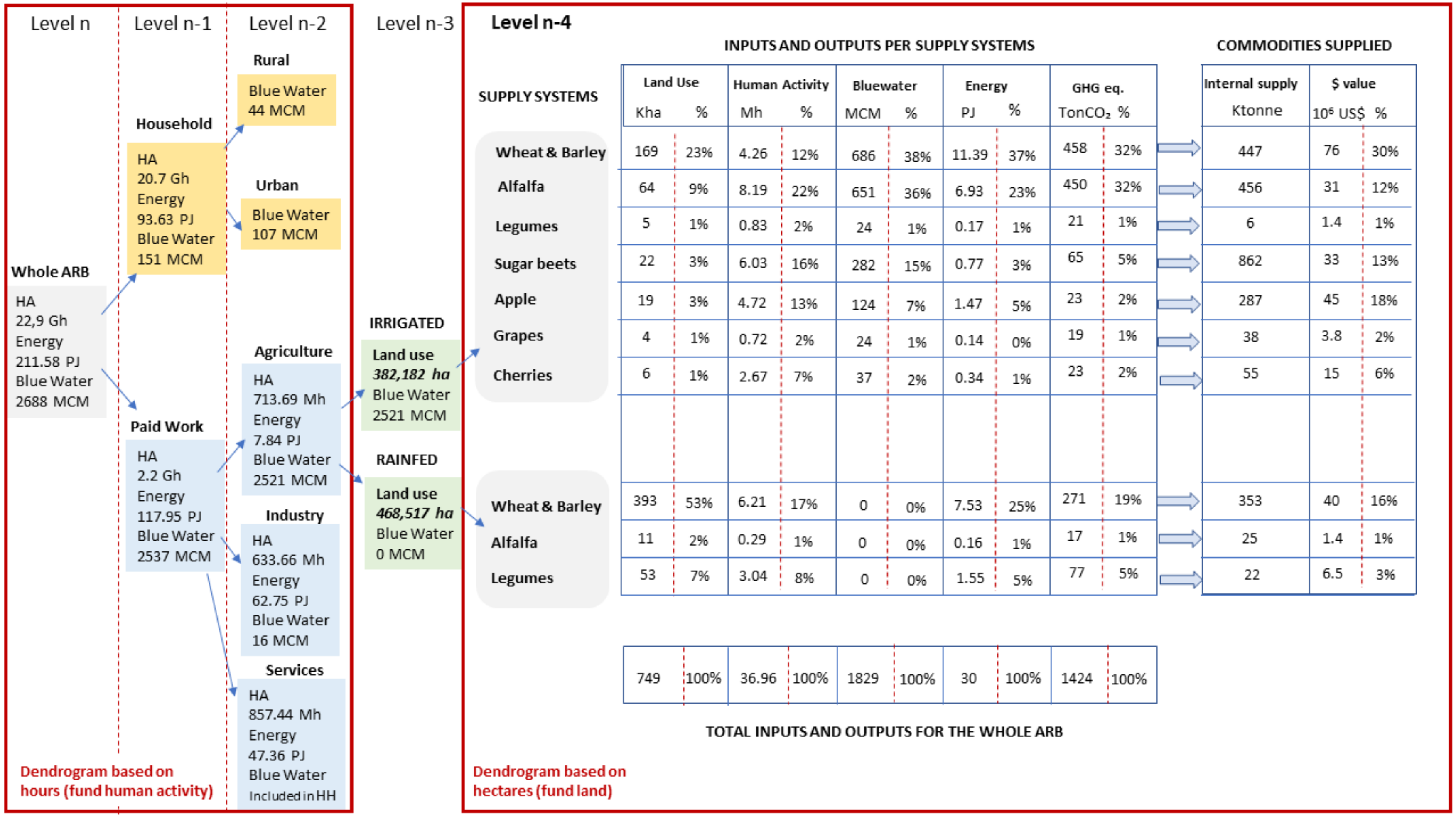

Figure 6. A multilevel, integrated representation of the metabolic pattern of the agricultural sector in the IARB (extensive variables). Abbreviations: HA = human activity; Gh = giga (10^9) h; Mh = mega (10^6) h; MCM = million cubic meters (10^6 m^3).

On the left side of Figure 6, we describe the metabolic pattern of the overall IARB and its main socio-economic sectors (lower-level compartments n, $n-1$, and $n-2$) using the fund element human activity (in hours) to assess compartment size (as is typical in MuSIASEM). The left side of the dendrogram thus provides a contextualization of the agricultural activities in relation to the socio-economic characteristics of Iran. However, going down to level $n-3$, on the right side of the dendrogram, when describing the metabolic pattern within the agricultural compartment, the logic of the accounting was changed. To focus better on the biophysical limits and potential environmental impact, the fund element used to measure the relative size of the various functional components (i.e., the different supply systems of crop commodities) from level $n-3$ downward was land use (measured in ha). As a result, the right side of the figure shows a matrix of which the horizontal vectors (rows) can be used to generate mutual information (i.e., the "sudoku effect" [91]). In this way, one can aggregate the metabolic profiles of crop and cultivation technologies across different levels of analysis (local production processes, supply systems operating in specific areas, and eventually to the whole agricultural sector of Iran). Note that the accounting of the different crop types illustrated in Figure 6 observed closure at the level $n-4$ (e.g., the land in production for apple, grape, and cherry adds up to the total land of the category "fruits" in the dendrogram).

This type of multilevel integrated representation is helpful in addressing policy-relevant issues, such as:

1. Checking how much of the internal food demand (commodity by commodity) of either the local IARB or the entire country is supplied by the local supply system. In this way, it is possible to obtain an indication about the importance of the various crop cultivations in the area studied for the internal food metabolism of Iran (food sovereignty).
2. Assessing the input requirements (land, water, energy, labor) inside the system to obtain the actual food supply. This assessment is not only important to identify the supply systems that are more input intensive (per hectare) and create higher environmental pressure, but also to assess the technical and economic viability (labor productivity) of the production systems for the farmers operating in the area.
3. Comparing the economic advantages and ecological impacts of the various crops cultivated. This information is relevant for an informed discussion about the relative advantages of trade versus food sovereignty. For example, in certain areas, it may be advisable to produce cash crops with high added value and low environmental pressure (notably on water resources) to obtain earnings for importing food crops that may be produced cheaper and more environmentally friendly (less water demand) elsewhere. Obviously, to extend the analysis of trade-offs to the level of the whole country, other agricultural areas of Iran should be analyzed in the same way as illustrated for the IARB (to cover the whole Iranian agricultural sector).

4.3. Contextualization of Food Production in the IARB

At the level of the Iranian ARB (level n), energy (EMR) and water intensity (WMR) increased from 9.24 to 11.04 MJ/h (19% increase) and 117 to 157 L/h (34% increase), respectively, over the 10-year period 2006–2016 (see Table A1 in the Appendix A and Figure 7). It being the most limiting factor, in Figure 7, we detail water use in the IARB for levels n, $n-1$, and $n-2$. Note that we considered only blue water, i.e., the water appropriated and controlled by humans for irrigation, industrial, and domestic uses. Most of the blue water consumption is associated with agricultural activities (94%, 92%, and 90% for years 2006, 2011, and 2016, respectively). Of the water withdrawal in the agricultural sector, 68% was obtained from surface waters and 32% from underground waters (Figure 7). These percentages remained constant over the period considered. Note, however, that official water withdrawal numbers may be underestimated, as [76] observed that the number of 650 thousand wells extracting water from aquifers in Iran had illegally increased by 1200% over a period of 40 years.

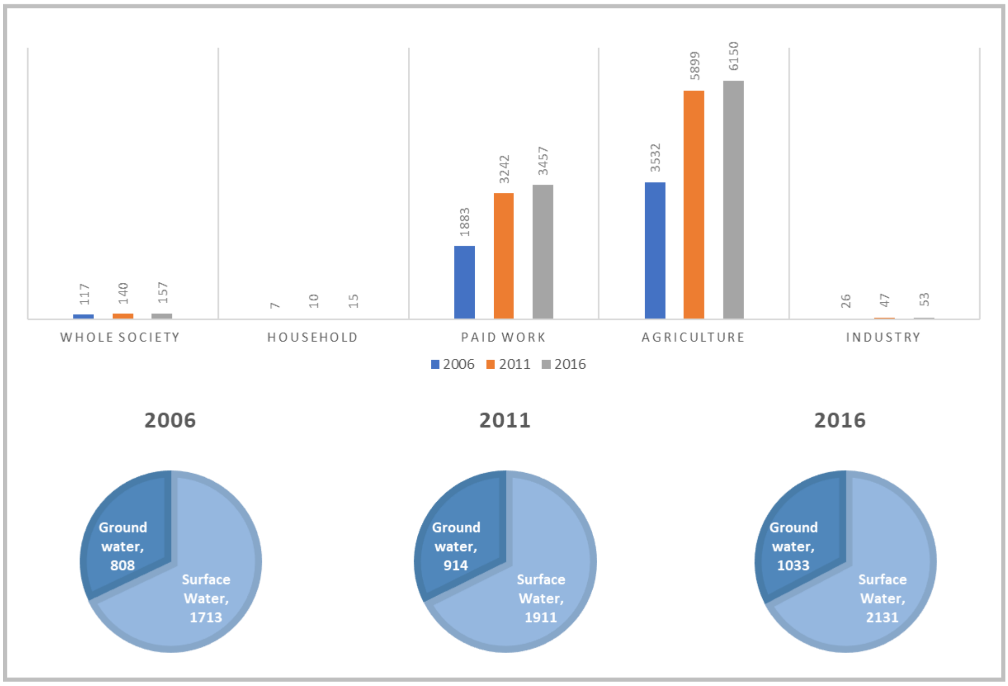

Figure 7. Water use intensity (water metabolic rate [WMR] in L/h) in the IARB, at levels n (whole system), n-1 (paid work versus household; note that the service sector is included with the household sector and not with paid work for lack of disaggregated data), and n-2 (agriculture and industry) (upper part) and the yearly water withdrawal rate (in MCM) by the agricultural sector from surface water and groundwater resources in the IARB (lower part).

In the period considered, the industrial sector consumed less than 1% of the total IARB water inputs. However, water use per hour of labor in the industrial sector followed the same trend as observed in the agricultural sector: the water metabolic rate in the industrial sector doubled during the period of 2006–2016 (from 26 to 53 L/h, see Figure 7), while the human activity invested in the industrial sector decreased by 35%. Driven by the changes taking place both in the agricultural and industrial sectors, the paid work sector saw a significant increase of more than 80% in its water metabolic rate in this same period, from 1883 to 3457 L/h of human activity. A similar increase (of more than 50%) was also observed for the energy intensity of the paid work sector; the energy metabolic rate increased from 53.5 MJ/h to 97.1 MJ/h (Table A1). These increases were coupled with a 30% reduction in human activity allocated to the paid work sector (HA_{PW}, see Table A1). Indeed, being a predominantly rural area, the population in the IARB decreased from 2.62 million in 2006 to 2.54 million in 2016 (3%). However, the economically active population, as measured by the human time allocated to the paid work sector, decreased with as much as 30%.

While water resources are critical in the IARB, the region is relatively suitable for agriculture compared to the more arid regions in the southern part of Iran (e.g., Sistan, Khuzestan, or Khurasan provinces); hence, further agricultural expansion in the IARB is almost inevitable given the government's policy of food self-sufficiency. The expansion of agricultural land in the IARB faces several different but interrelated types of constraints that could be modulated to some extent through the careful choice of cropping patterns and production techniques:

1. Moving into lower-quality lands (the best locations already being exploited) tends to reduce the flow-fund benchmark "crop produced per hectare" and tends to increase the flow-fund benchmark "inputs required per hectare". The effect on both benchmarks can be attenuated by the choice of suitable cropping patterns and production (incl. harvesting) techniques.

2. Water constraints: An increase in water consumption (extensive variable) is due to a combination of an increase in the hectares of the fund "land use producing crops" (extensive variable) and a potential increase in the flow-fund benchmark "water required per hectare". The latter factor can be modulated by the choice of cropping pattern and improved irrigation techniques. However, to date, the implementation of practices for increasing water efficiency have not led to water savings due to a lack of controlling and monitoring measures [92]. Any increase in water consumption and agricultural water pollution (fertilizers, pesticides) in the IARB will have implications for the agricultural production downstream in neighboring Azerbaijan.
3. Labor constraints: Iran has seen a contraction of the agricultural labor force during the past two decades as a result of its progressive urbanization (over the period 2006–2016, the share of agriculture in total paid work hours shrunk from 23% to 18%, see Table A1). Lack of agricultural labor may therefore favor cropping patterns that require less labor-intensive but more energy- and water-intensive (capitalization) production techniques. While energy availability is not a problem in Iran, this may have negative consequences on the consumption of water and GHG emission in the agricultural sector.

Relating the metabolic profiles of the crop typologies to the socio-economic and environmental context shows the existence of unavoidable nexus trade-offs associated with different policy choices. The very nature of these trade-offs entails that pros and cons cannot be properly weighed (using optimizing techniques) because of the unavoidable presence of uncertainty in the analysis and the legitimate but contrasting perceptions of priorities when considering different boundaries and concerns. For example, policies that encourage financial investments in modern agricultural technology could help the IARB (and Iran) to become a key producer (exporter) of fruits. This solution could also benefit individual farmers' by increasing income. However, when looking at the overall drain of labor in the agricultural sector, a specialization in fruit production for export could imply a shortage of work hours to produce staple foods, a move that could jeopardize national food security. In the same way, given the metabolic profile of legumes, a progressive elimination of this crop from the mix of agricultural production in the IARB (and from areas with similar water shortages) could benefit the hydrological performance of its agricultural sector. However, legumes play a key role in the preparation of traditional dishes (preservation of the cultural identity) and the local cultivation allows the preservation of local varieties, soil health, and rural traditions. How important is it for Iran to avoid reliance on imports for this traditional food? What alternative protein sources could be used? At which level is such a decision to be made?

5. Discussion: Strength and Shortcomings of the Approach and Future Research Needs

This study represents the first formalization of MuSIASEM at the river basin level. It considered several definitions of boundary based on the adoption of different logics: the natural boundary determined by orographic conditions (the area of the river basin defined across different countries), the socio-political (national) boundary (e.g., Iran), lower administrative boundaries (the Iranian provinces of the IARB), and functional boundaries to identify the metabolic characteristics of "boundary objects" such as the agricultural sector, agricultural subsectors (rainfed versus irrigated agriculture), and specific crop typologies. We have shown that the proposed accounting method can handle the multi-scalar relationships of the nexus between water, energy, and food systems, a key research need identified in the nexus literature, thereby integrating key information referring to the different agronomic, socio-political, and ecological contexts.

Our approach did not have the goal of identifying "the best" configuration of land and labor that would be valid for all the levels of analysis considered, nor did it pretend to indicate "optimal solutions" within specific levels of analysis. The results of our multi-level, multi-dimensional analysis were not intended as the final input for a decision support tool but to provide a flexible information space for an informed deliberation about the (unavoidable) trade-offs of nexus-related policies. We prefer to call it a deliberation support system.

Note also that the results we presented for the IARB have the only scope of illustrating the potentiality and shortcomings of the proposed approach. In particular, the diagnostic analysis illustrated in Figure 6 is a static one; the choice of indicators (flow/fund rations) was made by the authors and was not tailored to the different concerns existing among the many different social actors in the transboundary river basin (e.g., it would be important to also include fertilizer and pesticide use). It has been guided exclusively by the growing problem of water scarcity and data availability.

Indeed, an important limitation of our approach was data availability and compatibility. Available socio-economic statistics in Iran (and most other countries) are mostly aggregated into administrative units (e.g., municipalities, provinces), while hydrological data are organized at the river basin level. This required considerable work to approximate socio-economic variables for the river basin level. To fully implement the analysis and scale up the analysis to the river basin level, it is essential that the same exercise performed in this paper would also be conducted for the neighboring countries Turkey, Armenia, and Azerbaijan. This may seem challenging, but, being a complex issue, the regulation of water use in a transboundary basin requires a rich information space that can address the concerns of the various social actors.

The usefulness of our societal metabolism approach depends on the quality of the pre-analytical choices (i.e., the nexus attributes used to anticipate the possible changes in the existing metabolic state). These choices therefore should be made within participatory processes that involve all relevant social actors. In fact, it makes a difference if we discuss about how to protect the traditions and the food sovereignty of Iran; how to improve the standard of living of rural villagers; how to preserve the water resources downstream in Azerbaijan; or how to prevent the deterioration of water quality in the Kura-Aras River Basin (an important problem, according to [39]). Such a 'co-production' of the analysis with a variety of social actors would guarantee a more robust identification of relevant nexus attributes and a more useful selection of criteria to address the concerns expressed in sustainability discussions. Different choices of problem structuring will translate into different multi-criteria characterizations. In this regard, the enlargement of perspective offered by MuSIASEM is important to complement the generally dominant economic narrative exclusively concerned with generating more added value in economic activities. MuSIASEM can also be of support in solving multi-attribute decision making problems in water resource management, for example, by supporting the procedure of the Transboundary River Basin Nexus Approach (TRBNA) [93] or assessing water resource allocation scenarios [94,95]).

6. Conclusions

This study illustrated the potential of MuSIASEM in providing useful information for the multi-level governance of the resource nexus at the level of the river basin. The MuSIASEM accounting framework integrates social, economic, technical, and ecological criteria in a coherent framework of analysis. Indeed, the resource nexus in MuSIASEM is interpreted in a broad sense. It not only includes water and energy inputs, but it also includes a broader set of primary and secondary inputs essential for food production. These inputs, together with the useful output itself (food and useful byproducts) as well as the environmental pressures (unintended, mostly detrimental outputs), define the metabolic profile of crop types. Using relational analysis, MuSIASEM analyzed the metabolic pattern of social–ecological systems by tracking the characteristics of their structural and functional elements within *and across* hierarchical levels of analysis. By combining top-down and bottom-up information, MuSIASEM contextualized the problem structuring for specific regions and in relation to specific concerns. Our study has made evident that, in order to carry out an informed discussion over the pros and cons of agricultural policy, we must first of all be capable of providing a holistic view of the different aspects associated with the water–energy–food–environment nexus in relation to their consequences felt both in the socio-economic sphere (from the local to the national administrative level) and in the ecological sphere (i.e., the ecosystems embedding the agricultural sector; in this case, the transboundary river basin). The approach has thus addressed key nexus research needs identified in the literature.

In practical terms, we characterized the performance of the agricultural sector of the Iranian ARB for relevant typologies of crop production (cereals, sugar beets, fruits, legumes, and fodder) using the concept of metabolic profiles. Using metabolic benchmarks per ton of crop produced, per hectare of land use, and per hour of labor, we linked the agricultural activities in the region to (i) the socio-economic context at the local and national level, (ii) the hydro-ecological context of the transboundary Aras river basin, and (iii) local farming practices (rainfed versus irrigated agriculture). We illustrated the potential and usefulness of MuSIASEM for deliberation support with regard to local agricultural land-uses (considering available technological options) in relation to the drivers of change at the national level (Iran), such as the strive for food sovereignty and the progressive urbanization of the country and the rapidly increasing biophysical (water) constraints experienced in the transboundary river basin.

While our study was primarily aimed at illustrating the methodology, some conclusions can be drawn from our metabolic analysis of the agricultural sector in the Iranian ARB region. The selected crop types perform differently depending on the selected attribute of performance. There is no good or poor crop, but a different "usefulness" depending on the context and criterion considered. For example, expanding the cultivation of crops that provide a higher economic return for the farmers (and possibly foreign currency through export), such as fruits and sugar beets, may reduce the food security of the country (reducing internal supply of cereals and fodder) and endanger the cultivation of traditional crops and crop varieties (e.g., legumes). In the same way, crop production techniques (e.g., irrigation and use of fertilizers) that have a better economic performance may translate into an excessive environmental pressure on the available resources (critical water resources, GHG emission, water pollution) with potential transboundary consequences. Perhaps these are not exciting findings, but what is new is the possibility to explore different "what if" scenarios at different levels of analysis while generating integrated sets of indicators, allowing a multi-criteria evaluation of the resulting performance.

Our study offers the possibility for academics and governmental and non-governmental organizations to embrace the complexity of the nexus and to explore new methods and approaches to study the sustainability of economic development by considering the entanglement across different relevant aspects and concerns. The material presented does not pretend to be a source of robust evidence, but a preliminary exploration of a method for characterizing the entanglement over nexus attributes relevant for the sustainability of the Iranian Aras River Basin. To effectively guide nexus governance in the region, a co-production of the analysis with social actors as well as more recent and complete data sets would be essential.

Author Contributions: A.T. designed the study, collected the data, performed the analysis, and contributed to the writing of the paper. S.G.F.B. contributed to the interpretation of the results and the writing of the paper. M.G. guided the MuSIASEM analysis and presentation of results and contributed to the writing of the paper. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1 shows the internal energy end-use matrix for Iran and the Iranian Aras River Basin for the years 2006, 2011, and 2016. It describes the overall use of energy (i.e., energy throughput (ET) in PJ/y; an extensive variable) as well as the energy metabolic rate ($EMR_i = ET_i/HA_i$ in MJ/h, a flow/fund ratio, an intensive variable) of the different socio-economic subsectors. It was constructed as detailed in Sections 3.2 and 3.3, with human activity as the fund and energy as the flow. This table supports the text in Sections 2.2 and 4.3.

Figures A1 and A2 visualize the agricultural trends described in Section 2.2.

Table A1. The internal energy end-use matrix of IRAN and the Iranian Aras River Basin for the years 2006, 2011, and 2016. Data are elaborated from [44,62,65,80]. Abbreviations: HA: human activity; Mh: Mega hours (10^6 h); EMR: energy metabolic rate; ET: energy throughput.

IRAN										
Hierarchical Level		**2006**			**2011**			**2016**		
		HA (Mh)	**EMR (MJ/h)**	**ET (PJ)**	**HA (Mh)**	**EMR (MJ/h)**	**ET (PJ)**	**HA (Mh)**	**EMR (MJ/h)**	**ET (PJ)**
Level n	Whole Society	617,543	14.38	8883	658,311	16.59	10,921	700,154	17.71	12,401
Level $n-1$	Household	574,154	4.40	2524	614,772	4.38	2693	652,114	4.69	3056
	Paid work	43,389	73.28	3179	43,539	94.50	4114	48,040	97.26	4673
Level $n-2$	Agriculture	10,066	21.00	211	8098	32.42	263	8647	35.30	305
	Industry	13,754	122.97	1691	14,542	174.02	2531	15,325	192.46	2949
	Service	19,569	65.24	1277	20,899	63.22	1321	24,068	58.91	1418
IARB										
Hierarchical Level		2006			2011			2016		
		HA (Mh)	EMR (MJ/h)	ET (PJ)	HA (Mh)	EMR (MJ/h)	ET (PJ)	HA (Mh)	EMR (MJ/h)	ET (PJ)
Level n	Whole Society	22,910	9.24	211.58	21,822	10.34	225.64	22,211	11.04	245.18
Level $n-1$	Household	20,705	4.52	93.63	20,278	4.40	89.26	20,684	4.69	96.95
	Paid work	2205	53.49	117.95	1544	88.33	136.38	1527	97.07	148.23
Level $n-2$	Agriculture	713.69	10.99	7.84	478.82	18.17	8.70	514.12	18.83	9.68
	Industry	633.66	99.02	62.75	398.22	210.65	83.88	407.08	229.83	93.56
	Service	857.44	55.24	47.36	667.04	65.66	43.80	605.28	74.32	44.98

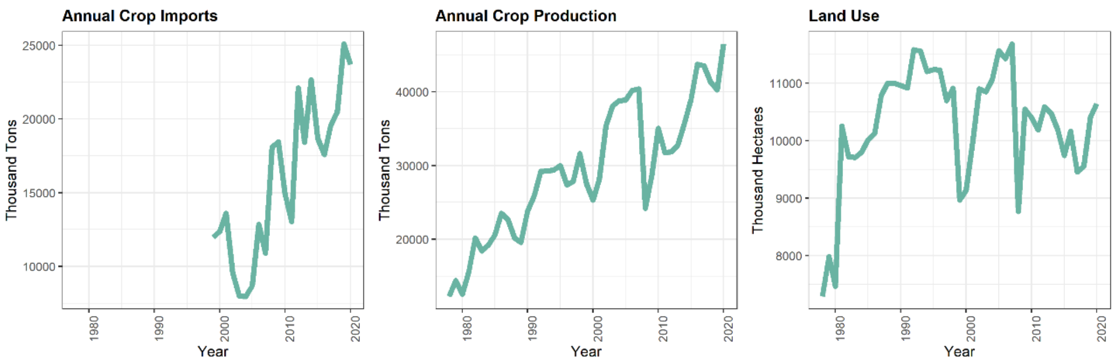

Figure A1. Trend in agricultural imports (in 10^3 t), total domestic agricultural production (in 10^3 t), and agricultural land use (in 10^3 ha), Iran, 1980–2020.

Figure A2. Trends in the annual (domestic) production of relevant crops (in 10^3 t), Iran, 1980–2020.

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