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Landscape social-metabolism in food-energy-water systems: Agricultural transformation of the Upper Snake River Basin

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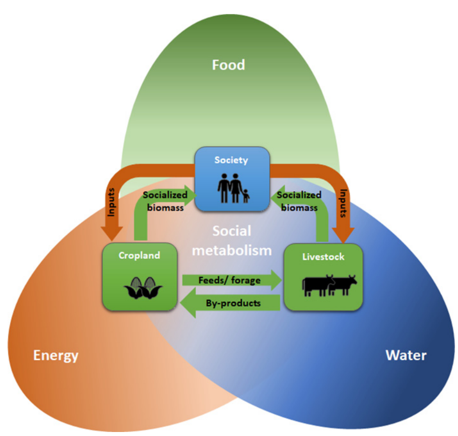
HIGHLIGHTS

- Applies the social metabolism approach for understanding the nexus of FEW systems
- Incorporates in the biomass flow accounting the reinvestment and reuse of manure
- Underscores reuse/reinvestment of by-products from livestock as part of land use
- Livestock production is more efficient in reinvesting biomass than crop production.

GRAPHICAL ABSTRACT



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ABSTRACT

This paper applies a social metabolism framework and energy flow analysis for evaluating agroecosystem and land use transitions in food-energy-water systems using the Upper Snake River Basin (USBR), Idaho, USA as a case-study. The study area is one of the primary agricultural regions of the State of Idaho. Dairy products are the primary agricultural outputs of the region; therefore, we modified a biomass accounting framework to explicitly incorporate the role of manure in the agroecosystem. Despite the increase of cropland between 2002 and 2012 in the basin, a decrease in energy input was observed for crop production. An increase in the industrial energy inputs for dairy production, on the other hand, showed that the basin is a clear example of a metabolic industrialized farm system – an example of land use intensification. We compare the energy return on investments (EROIs) as an indicator of agroecosystem transition for both crop and dairy production during the period 2002 to 2012. Contrary to our expectations, the analysis suggests that livestock production is a relatively energy efficient process in land management in the basin. This is due to the reuse of nutrient by-products from livestock as well as the refuse and residues from crop farming. At the same time, the findings provide insights on the percentage of manure to be reinvested as compost that would improve energy production efficiency. However, the reuse of

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manure, as it is managed in the basin, may have a negative implication on the nutrient balance of the agroecosystem that needs further investigation. Nonetheless, there is market potential for the reuse and reinvestment of biomass to make energy production in the basin more efficient.

1. Introduction

The Food-Energy-Water (FEW) system is a concept widely used for understanding the interactions or nexus of food, energy, and water systems. Its core idea is to mitigate trade-offs, build synergies, and improve resource utilization efficiency and sustainability in the context of climate change and resource shortages (Kliskey et al., 2017; Kurian, 2017; Ringler et al., 2013). Nexus approaches to FEW research highlight the importance of integrated modeling and explore ways in which component subsystem models can be designed to yield interoperable outputs (Bazilian et al., 2011; Si et al., 2019). They have also been used to explore resource management in systems where tradeoffs have a significant impact on stakeholders (Ringler et al., 2013). They are relevant for meeting the Sustainable Development Goals (Biggs et al., 2015; Griggs et al., 2017) by assisting in avoiding competition over resources and adverse environmental impacts. Related approaches include the water-soil-waste (WSW) nexus that considers contexts in which waste is explicitly considered as a resource (Schwärzel, 2014). However, these nexus approaches continue to fall short in terms of meeting expectations due to factors such as the paucity of tools for modeling its interconnections (Dargin et al., 2019).

Social metabolism (SM) theory, on the other hand, is a means to conceptualize the energy inputs, internal flows, and outputs of a system, and is thus well-suited to mapping the food (including nutrient inputs and waste streams), energy, and water flows in a FEW system (Haberl, 2001a, 2001b). SM is defined as the set of all anthropogenic flows, stocks, and transformations of physical resources and their respective dynamics assembled in a system's context (Ayres and Simonis, 1994; Fischer-Kowalski and Haberl, 1997). The application of SM to analyze land use change in agroecosystems is increasingly common in efforts to understand and address the sustainability of resource use and development (Guzmán and González de Molina, 2015; Haberl et al., 2011; Kušková, 2013; Plutzar et al., 2016; Xie et al., 2014). It is particularly useful for addressing processes of change in land use intensity (denoting changes in the levels of socioeconomic inputs such as labor, resources, energy, or capital; (Erb, 2012)). Its analysis provides pertinent information for understanding the types of relationship that a society has established with the environment and the context in which land is used and the land's capacity to meet society's needs (Cussó et al., 2006). However, energy analysis as part of FEWs studies has typically focused on energy production, that is power generation and its linkages, including transmission, to food and water systems (Bazilian et al., 2011; Hang et al., 2016). SM approaches suggest a common currency approach for assessing FEW systems, since water and hydrological processes can also be measured in terms of energy stocks and flows (Fischer-Kowalski and Rotmans, 2009; Martinez-Hernandez et al., 2017; Mohtar and Daher, 2016). Food production and nutrient cycling can also be expressed in terms of embodied energy and energy flows into, within, and out of a system (Martinez-Alier, 2009). There have been few, if any, studies to date that have applied the SM framework for characterizing and assessing FEW systems. The overall aim of this paper is to provide an empirical example of an SM approach for understanding the FEW systems in Southern Idaho, as a region economically dominated by agricultural production. Our study builds on the premise that an increase in inputs (i.e., intensifying the use of labor or resources) results in increased outputs (i.e., yields or wastes). Our objective is to provide insights into the temporal dynamics of SM and the metabolic regime of the Upper Snake River Basin (USRB) by estimating the energy return on investment (EROI) as a measure of the efficiency of energy production; and to characterize the FEW systems using empirical changes in land use, biomass production, nutrient flow, and energy consumption in the USRB between 2002 and 2012.

We will first describe the conceptual framework of SM in the context of agroecosystems. We then introduce manure as another type of biomass and establish research questions for its role in an SM approach. We provide a description of the study area in the next section as well as the method of analysis to quantity the EROI and modifications of the equations to explicitly incorporate the role of manure and by-products. We end with analysis, discussion, and conclusions.

1.1. Social metabolism (SM) in agroecosystems

Agriculture is becoming increasingly energy-intensive through increased use of fertilizers, a shift towards using complex machinery rather than human labor, and groundwater pumping (as well as post-harvest processing and transportation). In the US, the approximate ratio is 1000 l of fossil energy (oil) per ha (Capareda, 2013). Fodder production in places like the Magic Valley, Idaho has increased to support increasing dairy production. At the same time, animal manure represents one of the most underutilized fertilizer resources in the US (Capareda, 2013). Livestock production is often considered the least energy-efficient process in land management (Gingrich et al., 2018). However, one way to frame the basic challenge of farming is to produce the maximum flow of energy output to meet human needs while minimizing energy inputs and ecological disturbance, and livestock can be critical for ensuring the sustainable nature of agroecosystems and associated ecosystem services (Tello et al., 2015).

The theory of SM has connections to the disciplines of environmental sociology, industrial ecology, and theoretical ecology. The idea that humans extract resources and energy from the environment and are connected "metabolically" is at least as old as Karl Marx's description of *Stoffwechsel* (Foster, 1999), and it has become a central pillar of sociological studies of human-environmental interactions. Energy flows have been used to describe systems as disparate as forests and manufacturing organizations, and ecological principles have been used to shape the mapping and thinking about such systems (Ehrenfeld, 1997). The theory of metabolic ecology developed to track energy flows, stocks, and deficits from the individual to the ecosystem and enables the development of generalizable mathematical and statistical models from conceptual models of energy flows in the environment (Brown et al., 2004). Metabolic ecology is utilized to connect individual organisms to populations, communities, and ecosystems in a coherent and scalable manner (Marquet et al., 2004). Socio-metabolism is a systems approach that combines these different theoretical and mathematical frameworks to connect humans, technology, and the environment across scales.

There are numerous methods and modeling approaches for analyzing socio-metabolic transitions. Among the most widely used methods are: input-output analysis (Miller and Blair, 2009); material flow accounting (MEFA) (Fischer-Kowalski et al., 2011); life-cycle assessment (Rebitzer et al., 2004); hybrid methods (Nakamura and Kondo, 2006); and the human appropriation of net primary production/productivity (HANPP) (Haberl et al., 2007; Krausmann et al., 2003). HANPP is widely used for understanding SM and is considered a point of connection between SM and land use theories (Haberl et al., 2007; Krausmann et al., 2003). Like many SM methods, HANPP has been predominantly used at larger scales (national to global). It is calculated by considering the net primary productivity (NPP) for (hypothetical) undisturbed ecosystems and the actual NPP available to support heterotrophic food chains. However, the accuracy of assumptions and models of hypothetical NPP for undisturbed ecosystems (which is the sum of autotrophic production assumed to exist without human disturbance under current climate) is questionable, because ecosystems are constantly in a state of change and evolutionary dynamics may change slowly or quickly; thus, NPP for an "undisturbed ecosystem" depends entirely on both spatial and temporal context (Guzman-Casado and de Molina, 2017; Tello et al., 2015).

In this study, we used the agroecological approach described by Tello et al. (2015), which focuses on the actual NPP ($NPP_{\_actual}$) of landscapes and the NPP remaining in ecosystems after harvest ($NPP_{\_h}$). In this approach, both NPP terms are decomposed into different energy (biomass) flows appropriated by human society. The approach explicitly captures internal processes (or loops) linking societal and environmental relationships that are often lost in other SM or energy analyses (or modeling exercises) (van Noordwijk et al., 2011; Villamor et al., 2011). The approach also provides information about the structure and function of agroecosystems (Guzmán et al., 2018). For example, unharvested biomass and reused biomass play a vital role in keeping ecological services such as biodiversity and soil fertility for the sustainability and stability of agroecosystems (Van Apeldoorn et al., 2011). The energy performance of agroecosystems can be assessed using the EROI, which is a useful measure of the energy efficiency of the system (Tello et al., 2015; Tello et al., 2016) and provides information to support decision-making for production activities (Guzmán et al., 2018). Energy throughputs accounting and decomposition analysis of the final EROI provide a means to disentangle the role played by reuse of biomass and external input flows; this makes it possible to explore the contrasting energy profiles of traditional and industrial farm systems (Tello et al., 2016). According to Arodudu et al. (2017) deploying such a method would lead to the derivation of indicators suitable for assessing relevant environmental, social, and economic categories. Fig. 1 represents a much-simplified flowchart of the energy bookkeeping; three energy subsystems in boxes are presented - cropland or farmland (*green box*), society (*orange box*), and livestock (*blue box*).

$NPP_{\_actual}$ is the amount of NPP harvested and used by humans and the amount of NPP remaining in the landscapes for each species. It can be broken down into the following portions (Guzmán and González de Molina, 2015):

- *Socialized Vegetable Biomass* (*SVB*) is the phytomass that directly appropriated by human society prior to its industrial processing.
- *Socialized Animal Biomass* (*SAB*) is the animal biomass that is appropriated directly at the farm-gate that is appropriated by society. SAB is excluded from NPP.
- *Recycling biomass* (*RcB*) is the phytomass that is reincorporated into the agroecosystem such as seeds and vegetative reproduction organs and the phytomass recycled through livestock farming or through activity of wild heterotrophs. *RcB* are also divided into two portions:

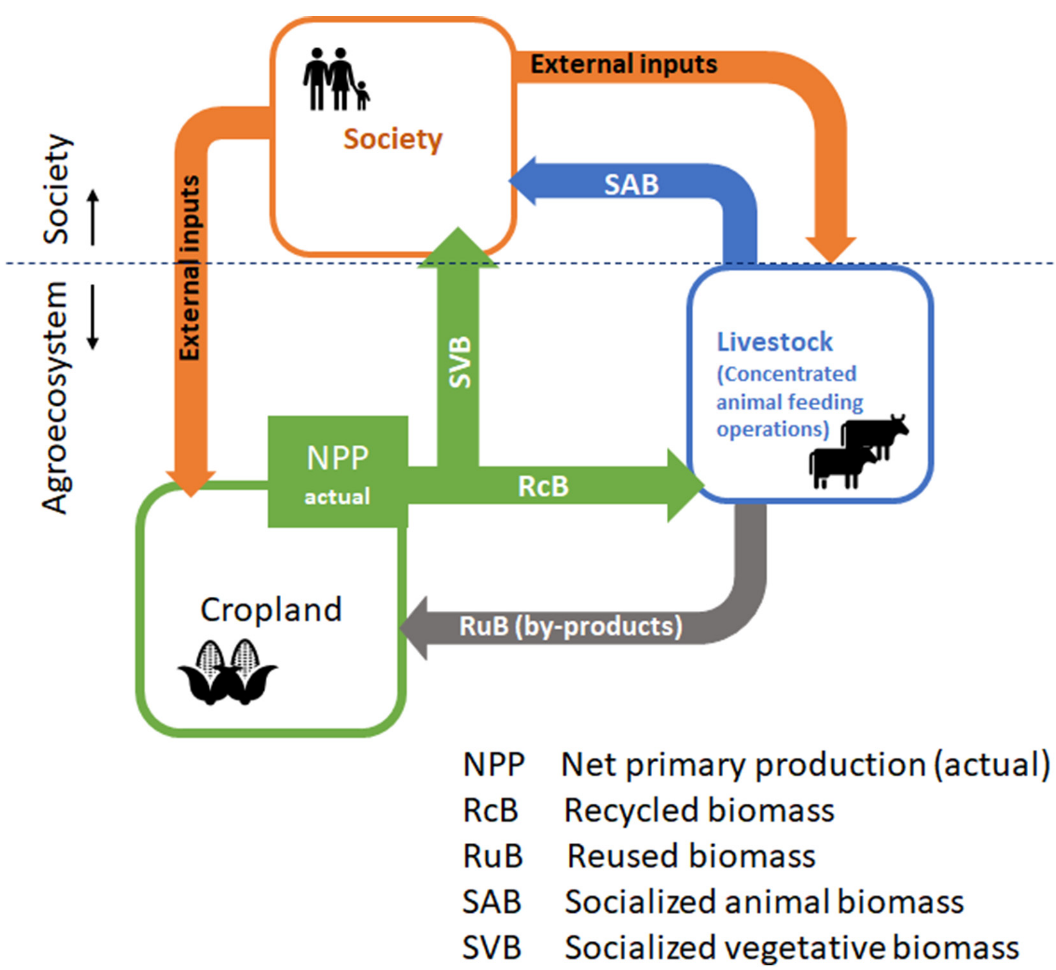

Fig. 1. Simplified energy flow (modified from Guzman-Casado and de Molina, 2017).

(1) *Reused biomass* (*RuB*) is the portion that is *intentionally returned* to agroecosystem by the farmer (e.g., animal feed); and (2) *Unharvested biomass* (*UhB*) is the portion returned to the agroecosystem by abandonment without the investment of any human work (e.g., litterfall and roots).

The majority of studies using this approach were applied over long periods to map a course of agricultural industrialization (Cunfer et al., 2018; Gingrich et al., 2018; Guzmán et al., 2018; Tello et al., 2016).

1.2. The role of livestock biomass/by-product in agroecosystems

Manure "as excreted" is defined as a mix of feces and urine. Unless specified as excreted, dairy manure contains other components of livestock production and manure management, including bedding, water from cleaning, flushing, cooling or other processes, runoff from confined areas, feed refuse, and dirt (ASAE, 2005; USDA, 2008). Manure is also a form of biomass and a potential or actual source of energy that is often ignored in energy analyses. In the agroecological approach to HANPP (Tello et al., 2015), manure is mostly not considered part of NPP to avoid double-counting (Gingrich et al., 2018). Rather, the final product from livestock is based on the number, live weight, and actual livestock production data. However, in dairy production in the US, manure is a high-volume by-product that can be considered a final product (for example as feedstock for biogas production) or reused or reinvested (as organic fertilizer) into agroecosystems. When manure is not utilized it must be considered as "waste," consequently creating problems for water and air pollution; the embodied nutrients (primarily Nitrogen and Phosphorous) in the manure are either outgassed during decomposition and volatilization or lost to the environment through water transport during infiltration and surface flow. For this reason, waste should be interconnected with other resources such as the water-soil-waste approach nexus in agroecosystems by recycling back to soil (Lal, 2015) to minimize losses and to maximize the use efficiency. One way is by returning back to agroecosystem for soil amendment and nutrient supplementation (Leytem et al., 2013). Moreover, exporting manure nutrients to off-farm users can have a substantial impact on nutrient balances (Koelsch and Lesoing, 1999). Galán et al. (2016) suggested that manure should be considered in an energy analysis. In this paper, we address this gap and explicitly incorporate manure in the energy analysis as a "by-product" of livestock production, assess the effects on the energy efficiency of the agroecosystem, and the describe potential emissions from the manure. Thus, we have the following research questions:

- Using the assumption of Koelsch and Lesoing (1999), what is the effect of reusing manure from livestock on cropland in terms of the final energy efficiency of the FEW systems?
- How does reinvesting manure back to the agroecosystem affect the agroecological functions of the FEW systems?

In this paper, we applied the EROIs from an economic perspective approach of Tello et al. (2015) and from the agroecological perspective approach by Guzmán et al. (2018), which recognizes that energy is invested not only in the production of biomass, but also in maintaining (or reinvesting) energy from manure in the maintenance of agroecosystems.

2. Methodology

2.1. Description of study area

The Upper Snake River Basin (USRB) in southern Idaho (Fig. 2) covers an area of approximately 35,800 miles^2 (92,722 km^2) and extends from basin headwaters at the Idaho-Wyoming border to King Hill, ID (Clark, 1998; Maret et al., 1997). The basin contains the East Snake Plain Aquifer, one of the largest and most productive aquifers in the US (Conservancy, 2014). The regional climate ranges from arid to semi-arid with sagebrush and bunch grass assemblages dominating natural landscapes.

The primary economic driver in the basin (as for the state of Idaho in general) is agriculture and agricultural services (Annex 1). Forage crops, potatoes, grains, and sugar beets are the primary crops, and the majority of cropland is cultivated under irrigation. In addition, dairy production and aquaculture are important economic sectors in the basin. The livestock industry has expanded rapidly; in 2012, approximately 80% of Idaho's cattle were located in the USRB and each cow produces 45 to 68 kg of wet manure every day (Matthews, 2013). Typically, dairy operations in this basin are dominated by open-lot bedded pack operations where manure is stockpiled in a drying area.

In recent years, there has been a decreasing trend in the number of farms and irrigated farms both in the basin and in Idaho (NASS, 2012). However, the average size (area) of farms increased by 2.8% in the basin and the number of livestock also increased by 19.2% (Annex 1). Furthermore, the average yield of wheat and forage increased by 4.3% and 12.5%, respectively, which is consistent with a trend of agricultural intensification in the region. The region is also expected to see a shift to earlier timing of surface water availability (Kliskey, 2019). Based on the 2018 U.S. Census Bureau, the basin is home to 24% of Idaho's total population, and the basin's population has increased by 8% since 2010.

Within the USRB, there are three well differentiated ecoregions: The Magic Valley, the Eastern Idaho valleys, and the Eastern Idaho mountain/forest area. Each region's economy has distinct land use characteristics: the Magic Valley mainly depends on dairy and crops under irrigated agriculture; in Eastern Idaho valleys, agricultural crops are grown under a mix of rain fed and irrigated agriculture; and the Eastern Idaho mountain/forests are the site of beef operations, forests, and tourism activities. The area with the most data available within the USRB is the Magic Valley. Agribusiness, that is the basic primary agricultural production enterprises and the processing of agricultural products, account for the majority of the capital generated and movement within the region (Hines et al., 2018). Seven counties of the top ten producers of agricultural market value in the state of Idaho are in the USRB, and five of those seven are in the Magic Valley.

In this study, we focused on the 20 counties of the USRB. Eight of these counties (i.e., Blaine, Camas, Cassia, Gooding, Jerome, Lincoln, Minidoka, and Twin Falls) represent the Magic Valley region, which is a major contributor to the total agricultural product of Idaho (especially the dairy industry). In 2012, agricultural products in the region generated $3.5 billion USD, or a net income of $682 million USD (USDA, 2012). Twin Falls, Idaho Falls, and Pocatello are the major cities in the basin. Several major food processing plants, such as those owned by Glanbia, Jerome Cheese, and Amalgamated Sugar, are located in the USRB. The basin is also considered the primary region producing farmed rainbow trout in the USA (NASS, 2017).

2.2. EROI

EROI is the ratio of total energy output to the total energy input of an energy production chain under investigation (Grandell et al., 2011). Also known as the energy efficiency, it has no unit but rather is represented as the fraction of energy obtainable from a production activity. The energy flow in the basin was determined by breaking down the $NPP_{\_actual}$, where $NPP_{\_actual}$ is expressed as

$$NPP_{act} = SB + RuB + UhB + AB \quad (1)$$

(Guzman-Casado and de Molina, 2017; Tello et al., 2015). *SB* is socialized biomass such as timber, woody biomass, cereal grain, milk, beef, etc. that is directly appropriated by human society and extracted or harvested from the landscape prior to industrial processing. *SB* is composed of socialized vegetative biomass (*SVB*) and socialized animal

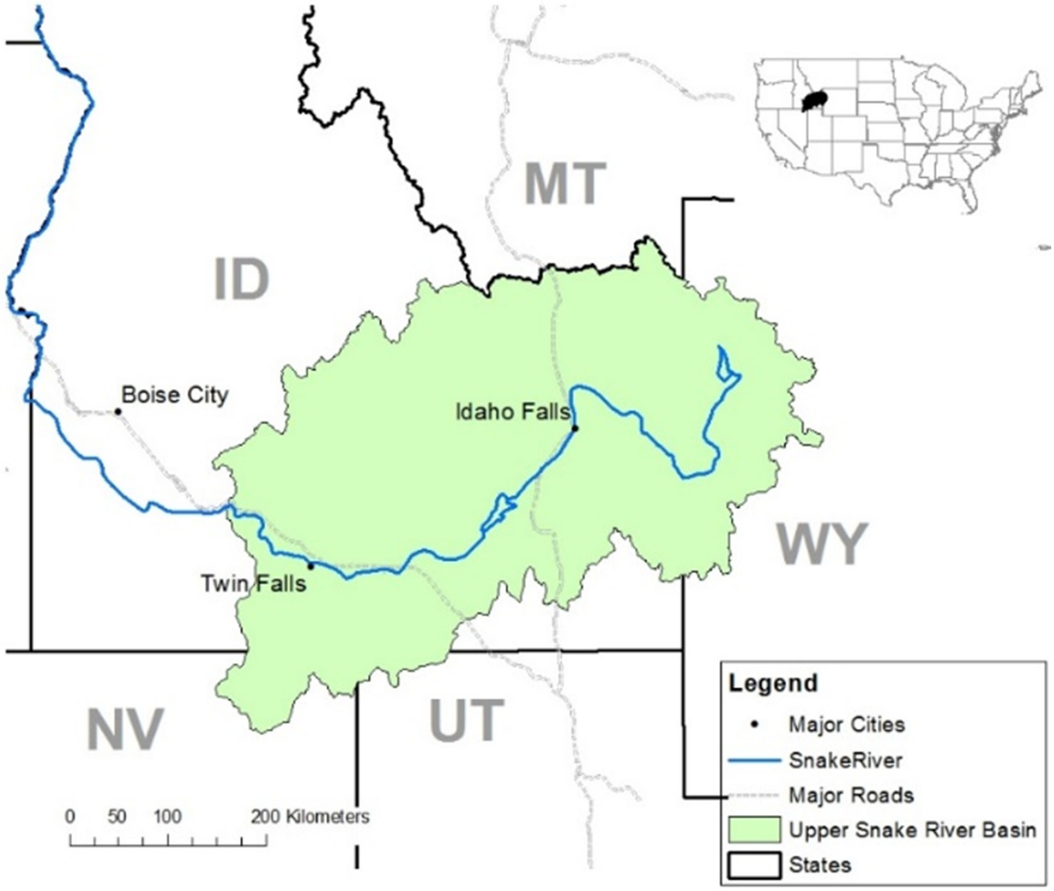

Fig. 2. Map of Upper Snake River Basin (USRB) in the State of Idaho (ID), bordering Montana (MT), Nevada (NV) and Utah (UT).

biomass (*SAB*); *RuB* is reused biomass, and refers to that fraction of total biomass which is intentionally returned to the system (e.g., animal feeds, manure, green manure); *UhB* is unharvested biomass and refers to biomass that was simply abandoned and allowed to return to the system, with no human labor used (i.e., fallowed land); and *AB* is accumulated biomass and refers to biomass that accumulates annually in the aerial structures (stem and crown) and roots of plants.

To capture the different parts of the agroecological structure of energy flows (Fig. 1) rather than a linear agroecosystem, Table 1 summarizes the description and modified equations for specific EROIs in which we breakdown the estimation of external and internal final EROIs.

2.3. Data collection and calculations

The main source of data for this study are the census data of 2002 and 2012 from the United States Department of Agriculture's (USDA) National Agricultural Statistical Service (NASS). The 2017 census data are not yet available; thus, the periods of 2002 and 2012 were considered for this study. The corresponding biomass of the major cropland and the livestock production in the basin was generated from NASS harvest yield data of 2002 and 2012. For the land use maps, we used the cropland data layer (CDL) maps of 2005 and 2015 (https://data.nal.usda.gov/dataset/cropscape-cropland-data-layer) and estimated the land areas using ArcGIS. The reconstruction of biomass production and the sources employed are described in detail in Guzman-Casado and de Molina (2017).

Crop residues were incorporated and calculated following the procedures (including the assumptions) from Haberl et al. (2007). This also includes the residue left during a harvest (such as straw, stalks, and stover), which is calculated by multiplying the harvest index for the total aboveground plant production (Guzman-Casado and de Molina, 2017; Prince et al., 2001; Turner, 1987). It is assumed that the crop residue of major crops such as corn, barley, and wheat are used as livestock feed or bedding, which are accounted for in *RuB*, whereas residues from potatoes are part of *UhB* because of unpalatability for cattle.

The *UhB* from crops was divided into two categories: (1) parts of the plant which are retained in the field (e.g., for erosion control and soil fertility), and (2) losses of parts of the plant due to harvest methods (Jölli and Giljum, 2005). In this study, we only consider the first category as we assumed that the amounts from the second category are insignificant due to ubiquitous use of modern harvesting machines in the USRB. To estimate *UhB*, we used the coefficients suggested by Jölli and Giljum (2005). The belowground biomass (i.e., roots) of specific crops (including weeds) were taken into account using the root-shoot ratio calculated from dry biomass values compiled by Guzman-Casado and de Molina (2017), Prince et al. (2001), and Turner (1987), which will later become part of the accumulated (*AB*) and unused biomass (*UhB*). Because most of forests in Idaho are in the northern part of State and no data on wood harvesting were available for the study area, we did not include timber harvest in the estimation of $NPP_{\_h}$. The $NPP_{\_actual}$ and $NPP_{\_h}$ values are expressed both in (metric) tons of dry matter biomass per year (t DM/yr) and as energy flow (Mega Joules per year, MJ/yr). We assigned the energy values estimated by Guzman-Casado and de Molina (2017); Ozkan et al. (2004); Pimentel (2009).

Estimates for manure and nutrient excretion by livestock were generated using the American Society of Agricultural Engineers (ASAE) Standards D384.2 (ASAE, 2005). Calculations of the gross energy (GE) of manure are based on the energy balance partitioning of livestock

Table 1
Modified energy efficiencies applied for USBR (Source: Tello et al. 2015; Guzman et al. 2018)

Type/form	Definition	Equation
Economic perspective:		
(a) Final EROI (FEROI)	Assesses the amount of energy invested to obtain a unit of energy in the form of biomass (not strictly in monetary terms or ecological productivity) (as measured at the exit gate of the agroecosystem)	$=\frac{SB}{RuB+EI}$
Additional variation, assumption and equation:	(a.1) If certain % of manure will be recycled back to the cropland (RuB_M);	$=\frac{SB}{RuB+RuB_M+EI}$
	(a.2) If certain % of manure will be reinvested as compost product ($W_{\%}$) only;	$=\frac{SB+W_{\%}}{RuB+EI}$
	(a.3) If certain % of manure will be reinvested as compost product ($W_{\%}$) and the rest of the manure will be recycled (RuB_M)	$=\frac{SB+W_{\%}}{RuB+RuB_M+EI}$
	(a.4) Crop FEROI	$=\frac{SVB}{RuB+EI_{veg}}$
	(a.5) Livestock FEROI	$=\frac{SAB}{RuB_M+EI_{livestock}}$
	(a.6) Livestock (+ by-product) FEROI	$=\frac{SAB+W_{\%}}{RuB_M+EI_{livestock}}$
(b) External FEROI (EFEROI)	Assesses to what extent the external inputs (EI) relate to the final output crossing the agroecosystem boundary (*net efficiency*)	$=\frac{SB}{EI}$
Additional variation, assumption and equation:	(b.1) If certain % of manure will be utilized as compost product (W);	$=\frac{SB+W_{\%}}{EI}$
(c) Internal FEROI (IFEROI)	Assesses the portion of biomass reinvested in the agroecosystem as reused biomass (*RuB*) that is useful to society:	$=\frac{SB}{RuB}$
Additional variation, assumption and equation:	(c.1) If manure will be reused back to cropland (RuB_M); and	$=\frac{SB}{RuB+RuB_M}$
	(c.2) If certain % of manure will be utilized as compost product (W) and the rest be reused back to cropland (RuB_M)	$=\frac{SB+W_{\%}}{RuB+RuB_M}$
Agroecological perspective:		
(d) $NPP_{\_actual}$ EROI	Explains the *real* productive capacity of the agroecosystem, whatever the origin of the energy it receives (e.g., solar for the biomass or fossil for part of EI)	$=\frac{NPP_{actual}}{Total\ inputs\ consumed}$
Additional variation, assumption and equation:	(d.1) If manure will be reused back to cropland (RuB_M)	$=\frac{NPP_{actual}}{Total\ inputs\ consumed+RuB_M}$
(e) Agroecological EROI	Expresses what is really recycled without human intervention. It provides exact idea of the total energy required to obtain SB	$=\frac{SB}{Total\ inputs\ consumed}$
Additional variation, assumption and equation:	(e.1) Agroecological EROI (+ by-product) If certain % of manure will be utilized as compost product (W) and the rest of the manure will be recycled (RuB_M)	$=\frac{SB+W_{\%}}{Total\ inputs\ consumed+RuB_M}$

Note: SB = Socialized biomass (SAB + SVB); RuB = Reused biomass; EI = External inputs or Energy inputs; Total inputs consumed = RuB + UhB + EI; RuM = reuse of manure to cropland; and W = compost product/ by-product

animals (Aguilera et al., 2015). This includes energy in feed and the embodied energy of feces, methane emissions, and urine. In this study, we focused only on the typical manure (urine and feces combined). The calculations are standardized by considering that the metabolizable energy of the feed consumed by the animals is 70% of the gross energy available in the feed, suggesting that 30% of the gross feed energy is excreted by the animals (Guzman-Casado and de Molina, 2017). Only the ammonia (NH_3), methane (CH_4), and nitrous oxide (N_2O) emissions from the manure were estimated for the dairy using the emission rates by Leytem et al. (2011). For this study, the emissions were presented in metric tons and only for cows.

Energy inputs (EI) for both cropland and livestock production are comprised of: (1) direct energy, which refers to the GE of the fuels directly used in the production process (e.g., diesel, gasoline, and electricity are used for operating machinery, vehicles, and irrigation pumps) (Aguilera et al., 2015); and (2) indirect energy requirements which includes all remaining processes needed to produce the input and its use at the farm (e.g., fertilizers). EI were generated from Guzman-Casado and de Molina (2017); Ozkan et al. (2004); Pimentel (2009). The energy in the net imported biomass such as seeds and feed is the GE of the different products calculated using conversion factors suggested by Guzmán and González de Molina (2015) and Guzman-Casado and de Molina (2017) to avoid problems of double counting. In terms of human labor, we used the dietary energy consumption (2.2 MJ/h) as suggested by Fluck (2012); Guzmán et al. (2018) to avoid the same issue of double accounting.

3. Results

3.1. Land use and $NPP_{\_actual}$

Of the major land use types identified in the basin between 2002 and 2012, cropland and pasture/shrubland increased in land area. Pasture

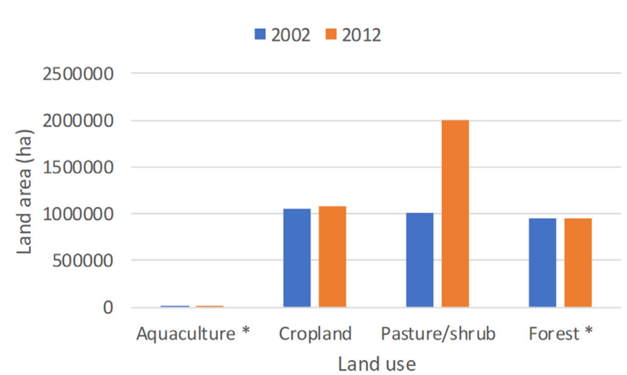

Fig. 3. Major land uses for the period between 2002 and 2012. Sources: NASS (2002) and NASS (2012); [*] Generated from USDA, NASS Cropland Data Layer (CDL) of 2005 and 2015; Forest includes deciduous forest, evergreen forest, herbaceous and woody wetlands and mixed forest.

Table 2
Net primary productivity (NPP in Dry Matter) of cropland over the two time periods.

Crops	Area (ha)	2002						2012						
		Biomass						Area (ha)	Biomass					
		Above ground		Below ground (t DM) `1000	Weeds		Total (t DM) `1000		Above ground		Below ground (t DM) `1000	Weeds		Total (t DM) `1000
		Harvest (t DM) [a] `1000	Crop residue (t DM) `1000		Aerial (t DM)[c] `1000	Roots (t DM) [d] `1000			Harvest (t DM) [b] `1000	Crop residue (t DM) `1000		Aerial (t DM) [c] `1000	Roots (t DM) [d] `1000	
Barley [e]	208,600	573.4	671.8	261.4	29.8	6.3	1543	149,857	642.2	752.4	292.8	29.6	6.2	1723
Beans	20,947	58.3	80.4	83.2	5.4	3.2	231	21,431	65.6	90.4	93.6	5.4	3.2	258
Corn [e]	4620	39.4	37.8	18.5	3.4	0.8	100	20,447	228.4	219.4	107.4	15.2	3.6	574
Corn, silage [f]	39,008	668.7	2698.2	336.6	1.0	1.0	3715	68,080	1191.3	4807.0	599.8	17.4	1.7	6617
Forage/hay [g]	310,168	3068.6	3590.4	7591.3	79.3	90.4	14,420	310,848	3206.5	3751.6	7932.2	79.5	90.6	15,060
Oats	1983	9.6	14.4	9.6	0.5	0.2	35	2845	11.8	17.7	11.8	0.7	0.3	42
Potatoes	133,437	1458.0	899.2	707.2	31.2	9.4	3105	104,855	1300.0	801.8	630.5	24.5	7.4	2764
Safflower	63,908	1.0	3.7	3.1	0.4	0.2	8	64,204	2.1	8.2	6.6	0.8	0.5	18
Sugar beets	964	936.8	569.6	602.6	16.3	6.5	2132	2101	1005.3	611.2	646.6	16.4	6.6	2286
Wheat [e]	264,931	1182.2	1422.6	521.0	17.8	3.6	3147	279,384	1510.0	1817.1	665.4	18.8	3.8	4015
Total		**7996.2**	**9988.4**	**10,134.8**	**194.2**	**121.6**	**28,435**		**9163.3**	**12,876.8**	**10,987.1**	**208.4**	**124.0**	**33,360**

Notes: Conversion: 1 US ton (t) = 907.2 kg; [a] Based on NASS harvest yield data of 2002; [b] Based on NASS harvest yield data of 2012; [c] Conversion coefficients from Guzman-Casado and de Molina (2017); Poudel et al. (2002); Chao et al. (2002); Rios and Carriquiry (2007); [d] Conversion coefficients from Loper and Schroth (1986), and Guzman-Casado and de Molina (2017); [e] Crops for grain; [f] Crops for silage; and [g] Hay includes alfalfa, other tame, small grain, and wild hay and all haylage.

and shrubland had the largest increase by 30% annually whereas cropland increased in land area by 0.3% annually (Fig. 3). Aquaculture had also a slight increase over ten years but very small in comparison with the major land uses. Forest, on the other hand, had a slight decrease in land area.

The area and total net productivity (including the *SVB* in the form of crop harvests) in cropland is presented in Table 2. In terms of land area, the top three major crops are forage crops, barley, and wheat across the time periods. In 2012, a slight decrease was observed in barley and potatoes production; whereas the rest of the major crops had increased in land area. This increase is particularly notifiable with forage/hay and corn (for silage), suggesting these are connected to the increasing livestock production in the basin. In terms of harvests, forage/hay, wheat, and potatoes are the top producing crops. Potatoes were the only crop that decreased in both land area and biomass (harvested) production; whereas barley decreased in land area but increased in biomass production, suggesting a process of intensification. In 2002, the total biomass in the cropland (in dry matter) was estimated at 28.4 M ton and increased in 2012 to 33.4 M ton, a 1.7% average annual increase.

The gross energy from these crops are presented in Table 3. In 2002, the NPP was estimated at 183,706 TJ (Tera joules) and in 2012, the estimated NPP amounted to 234,837 TJ, a 2.2% average annual increase. The substantial increase in energy from crops was attributed to corn (both for grain and silage) and wheat. The GE from weeds (both aerial and roots) had the least energy value across the two time periods, which represents the AB that will reuse to cropland without human labor. The GE from combined crop residue and below ground (which form as *RcB*) is higher than the SVB's GE across the two time periods, suggesting their importance in the agroecological functioning of the system.

3.2. Livestock products (SAB), manure and emissions

The estimated livestock products sold from farm gate (*SAB*) and its corresponding energy value for 2002 and 2012 is presented in Table 4.

Table 3
Net primary productivity (Gross Energy) of cropland over the two time periods in Terra Joules (TJ).

Crops	Energy value (Gross Energy)											
	2002						2012					
	Above ground		Below ground	Weeds		Total Energy	Above ground		Below ground	Weeds		Total Energy
	Harvest (SVB)	Crop residue		Aerial	Roots		Harvest (SVB)	Crop residue		Aerial	Roots	
Barley	9841	9251	3601	412	86	23,192	11,022	10,362	3601	407	86	25,418
Beans	142	1138	203	20	12	1515	159	1278	228	21	12	1665
Corn	616	632	310	47	11	1616	3572	3432	1797	209	50	8801
Corn, silage	7850	31,676	3953	117	12	35,757	13,985	56,431	7042	204	20	63,472
Forage/hay	9493	11,107	23,484	245	280	35,116	9919	11,606	24,539	246	280	36,145
Oats	165	199	133	7	3	508	203	244	163	10	4	610
Potatoes	4907	2863	2380	99	30	10,280	4375	2553	1896	246	23	9051
Safflower	22	86	71	6	4	189	48	188	154	11	7	390
Sugar beets	14,032	8531	9025	224	90	31,901	15,058	9155	9685	225	90	33,898
Wheat	18,979	17,849	6536	224	45	43,632	24,241	11,606	8349	236	47	55,388
Total	66,047	83,333	49,695	1404	3682	183,706	82,584	118,047	58,111	1648	621	234,837

Notes: Conversion: 1 Kcal = 4186.8 J; 1 MJ = 10^6 J; 1 GJ = 10^9 J; 1 TJ = 10^{12} J. An average human being needed an energy intake of 3.5 GJ/year.

Table 4
Livestock products sold from farm gate (SAB) and energy value in USRB for 2002 and 2012 (in TJ = Tera Joules).

Livestock type	Mean size (kg/unit)	Total weight (ton)		Unit energy (MJ/kg) [c]	Energy value (TJ)	
		2002 [a]	2012 [b]		2002	2012
Cattle and calves [e]	226	44,630	67,370	7	314.41	471.59
Milk	800 [d]	329,498	544,496	3	897.76	1481.90
Swine	68	1496	185	10	13.57	1.68
Sheep	45	7866	6930	9	64.22	56.59
Layers	1.8	1	7	5.87	0.01	0.04
Broilers	0.9	2	2	5.87	0.01	0.01

Notes: [a] NASS, 2002; [b] NASS, 2012; [c] Guzman-Casado and de Molina (2017); [d] average milk production provided by the NASS, 2002 and NASS 2012; and [e] sales at 226 kg/head.

An examination of livestock products sold over the time period and its energy equivalent showed that almost half of the total gross energy from livestock products were generated from milk products. In 2012, the energy output from livestock products decreased in swine, beef, replacements/heifer, and sheep.

The estimated livestock manure production and the gross energy equivalent are summarized in Table 5. An increase in the number of livestock heads was observed from 2002 to 2012 by 1.4% annually. The largest annual increase in livestock number was observed in poultry layers (5.6%), milk cows (3.3%), and cattle (1.6%), including dairy replacement heifers. In contrast, the largest annual decrease in livestock number was observed in swine (−10%), beef cows (−2.0%), and goats (−0.6%). The change in numbers of cows reflect an ongoing transition in the USRB from beef production to dairy production as the primary livestock land use.

In 2002, the total manure produced was 10.9 M tons generating a gross energy of 51,875 TJ. From 2002 to 2012, an increase of 13% in total manure production amounting to 12.4 M tons was recorded in the study area generating a gross energy of almost 65,000 TJ. The largest producer of livestock manure was milk cows in both years. In contrast, a decrease in manure production was observed in beef cows, swine, sheep, broilers, and goats.

Using the NH_3 (ammonia), CH_4 (methane), and N_2O (nitrous oxide) emission rates from Leytem et al. (2011), the total emissions from cows for the 2002 were 25,316 ton NH_3 (or 69.36 ton day^{-1}), 93,475 ton CH_4 (or 256.1 ton day^{-1}), and 1947 ton N_2O (or 2.4 ton day^{-1}). For 2012, the total emissions increased to 30,266 ton NH_3 (or 82.92 ton day^{-1}), 111,753 ton CH_4 (or 306.2 ton day^{-1}), and 2328 ton N_2O (or 6.38 ton day^{-1}).

Table 6
Estimated energy inputs (EI) invested in both crop and dairy production in USRB between 2002 and 2012 in TJ (terajoules).

Inputs	2002 (TJ)			2012 (TJ)		
	Crop [a, b]	Dairy [f]	Total	Crop [a, b]	Dairy [f]	Total
Energy carriers:						
Electricity	3283	1392	4676	2988	2503	5491
Gas	1986	565	2551	28	707	735
Gasoline	1081	549	1630	3172	665	3837
Diesel	6115	1292	7407	5557	1661	7218
Sub-total	12,464	3798	16,261	11,745	5536	17,661
Industrial:						
Nitrogen	6802	–	6802	5473	–	5473
Phosphorous	686	–	686	632	–	632
Potassium	327	e	327	445	e	445
Micro-nutrients	623	–	623	577	–	577
Insecticide	1075	6	1081	856	7	863
Herbicide	1303	–	1303	1344	–	1344
Machinery	2227	347	2574	2320	415	2734
Transport	1667	–	1667	2203	–	2203
Irrigation [c]	4069	–	4069	4814	–	4814
Equipment	13,994	12,575	26,569	14,058	15,035	29,093
Sub-total	32,772	12,928	45,701	32,721	15,456	48,177
Non-industrial:						
Human labor [d]	38	129	167	35	154	190
Feeds	–	10,923	10,923	–	13,059	13,059
Seeds	2528	–	2528	2559	–	2559
Sub-total	2565	11,052	13,618	2594	13,213	15,807
Total inputs (EI)	47,802	28,956	76,758	47,060	35,984	83,424

Notes: [a] Pimentel (2009); [b] Ozkan et al. (2004); [c] Includes materials, maintenance etc.; [d] Energy as dietary energy consumption as suggested by Fluck (1992); [e] data not available; [f] input data are limited to cattle (i.e., milk and beef cows], milk and meat only.

3.3. Energy inputs (EI)

The EI required for crop and dairy production highlight the origin of these inputs outside of the agroecosystem (i.e., USRB), including indirect energy (e.g., energy needed for fertilizer production). The EI were divided into fuel, industrial, and non-industrial categories according to crop and dairy production (Table 6). Among the EI categories, the industrial EIs had the largest requirement (ranging from 46% to 70%) in total production for both years. This suggests that the agricultural system in the basin is an example of a metabolic industrialized farm system, where industrial, energy-intensive inputs have largely replaced human and animal labor. Over the time series, the increase in energy requirements from industrial inputs were mainly attributed to the use of machinery and equipment, whereas a slight decrease was observed in the use of inorganic fertilizer. Within crop production, a slight decrease

Table 5
Livestock's manure production and energy value in USRB for 2002 and 2012 (in TJ = Tera Joules).

Livestock type	Size [a] (kg/unit)	Population/Number [b]		Manure production			Energy value (Gross Energy)		
		2002	2012	Manure (kg/day) [c]	Total (ton)		Unit energy (MJ/kg)	Energy value of the manure in TJ	
					2002	2012		2002	2012
Cattle [d]	113	628,454	747,338	2.8	2,402,076.9	2,856,475.4	17.4 [f]	11,401.4	13,558.2
Beef cows	454	239,940	200,487	8.4	2,703,027.8	2,258,572.6	17.4 [f]	12,829.8	10,720.2
Milk cows	454	293,595	437,375	14.4	5,669,956.4	8,446,660.1	17.4 [f]	26,912.2	40,091.8
Swine [e]	68	11,359	5520	1.4	20,565.6	9994.1	19.4 [g]	108.8	52.8
Sheep	45	158,578	142,159	0.5	115,481.2	103,524.4	19.4 [g]	620.1	555.9
Layers	1.8	7450	17,147	0.04	359.6	827.8	10	1.0	2.2
Broilers	0.9	2309	2269	0.02	74.3	73.0	6.9 [h]	0.2	0.2
Goats, milk	34	1175	1104	0.18	288.4	270.9	19.7 [g]	1.6	1.4
Total		1,342,860	1,553,399		10,911,830.4	12,407,228.7		51,875.2	64,982.9

Notes: [a] Weights represent the average size of the animal during the stage of production dairy (Lorimor et al., 2004); [b] NASS, 2002 and 2012; [c] Assumed 70% recovery and 74% - 88% moisture content; [d] Cattle (including calves); [e] Mature and finishing types; [f] Sweeten et al. (1986) and LePori and Soltes (1985); [g] Capareda, 2013; [h] Foged (2012).

in all EI was observed across the time series. This is particularly in the use of nitrogen and phosphorus fertilizer. In contrast, an increase in all EI was observed in dairy production for the time series. The increase was mainly from feeds, equipment and electricity. In terms of fuel (e.g., diesel, electricity, etc.), crop production (26–25%) had the higher EI requirements compared to dairy production (13–15%) for both time periods. On the other hand, feeds (36–37%) and equipment (42–43%) are the main EI in dairy production. In addition, dairy production had higher EI requirements in terms of human labor as compared to crop production. However, the total laborers or workers for the whole agricultural production decreased in 2012 probably due to the farm consolidation and use of less labor per cow on bigger production units (Annex 1). There is also a documented labor shortage in the dairy industry in the USRB, so declining labor requirements may reflect a lack of manpower rather than an increase in productivity or efficiency (IDA, 2017).

3.4. EROIs: economic and agroecological viewpoints

An examination of the $NPP_{\_actual}$ for the basin between 2002 and 2012 (Fig. 4a) shows that the actual NPP increased by >20% for the time series. More than half of the total $NPP_{\_actual}$ is reused biomass (*RuB*). The biomass appropriated by humans (*SVB* + *SAB*) also increased in 2012. Since the manure from livestock is a renewable and energy-rich biomass, the estimated gross energy equivalent for the whole basin in 2002 was 112,481 TJ and increased in 2012 by 35% (152,180 TJ) (Fig. 4b). The amount of energy from the manure is higher in both years than the socialized biomass combined (*SVB* + *SAB*), suggesting that the energy from the manure should not be ignored.

From an economic viewpoint, the Final EROI, which is the most relevant EROI term with respect to energy performance and the allocation of external and internal EI aimed at meeting human needs, remained almost constant from 2002 to 2012 (Table 7). Taking into account only the net efficiency for crop biomass production, the Crop FEROI is higher compared to overall Final EROI. On the other hand, if livestock products (*SAB*) are only considered, the Livestock FEROI is the lowest because the *SAB*s were so small compared to EI. For this reason, several studies are concluding that livestock production is energy inefficient (Gingrich et al., 2018; Guzmán et al., 2018). In terms of utilizing external and reuse of energy for human needs, the External FEROI increased 7% in 2012, suggesting that an improvement of utilizing external energy. In contrast, the Internal FEROI decreased by 5%, suggesting a low reinvestment of biomass to the agroecosystem but more reliance on external energy (i.e., industrial energy for dairy production and increased dairy processing capacity, see Table 6).

From an agroecology perspective, the basin's $NPP_{\_actual}$ EROI slightly increased from 2002 (0.90) to 2012 (0.93), suggesting that the basin improved in meeting societal needs as well as maintaining the associated ecological function (e.g., unharvested biomass roles). The AE FEROI was low across the time series because the socialized biomass

Table 7
Economic and agroecological EROIs agroecosystem of the basin for 2002 and 2012.

EROIs	Year	
	2002	2012
Economic viewpoint		
(a) Final EROI	0.26	0.25
Crop FEROI (Eq. a.4)	0.30	0.29
Livestock FEROI (Eq. a.5)	0.01	0.01
(b) External FEROI	0.65	0.72
(c) Internal FEROI	0.44	0.39
Agroecological viewpoint		
(d) $NPP_{\_actual}$ EROI	0.90	0.93
(e) AE FEROI	0.20	0.20

particularly from the animal product (i.e., milk) remains low and the amount of reused manure (i.e., *RuB*) from livestock was substantially larger.

Reinvesting of manure as by-product (*W*) alone or combined with the reuse of the manure back to cropland (RuB_M) would change the energy production efficiencies. Fig. 5 illustrates the effect on the EROIs when incorporated in the biomass flow according to the percentage level of reinvesting to by-product (such as compost) and reuse of manure back to cropland. In terms of Final EROI, the highest net efficiency is when manure is reinvested as by-product and when the reuse of manure is accounted for (Fig. 5a). However, reuse of all manure back to cropland i.e., Final EROI $_{(\text{reuse of manure})}$ alone would slightly reduce the efficiency.

In Table 7, Livestock FEROI is very low. However, adding the by-product to the estimation of socialized biomass increased the Livestock FEROI (Fig. 5b) - much higher than the crops (0.29 in 2012) and the overall FEROI (0.25). Moreover, the highest increase is the reinvestment of all manure to by-product. Thus, the livestock production would become the most efficient from an economic viewpoint of net efficiency, if the manure would be reinvested as by-product. The same is observed for External FEROI, if by-products are included in the socialized biomass, the efficiency increased two-fold. In terms of reuse of biomass (Fig. 5c), the Internal FEROI is 0.44 in 2002 and dropped to 0.39 in 2012 but adding in manure as both energy input (reuse) and output (by-product), changes the performance. However, accounting manure only as a reuse would not improve the efficiency.

With regards to agroecological viewpoint (Fig. 5d), the higher the percentage of manure being reinvested as by-product, the $NPP_{\_actual}$ increases too. However, it requires 100% of manure conversion to be at the same efficiency as when manure is unaccounted for (Eq. d. in Table 1), which may be unrealistic. On the other hand, the AE-FEROI would increase when 50% or more of total manure is reinvested to by-product. The same increase can be achieved by combining the by-products and reuse of manure at 50% or more of the total production.

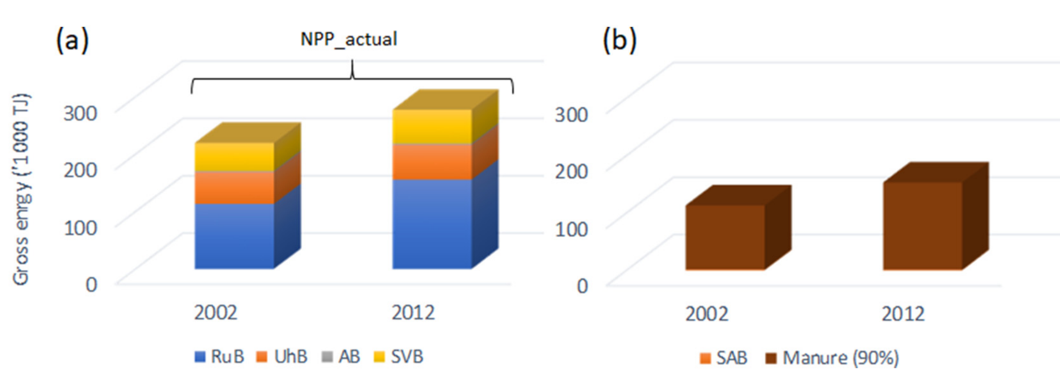

Fig. 4. Energy indicators of agroecosystem and energy from manure.

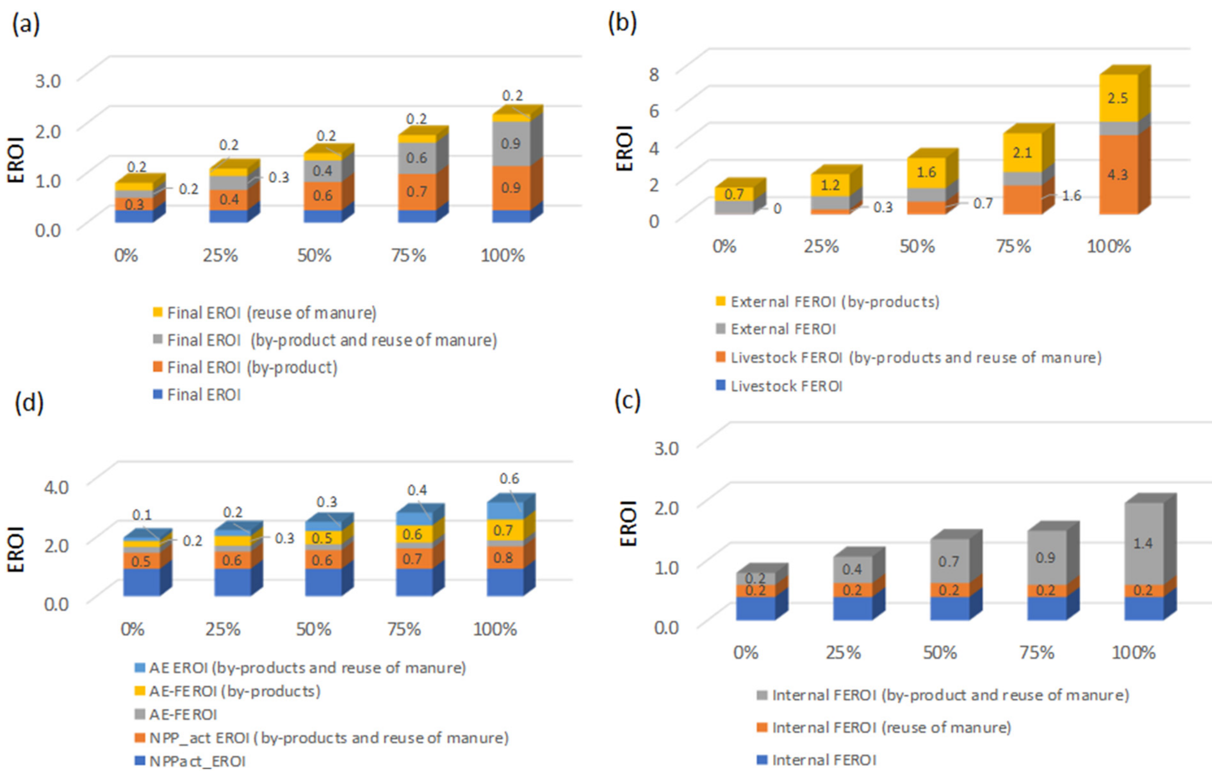

Fig. 5. Effect on the (a) Final EROIs or net efficiency; (b) External EROI; (c) Internal EROI; and (d) agroecological perspective EROIs, if manure is reinvested into by-product (e.g., compost) using the 2012 data.

4. Discussion

4.1. Effect of reinvesting and reuse of manure

The reuse of biomass (particularly the manure) plays an important role in the energy efficiency in the basin. Interestingly, the EI for crop production decreased from 2002 to 2012, suggesting an increase of energy efficiency brought by the reuse of biomass for livestock production (e.g., crop residues left for grazing animals) and reinvestment of manure as organic fertilizer. In both years, the Livestock EROIs were very low. Our analyses showed that improvements can be made by reinvesting the manure to by-product (as compost) combined with accounting the reuse of manure in the biomass flow. However, the reuse of manure back to cropland alone would not improve the energy efficiency (e.g., Final and Internal EROIs); at the same time, it would further reduce the real productive capacity of the agroecosystem. In the Magic Valley, manure accumulation is so substantial that ignoring it would drastically reduce the energy performance of the system (Fig. 4). Thus, this study provides insights of the percentage rate of manure that would economically and agroecologically efficient.

Nevertheless, from an ecological perspective (i.e., nutrient balance) a different story emerges. By reusing manure on fields adjacent to dairy CAFOs, *all* of the constituents are retained in proximity to the cattle, *except* what is lost through emissions to atmosphere, erosion, infiltration to the aquifer, and runoff to surface water bodies. This leads to an accumulation of phosphorous and nitrogen in croplands adjacent to dairies, but this nutrient balance issue could be mitigated if manure were collected, processed, and shipped (either raw, dried, or composted) out of the system. The state of Idaho has a requirement that any farm emitting >90,909 kg (or 90 ton) NH_3 year $^{-1}$ adopt a certain number of best management practices to reduce the emissions as well for CH_4. An in-depth study of how farms are reducing their emissions and linking with energy efficiencies is proposed for future investigation.

In terms of overall EROIs, comparing our results with other studies show that if considering only the EROIs (i.e., Final, Internal, and External), provide a very low estimate of energy efficiencies at the landscape level (Table 8). However, adding the manure (e.g., at 50%) would increase both the Internal and External EROI (numbers in brackets); whereas solely looking at the Livestock EROI would increase it significantly.

Table 8
Comparison of economic EROIs with other studies.

EROI	Our study	Fraňková and Cattaneo (2018)	Guzmán et al. (2018)	Guzman-Casado and de Molina (2017)
	2012	2012	2008	
Final EROI	0.25 (0.60)	0.61	0.6	–
External EROI	0.50 (2.02)	1.97	1.2	–
Internal EROI	0.39 (0.20)	0.89	0.8	–
Livestock EROI	0.01 (3.28)	na	na	0.03–0.04

Note: Numbers in brackets include the by-products and reused of manure.

4.2. Policy implications

4.2.1. Towards land intensification and FEWS

Land intensification is usually understood through other methods without clear understanding of the flow of materials and energy (Aldwaik and Pontius Jr, 2012; Erb, 2012; Villamor et al., 2014). In this paper, we highlight land transition in terms of changes of socio-economic inputs (e.g., resources, energy), which impact the dynamics of FEW systems. With the SM approach combined, an in-depth analysis of the flows and exchanges of materials (and energy) between society and agroecosystems is made possible. For example, despite the slight increase in croplands, intensification of socio-economic inputs and outputs were observed over time. This is particularly the case for the NPP increase due to the production of biomass from livestock by-products. Although the literature includes livestock products as part of estimating the actual NPP (Marco et al., 2017), it often limits or tends to disregard the manure. This is because most of the case studies are in pasture systems, where estimation of manure is difficult. Accounting for manure energy strongly depends on system boundaries (Aguilera et al., 2015). In our case study, animal biomass is readily captured because most of the dairies are in CAFOs.

Livestock farming is often considered a low efficiency energy converter because of the large share of energy intake of animals that is spent maintaining their body metabolism with only a small portion used to produce meat and milk (Guzman-Casado and de Molina, 2017; Marco et al., 2017). This is true if we considered the Livestock FEROI of 0.01 in both years (Table 7); whereas, the main product represented in socialized animal biomass is milk. However, the efficiencies could be reversed if a higher percentage of manure is converted to compost. Our findings show that above 50% of the manure should be converted to composts to improve the efficiencies (i.e., EROIs). Doing this could play a role in future sustainable intensification (Smith, 2013), since many pasturelands are converted to CAFOs to spare lands for restoration/rehabilitation. This same intensification, however, means that nutrients accumulate and can contaminate water resources (e.g., aquifers). Other options are to reuse biomass through production of biogas with anaerobic digestion; however, the present energy power source (i.e., hydroelectric power) in the study area provides electricity so inexpensive for most farmers that they have little financial incentive to invest in digesters (Villamor et al., 2020). Marco et al. (2017) suggests that multi-functional uses of livestock such as draught power, meat, dairy products, and manure can sustain the biomass flows of agroecosystems.

One of the overarching aims of the Sustainable Development Goals is the production of a stable, resilient planetary life-support system as a prerequisite for future human development (Griggs et al., 2014). However, some management approaches to increase human benefits such as food security may come at a significant cost to the global environmental systems. For example, a tradeoff may exist with FEWs in relation to energy use for irrigation of crops and dairies. To comprehensively understand the impacts of the dairy industry, there needs to be a better understanding of electricity use (which is limited due to data availability) and which irrigation systems are used for feed and industrial production (see Section 4.3. for further limitation on water). According to Daccache et al. (2014), modern irrigation systems (e.g., drip irrigation, pressure sprinkler) lower the amount of water used for irrigation but usually show the increased energy demand of water used (per m^3) due to pressuring requirements and the use of more energy-intensive water sources (e.g., aquifers). Tradeoffs may happen when the cost for modern irrigation becomes high because farmers may switch to more profitable but also more water demanding crops (García et al., 2014); this also affects water use efficiency, which is critical in an arid region such as the Magic Valley. Currently, farmers in the USRB enjoys cheap electricity from hydropower, but the basin is facing challenges from declining water levels of aquifers which threatens sustainable management of water resources (Anderson and Woosley, 2006).

4.2.2. Market potential and related practices in USRB

Hines et al. (2018) distinguishes between gross and base as two ways of measuring economic contributions of agribusiness to the Magic Valley and the state economy. The gross measure simply counts economic activity, including sales or outputs of an industry. The base measure credits to an industry the amount of exporting sales out of the system, or added value, of its backward (impact) linkages to the area. Similar analysis can be done with gross energy (GE) flows in the Magic Valley region. Following such analysis, manure generated by livestock in the Magic Valley and the rest of the USRB can be considered or measured under the gross analysis, since almost all of it is managed and redistributed within the USBR borders. The small portion that may be exported is offset by a few imports of manure among the region's bordering counties. In most cases, manure generates no income for the producer. There are several common practices to move solid and slurry manures out of the production areas (dairies or feedlots) to farmland for application as nutrients for crops and amendments for soils. Some of the variations on fresh and stockpiled manure management include, collection from the site or stockpile and application on land owned by the production unit, this can be done with their own equipment or, very commonly, by contracted custom operators. Loading by the production unit and transport paid or done by a third-party crop farmer that uses the manure in his/her fields. Multiple variations of these operations, differing by who pays for cleaning, loading, transporting, and application of the manure exist. Rarely though is the manure, as a product, paid for by the receiving or using party. The cost-sharing of the movement of the manure outside of the productive area is considered the "payment or savings" for the livestock producer. While the receiving of the nutrient and organic matter rich soil amendment (providing savings in fertilizer costs and soil health improvements) is the benefit for the crop farmer side of the arrangement. Second to direct manure application, composting is the most common treatment practice used in the USRB for solid manure. There are again several arrangements options possible between livestock production units' owners, custom composter companies, and purchasers or receiving crop producers. Transportation costs for compost are considerably less than that for solid manure, this allows livestock producers and custom composters to be able to dramatically reduce their transportation costs to further distances within the USRB and in some very few cases outside it. Livestock producers are willing to absorb the extra cost of producing compost to allow for a broader market and further distribution of nutrients within the USRB. In general, there is no profits generated from compost to the livestock producer but as cost savings. Crop producers, in turn, pay for the purchased compost, taking credit for the nutrients present in it towards their crops' needs. Some crop producers have other arrangements, including covering the actual cost of composting.

A great portion of forage crops in the Magic Valley region of the USRB have had a similar scenario, as with manure, in the sense of being a gross economic contributor, in this case with a significant ripple effect in the local economy. By 2012, around 45 to 50% of the planted crops surface in the Magic Valley, were used to feed dairy and beef cattle within the region, adding mostly to the gross contributions. In the Magic Valley agribusiness generate directly or indirectly over 50% of the gross regional product. Counting its ripple effects, agribusiness contributed 67% of the base output of the Magic Valley. The dairy processing industry (mainly cheese production and other dairy products) had the largest base output (37%), followed by potato and sugar beet processing (Hines et al., 2018). The USRB counts for 69% of the state of Idaho farm cash receipts, and the Magic Valley region alone counts for 47% of the state receipts (Westerhold, 2019).

4.3. Limitations

The application of this study in the FEW systems is limited in the sense that water is not explicitly included. This is because water has gross energy content of zero (0) and it does not directly impact on EI (Guzmán et al., 2018). Instead, we only used the energy input from irrigation (Table 6) as suggested by Pimentel (2009). However, the irrigation systems used in the basin have a large range of inefficiencies resulting from the type and application methods of irrigation (Hsiao et al., 2007). Substantial amounts of energy are required for some irrigation systems (particularly groundwater pumping) and these must be further investigated.

The estimation of energy input and output were also limited by the following: (1) USRB is assumed to be a closed system and only considers the biomass or produce prior to processing (excluding the transporting of compost to nearby towns); (2) the 2002 and 2012 yields for aquaculture were not available and not included in the final socialized biomass; (3) recycling of nutrients as an animal feed was not considered because data on the manure treatment (e.g., chemical or heat treatment including labor requirement) were not available; and (4) data on electricity for running irrigation for dairy production were also not available. Manure from pasture system was also not included due to the overlap of pasture land and shrubland as well as the number of cattle is not available for the target period. Furthermore, sustainable manure management (including storage methods) must consider realistic yields expectations and credit existing sources of nutrients (i.e., past application, recent legume crops) (Leytem et al., 2013). The method of manure application can have a profound effect on air quality. Broadcast application of manure is the most ubiquitous application method of both liquid and dry manure. Incorporation of manure into soil at time of application generally improves nutrient use relative to broadcast application (Leytem et al., 2013). Thus, method of application should be considered for future study.

New synthetic fertilizers and pesticides should also be considered for crop production. Site specificity and ecosystem type between regions within the basin should be considered (e.g., Magic Valley versus eastern portions of the USRB) due to the differences in production inputs and methods, rainfall and soil type. According to Cunfer et al. (2018), drier areas with poor soils have higher (energy) fertilizer imports than wetter areas.

5. Conclusions and recommendation

This study provides an example of the application of SM theory for understanding land intensification of the agroecosystems in the Upper Snake River Basin between 2002 and 2012. Further, this paper contributes to the understanding of the agricultural and livestock practices, land management, its capacity for covering the needs of the population, its environmental impacts, and long-term sustainability in the USRB. The historical changes in society-nature interrelations of the USRB over the two-time period show that the basin is an example of a high metabolic industrialized system, in which crop and dairy productions rely heavily on industrialized inputs (as a case of land intensification). In terms of energy outputs, the top three biomass producers are manure from livestock production, forage, and corn from crop production. Because of the growing number of livestock in the basin (through Concentrated Animal Feeding Operations), it is important to both reuse and reinvest the manure as by-product back to the agroecosystem to make the livestock production a more efficient agricultural system in the basin. Hence, we modified the energy accounting frameworks by Tello et al. (2015) and Guzmán et al. (2018) to explicitly incorporate the role of manure in agroecosystems. However, it should be noted that accounting for manure energy strongly depends on system boundaries to avoid double accounting. Findings suggested the percentage of manure to be reinvested as by-product (i.e., compost) that would improve energy production efficiency. Furthermore, a market potential was explored as appropriate for the basin. If practiced in the basin, Livestock_EROI is relatively higher compared whereas Final EROI is almost the same with other studies (Fraňková and Cattaneo, 2018; Guzman-Casado and de Molina, 2017). Nevertheless, this study faces several challenges and limitations to capture the whole dynamics of FEWS, including the negative implication on the nutrient balance of the agroecosystem (e.g., greenhouse gasses emissions and accumulation of phosphorous and nitrogen) that need further investigation.

Energy is now used as a surrogate for human consumption and economic growth (Griggs et al., 2014). Thus, we contend that the application of SM using energy is an innovative way to understand the flow of materials in FEW systems at the farmgate-level. Incorporating the flow of materials (energy) outside the farm, e.g., exchanges of flow with food processing and public sectors would provide a wider scale understanding of the drivers of land intensification as well as the dynamics of FEW in the whole basin. To be able to understand the integration (i.e., the nexus) among food systems, water systems, and energy systems it is useful to be able to examine linkages, changes, and dynamics within and between the three systems using a common currency (Bazilian et al., 2011; Hang et al., 2016). Water balance and hydrological processes can be represented in terms of energy expenditure and energy flows; food systems can similarly be represented from a thermodynamic perspective, and; clearly energy systems are inherently and explicitly represented using energy. Thus, the energy flow accounting provided by the SM approach provides a common framework and a common currency with which to examine the efficiency of food production systems in a FEWS context and if applied to future projections could be used as a metric for measuring the resilience of food productions systems under different configurations and perturbations.

Credit author statement

Grace Villamor: Conceptualization, Methodology, Data curation, Writing-Original Draft preparation. Andrew Kliskey: Supervision, Conceptualization, Writing- Original draft preparation and Editing. David Griffith: Writing-Review and Editing. Audrey Martinez: Visualization and Data Curation. Mario de Haro-Marti: Writing-Review, Market analysis and Data curation. Maribel Alfaro: Data curation. Lilian Alessa: Supervision and Conceptualization.

Declaration of competing interest

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

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Annex 1. Agricultural production system between 2002 and 2012 in USRB compared to state wide Idaho Source: USDA)

	2002		2012		Annual change % (Idaho)	Annual change % (USRB)
	Idaho	USRB	Idaho	USRB		
Population	1,293,953[a]	449,764[a]	1,567,650[b]	528,579[b]	2.1	1.7
Workers (#)	49,390	29,444	48,225	27,592	−0.2	−0.6
Total farms (number)	25,017	11,331	24,816	10,769	−0.1	−0.4
Irrigated farms (number)	15,901	8395	15,732	8123	−0.1	−0.3
Irrigated land (ha)	1,328,563	970,221	1,359,578	989,379	0.2	0.2
Average size of farms (ha)	190	275	191	283	0.1	0.3
N fertilizer consumption (kg/0.4 ha) [c]	91–145[d]	–	66.6[e]	–		
Chemical fertilizer treated farm (ha)	1,433,932	909,758	1,439,452	940,350	1.6	0.4
Manure treated farm (ha)	113,579	69,859	115,298	76,013	2.6	0.8
Trucks <40 hp (#)	14,177	6470	11,020	4657	1.2	−1.2
Trucks 99–40 hp (#)	19,725	8800	18,769	7798	−0.2	−0.4
Trucks >100 hp (#)	14,810	8925	17,830	10,846	1.1	1.4
Average barley yield (t/ha)	2.9	3.1	3.2	4.3	1.0	3.8
Average forage yield (t/ha)	9.0	9.8	9.3	10.3	0.3	0.5
Average wheat yield (t/ha)	4.8	5.1	5.9	6.2	2.2	2.2
Average potato yield (t/ha)	49.2	48.1	65.4[f]	65.4	3.2	3.6
Livestock number (cattle)	1,989,548	1,161,989	1,445,150	1,385,200	−2.7	1.9

Note: [a] 2000 Census data (https://data.ers.usda.gov/reports.aspx?ID=17827); [b] 2010 Census data (https://data.ers.usda.gov/reports.aspx?ID=17827); [c] No data is available from the USDA for Idaho on fertilizer use and prices; [d] Stark and Westermann (2008); [e] 2011 data from www.epa.gov/nutrient-policy-data/commercial-fertilizer-purchased#table1; [f] Patterson P (2012).

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