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FOSSIL TO RENEWABLE TRANSITION FOR SUSTAINING FOOD, WATER AND ENERGY

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ABSTRACT

Human appropriation of land and evapotranspiration for crop-livestock and dams to sustain people in cities are major drivers affecting the provision of global ecosystem services as climate, water, carbon, nitrogen, and phosphorus regulations. Human carbon emissions from fossil burning and land use worsen both the depletion of planetary services and global warming. The recognition that problems arise essentially from fossil-driven land use enlighten realistic solutions. In particular, finite fossil resources must be redirected to forge new renewable-based economies. The objective of this article is to show that healthy feedback loops of renewable markets are economically viable and a *sine qua non* condition for improving the resilience of natural and anthropic ecosystems to cope with forthcoming challenges of climate change. Urban and rural areas of a Brazilian municipality, São Gabriel do Oeste, are used as an illustrative case study to reducing carbon and water footprints through fossil resources reallocation to technological and social innovations in distributed renewable energy (biogas-to-power), stormwater recovery, wastewater treatment (biodigester), waste recover and recycling (organic fertilizers and soil conditioners), and recovery of basic ecosystem services.

Keywords Food and energy security, Biomass and fertilizers, Rural and urban sustainability, Mitigation and adaptation, Carbon and water footprints.

INTRODUCTION

It has been argued that humanity ‘decoupled’ from nature about 10 millennia ago, given birth to the Anthropocene Era (Grivetti, 2014; Monastersky, 2015; Ruddiman, 2013). The *animal spirit* of hunters and foragers, searching for food in random or more sophisticated Lévy walks (Baronchelli and Radicchi, 2013; Raichlen et al., 2014), was abandoned in the Neolithic Revolution (Bogaard et al., 2013; Grivetti, 2014; Weisz et al., 2001). While searching for food, human wastes were relatively well-distributed in landscapes, alike to other biogeochemical cycling of nutrients in nature (Holtgrieve et al., 2009). Nevertheless, human settling in land warped eventual resource conflicts to permanent conquer of land and people labor. The loss of recycling feedbacks due to humankind settling in the landscape can be regarded as the first ecological disruption imbued with the spiritual concept of ‘heaven lost’ (decoupling) or the tangible social concept of (centralized) ‘property’ that turned the sustainable primate into unsustainable human.

Enslaved people usually accomplished the land-labor in ancient civilizations, which landmarks the appropriations of manpower, net primary production (HANPP) (Weisz et al., 2001), and terrestrial evapotranspiration (HAET) (Sterling et al., 2013). Population growth from ancient civilizations to the industrial revolution allowed mankind taking control on climate due to greenhouse gas emissions from land use (Ruddiman, 2007). Land use has also been contributing to losses in the 'green water' flows (evapotranspiration, percolation, infiltration, and aquifer recharge) of the terrestrial water cycle (D'Odorico et al., 2010).

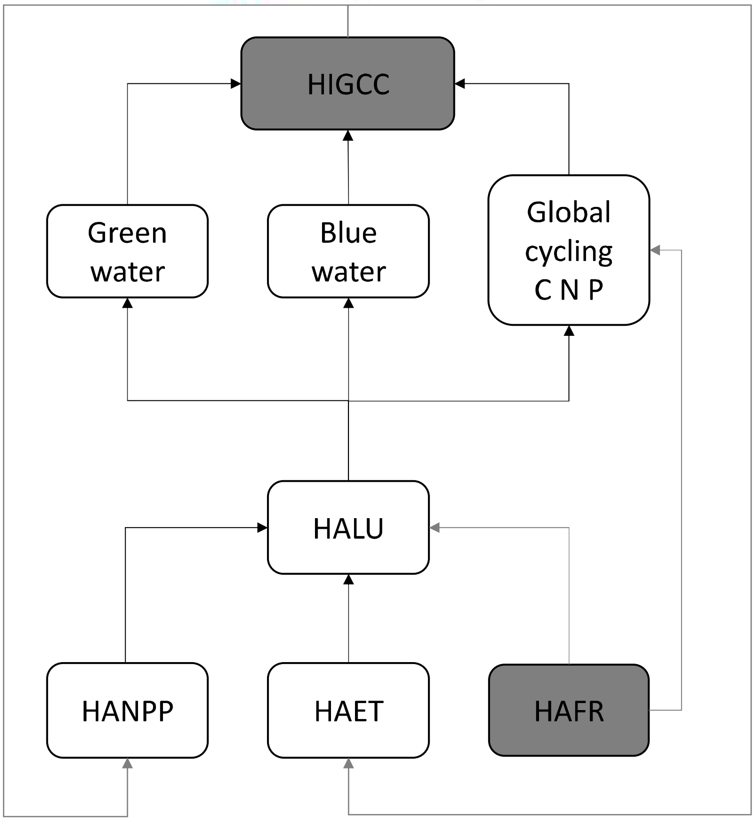
Human impacts on ecosystem services from early agriculture to industrial revolution, though still controversial, have been recently recognized (Monastersky, 2015; Ruddiman, 2013; Smith and Zeder, 2013). Following industrialization, the exponential human appropriation on fossil resources (HAFR) resulted in drastic land-use changes that, accordingly, accentuated biodiversity losses (Haberl et al., 2012), greenhouse gas emissions (Vitousek et al., 1997), and changes in hydrological (D'Odorico et al., 2010; Sterling et al., 2013) and the coupled nitrogen-carbon (N-C) cycles (Gruber and Galloway, 2008). The production of N synthetic fertilizers with C fossil energy, known as the Haber-Bosch process, has expressively increased following the postwar transition from bombs to food in the midtwenty century (Howarth, 2008). Fossil, nonrenewable resources have therefore boosted humanity growth at the expenses of global environmental services degradation and capital concentration since the end of the Second World War.

Under these spotlights, the objective of this article is to show that C fossil resources reallocation to engineering and social innovations is the key solution to make modern human societies more sustainable by reducing their carbon and water footprints. The envisaged solutions, based on a Brazilian case study, are associated to changes from highly centralized and nonrenewable to distributed and renewable power/food systems.

Framing the problem: unsustainable flows of resources

Figure 1 illustrates major feedback loops in the unsustainable human appropriation of Earth resources. From early civilizations to the dawn of the industrial revolution, humanity took control on HANPP and HAET in terrestrial ecosystems that contributed to the human appropriation of land use (HALU). Following the Second World War, HALU influences on ecosystem services (nutrients, blue and green water cycles) were further boosted by the human appropriation of (energetically dense) fossil resources HAFR (Figure 1). A healthy mature man should labor for about 2.5 years to reach the same energy content of a single fossil oil barrel; that is the elementary reason for HAFR being so important. Human labor in social pyramidal systems (many poor below, a few rich above) were steadily reinforced by fossil-driven machines that enhanced HALU with monocrops that increased human population far beyond the planetary safety boundaries (Rockstrom et al., 2009; Sterling et al., 2013).

Figure 1. Earth system feedbacks regarding unsustainable human impacts on Earth water, nutrient and climate. See text for explanation.



Boosted by HAFR (Figure 1), the number of water reservoirs, rural productivity and urban development has been growing exponentially (Monastersky, 2015). The associated C emissions to the atmosphere by these fossil-driven land use and fossil fuel burning (Houghton et al., 2012; Lima et al., 2008) has been affecting global flows and stocks of N and P (Gruber and Galloway, 2008; Watanabe et al., 2012; Watanabe and Ortega, 2011). Human interferences on the global C, N, P cycles, and the green and blue water cycles are the major drivers of human induced global climate change (HIGCC, see Figure 1) (Rockstrom et al., 2009; Sterling et al., 2013). Water bodies eutrophication (pollution) is largely affecting the quality of the blue water and it has been associated to the intensification of N, P usage in agroecosystems and also the lack of a N, P recovery in urban wastewater treatment systems (Baker, 2011; Kahiluoto et al., 2014; Schröder et al., 2011; Watanabe et al., 2012). This picture contrasts to ancient times, when human wastes were naturally distributed and recycled. The strong loss of waste recycling can be mostly attributed to the large-scale Haber-Bosch synthetic fertilizer markets.

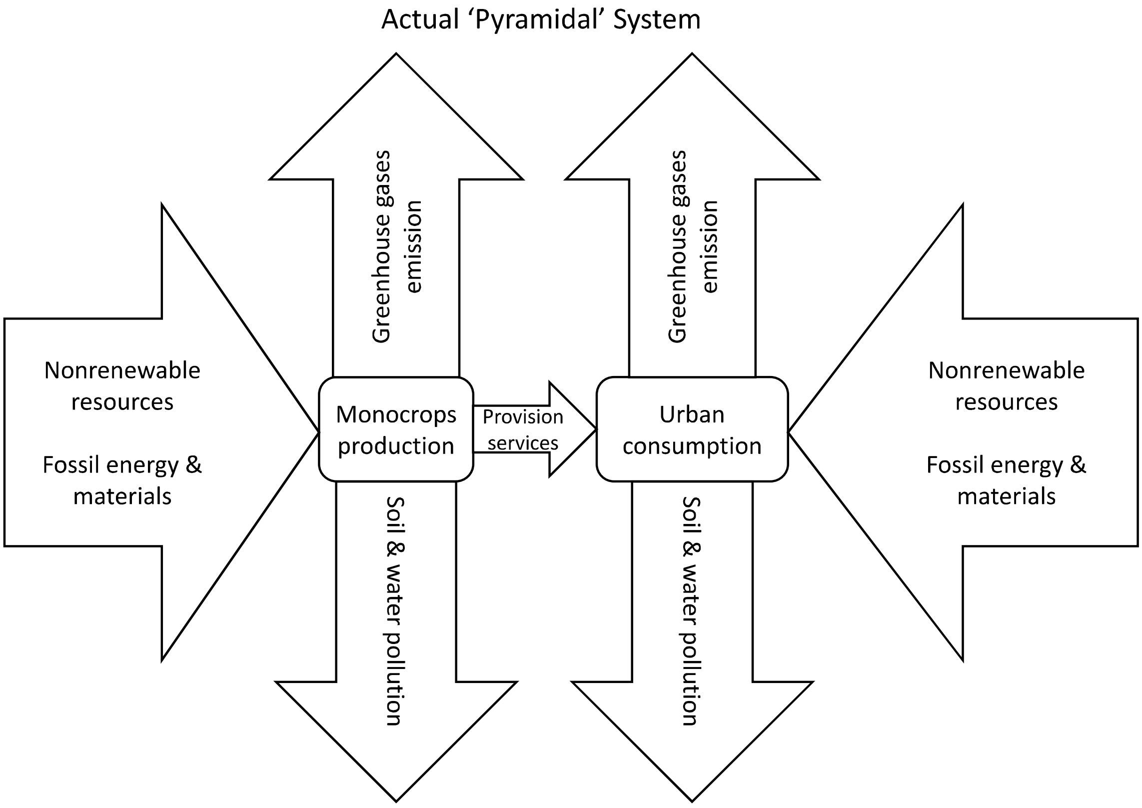
Assuming the Earth as a homeostatic, autopoietic system (Fernández et al., 2014) that expulses entropy for rendering internal coherence through self-regulating feedback loops (a measure of resilience), it is reasonable that HIGCC emerges as a natural negative feedback to alleviate unsustainable HALU hastened by HAFR (Ortega, 2004; Watanabe and Ortega, 2011) (Figure 1). The negative feedback loop of HIGCC on HAFR is unconsidered here, but, in a general sense, it tends to reestablish the buried C stock but very slowly (geologic timescale). Therefore, the urgency in promoting the transition from fossil to renewable economies is not a pure matter of sustainability (steady use of resources considering future generations) and HIGCC. Instead, the paradigm is the revamping adaptation to sustain humanity in the long-term taking into consideration the foreseen scarcity of fossil resources.

A skeptical view may claim that Earth-Sun are the key interactions involved in climate regulation eventually disrupted by unpredictable volcanic eruptions (Domingues et al., 2008). From this point of view, it would be effortless spending funds to stimulate less fossil-reliant economies. Nevertheless, the costs associated to HIGCC (Figure 1) can be much superior under no-action scenario (Leclère et al., 2014). It is far more prudent to mitigate climate change without being constrained by existing 'pyramidal' fossil-based economic systems and institutions, instead of risking to make the world uninhabitable to humanity (Rosen and Guenther, 2015).

Framing the solutions: feedback loops at local, regional scales

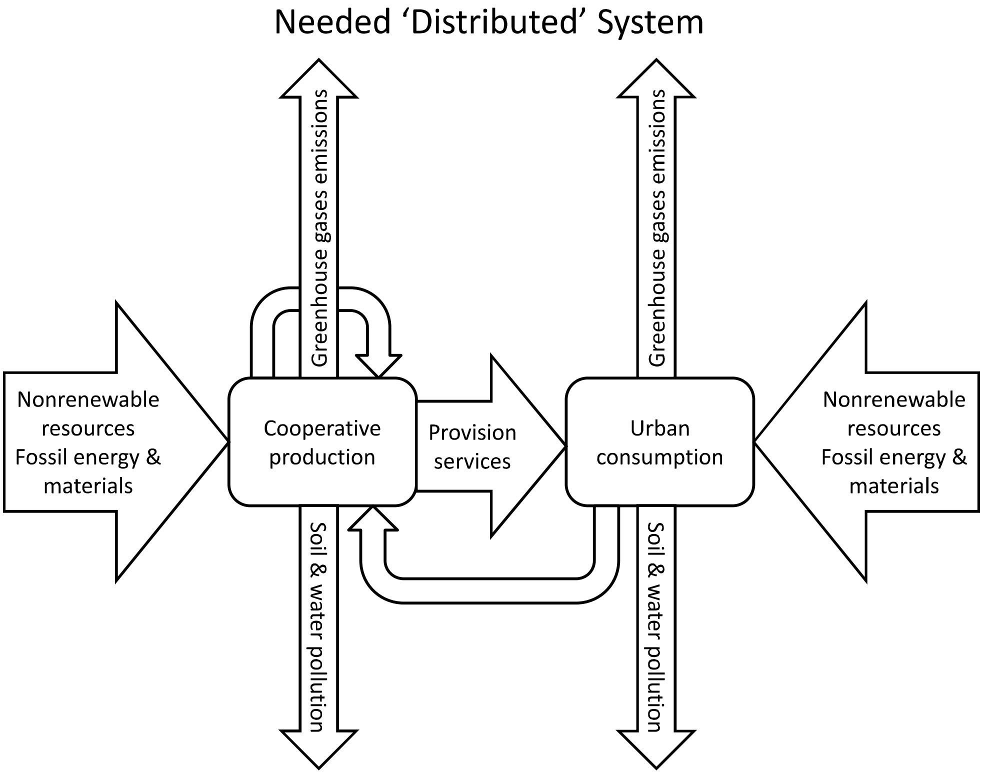
Rural production is a human activity essentially dedicated to the provision of food, fiber and more recently bioenergy (Power, 2010) for urban areas, where most of world people are living. The flows of materials in rural and urban areas are sketched in Figure 2. The arrow dimensions grossly indicates its relative importance from the total flow in the coupled system. Provision services of monocrops to urban in 'pyramidal societies' demand many fossil resources represented by lateral inflows. The magnitude of the provision services flow is very small in comparison to the lateral inflows and vertical outflows of wastes in the atmosphere, pedosphere and hydrosphere. The anthropogenic 'pyramidal' system reliant on HAFR represented in Figure 2 is inefficient due to: i) the large quantity of nonrenewable materials and energy involved in provision services of production and consumption; and ii) the financial resource concentration by means of ecosystem services losses leading to socioenvironmental distortions at local, regional and global market scales.

Figure 2. Unsustainable, unidirectional flows of rural-urban interactions boosted by HAFR. That model represents the actual socioeconomic 'pyramidal' growth leading to HIGCC (see Figure 1).



A solution to reduce the inflows of nonrenewables and outflows of hazardous residues in rural areas is the land management (Power, 2010) by distributed systems as cooperatives able to recycle intensive livestock manure, especially under crop-pasture rotation (Carvalho et al., 2014) in agroforestry arrangements (Buller et al., 2015a; Knoke et al., 2012). Alternatively, public policies for urban areas should also incentive both renewable power and efficient recycling of nutrients in wastewater treatment plants. Those sustainable feedbacks are illustrated in Figure 3. The outcomes of the sustainable feedbacks are, in essence, the reduced reliance on fossil resources by the transformation of the landscape from large monocrops to more distributed systems able to safely recycle potential hazardous pollution in the production and consumption productive chain in rural and urban ecosystems.

Figure 3. Back to sustainability: feedback recycling loops (internal rural, and urban returning to rural) in more renewable societies that produce provision services with reduced fossil reliance, prevent atmospheric and soil/water pollution, improve overall ecosystem efficiency, and recover to some extent ecosystem services.



Technology and innovation are crucial to the successful implementation of desired feedback loops in rural and urban areas depicted in Figure 3. The return of N, P, K and micronutrients to distributed, cooperate crop fields by means of renewable energy (Buller et al., 2015a) reduces C emissions and eutrophication (Bergier et al., 2014a; Kahiluoto et al., 2014). The following section presents the case study in Brazil, an 'en route' or emergent case of 'modern less-reliant fossil societies' that recover ecosystem services to adapt and to cope with climate change.

The case of São Gabriel do Oeste in Brazil

São Gabriel do Oeste (SGO) has today about 23,000 inhabitants. The municipality was created in the mid-twentieth century at the Upper Taquari River Basin (Figure 4), between the Pantanal savanna (wetland in lowlands) and the Cerrado savanna (originally woodland in highlands). The current SGO socioeconomic development is largely sustained by monocrops (soybean and corn) and swine livestock (see the right-sided image in Figure 4) followed by cattle, where it is possible to identify human land use over the landscape. Agricultural and livestock products are usually negotiated internally in Brazil or exported depending on market prices.

Figure 4. Case study in the Upper Taquari River Basin (Coxim River headwaters), in the geologic boundary of the lowlands Pantanal (wetland savanna) and the highlands Cerrado (Savanna). Source: SRTM data (left image) and Google Pro satellite composition images (right).

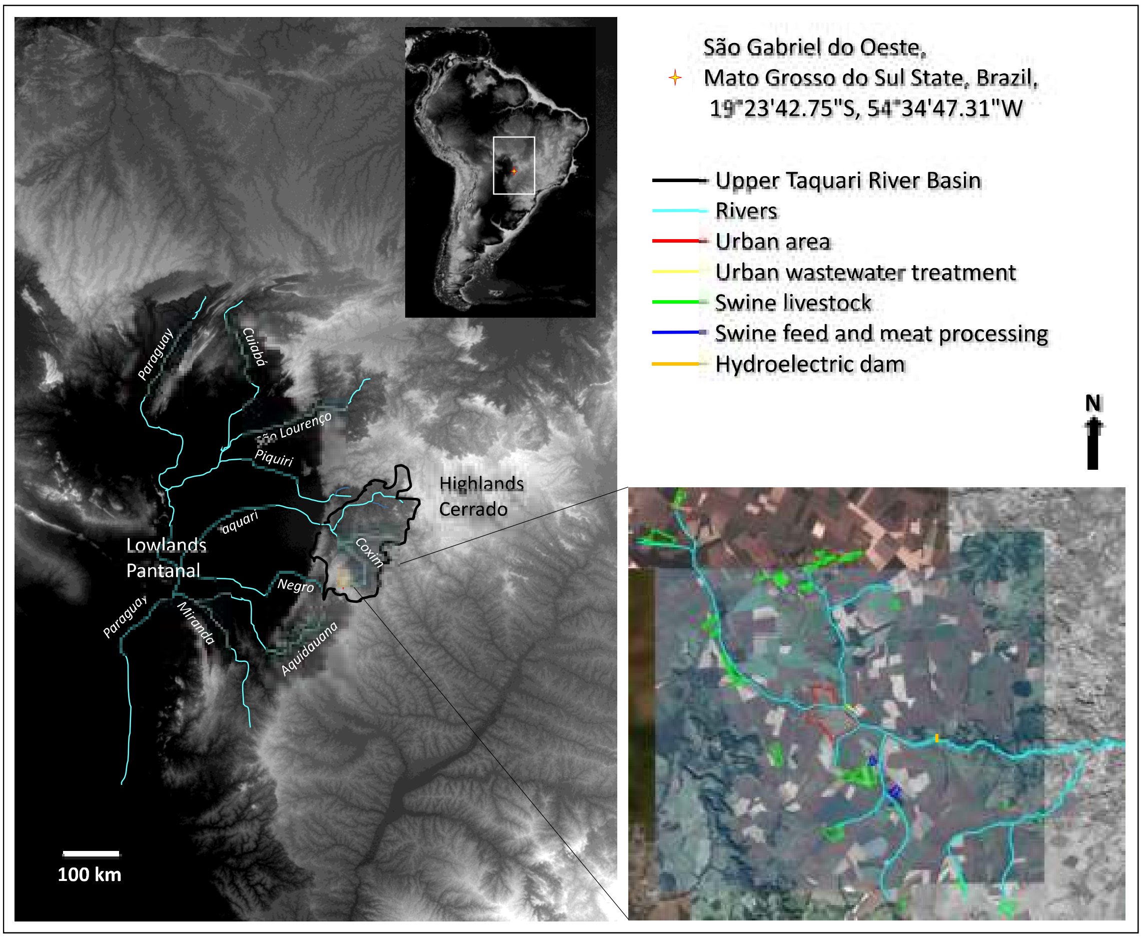
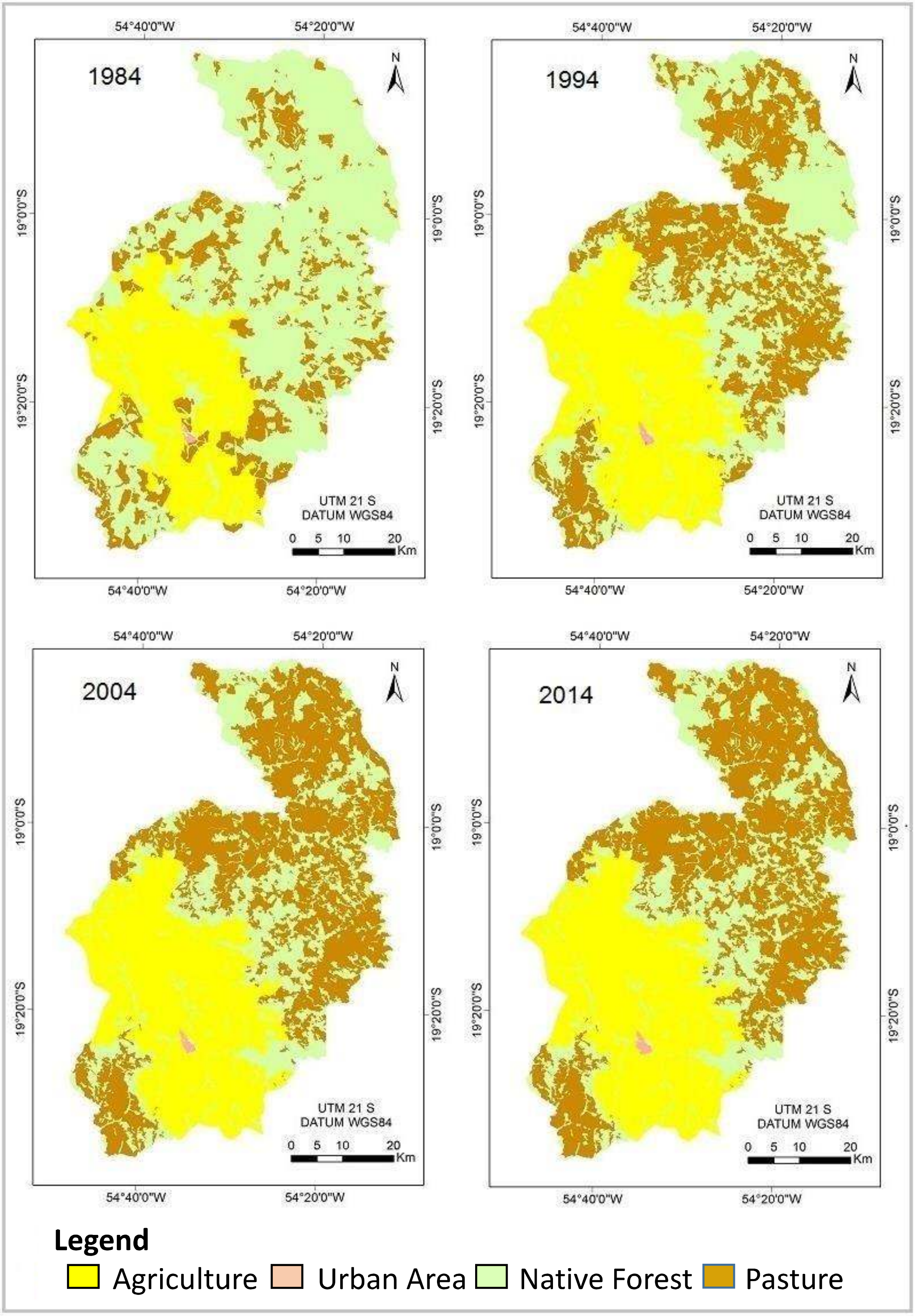


Figure 5 shows SGO land-use changes from 1984 to 2014 based on classification of Landsat imagery data. In the last 30 years, the native forest was suppressed by 48% (115,262 hectares), giving place to agriculture (32,817 hectares), urban area (284 hectares), and cultivated pasture (81,934 hectares). Deforestation for monocrops and pasture reduces evapotranspiration and soil infiltration, whereas enhances runoff and river discharge (D'Odorico et al., 2010; Watanabe and Ortega, 2014). Unnatural changes in the decadal oscillation of the annual flood-pulse of the Paraguay River, and large macrophytes productivity in Pantanal floodplains can be to some extent associated to highlands landscape change from natural ecosystems to fossil dependent agroecosystems (Bergier, 2013). SGO is an example of HALU boosted by HAFR (Figure 1). SGO land-use changes allowed achieving outstanding economic indexes as per capita Gross Domestic Product (GDP) 48% higher than that of Brazilian GDP average, and Human Development Index (HDI) of 0.729 in 2010, about 2% higher than the Brazilian HDI average (Buller et al., in press). Elevated GDP and HDI reflect in higher protein and caloric consumption (Tilman et al., 2011) that led to more innovation (Bettencourt et al., 2007), and economic growth (Buller et al., in press).

Figure 5. Land-use changes in SGO municipality in the last three decades. Prepared by Marilia R. Zanetti (CNPq student, grant number 562441/2010-7).



It has been shown that nations with high GDP are less corrupted (Ambraseys and Bilham, 2011). In the case of Brazil, in general, the struggle of corruption has been gradually increasing, and social inclusion has gained importance in public policy. It is then expected that GDP and GDP/capita can increase, which may demand more HALU to boost food (protein) production (Tilman et al., 2011).

In this context, the development of sustainable agricultural intensification (Valin et al., 2013) based on provision services with ecosystem services (Power, 2010) in cooperative schemes (Bergier et al., 2013a; Buller et al., 2015a) is a reasonable scenario to Brazil.

Innovations in renewable power, and nutrient and water recycling with social inclusion

The swine agroindustry is the most recent economic development in SGO whose monetary influx share is about 40%. From 2008 to 2015, the swine production has more than doubled. Most of swine livestock facilities (with a minimum of 1 to 2 thousands swine) were deliberately built closer to rivers to easily dispose swine wastes (See Figure 4). A few years later, the opportunity to reclaim certified emissions of reduction under the International Kyoto Protocol gave birth to anaerobic digesters to treat the swine wastes. Pointedly, local people realized that the digester biogas with ~60% vol. CH_4 could be managed for power (see http://tinyurl.com/o3zo6f7). Those engines have been wisely used in distributed swine farms for electric and hydraulic power in fertigation with an outstanding 40% efficiency in energy conversion (Bergier et al., 2013a). Such leapfrog engine economically allows the continuous power on-farm and surplus selling to the national electric grid. The efficient conversion of biogas-to-power became much more attractive in financial, socioeconomic and environmental concerns than the simple biogas flaring for obtaining certified emissions of reduction. Besides to biogas for electric power, its usage for powering fertigation systems opened the opportunity to dispose digested swine wastes in crop/pasture, improving unfertile Oxisol soils (Buller et al., 2015a). As an alternative to delivering the effluent directly to Pantanal´s river headwaters, fertigation with cheap renewable energy allows accurate dosage of nutrients in soil, accordingly to its nutritional status and crop demand, reducing the risk of soil contamination and water eutrophication (Bergier et al., 2014a).

An important issue is that the local agricultural cooperative (COOASGO) has its own animal feed fabrication facility (Figure 4), selecting good-quality soybean and corn grain, preferentially from local farmers, including those with fertigation system. This quasi-distributed (or less pyramidal) system keeps swine productivity and sustainability at a relative better level (Buller et al., 2015a), with economic and socioenvironmental improvements, promoting in some extent the required distributed loop of nutrient recycling depicted in Figure 3. Moreover, in the same perception of innovation in water resources (Parolari et al., 2015), Embrapa has been stimulating the adoption of stormwater recovery/storage systems (Bergier and Almeida, 2010), reducing water acquisition costs and preventing the depletion of high-valued aquifer (see http://tinyurl.com/kg9g8f2). The stormwater recovery/storage is an important strategy to mitigate impacts over the blue water cycle (D'Odorico et al., 2010). The recovery of the green water cycle (D'Odorico et al., 2010) can be enhanced by the adoption of integrated agroforestry systems (Bergier, 2013; Buller et al., 2015a; Watanabe and Ortega, 2014). Nonetheless, ideally, forest recovery should emphasize native species considering their importance as C soil sink and as a source of biodiversity (Buller et al., 2015b).

A new technology was successfully developed for separating the solid organic fraction of the swine wastes (see also http://tinyurl.com/ncw6qty). The solid fraction (recalcitrant C and minerals, sediments) of the biodigester and effluent lagoon is separated by rotary sieves and accumulates in a tank with a slow-rotation mixer. The preconcentrate is pumped to a high-speed rotary sifter (decanter) returning the liquid to the effluent lagoon or biodigester whereas the solids are stored in 700-kg bags. The separated solid is a ready-for-use organic fertilizer (see Table 1) also prone to pyrolysis for high-value swine-biochar production (Bergier et al., 2013b).

Table 1. Chemical properties of the solid and liquid phases of digester and effluent sediments.

	Separated solids from digester sediments	Separated solids from effluent sediments	Separated liquids from effluent sediments	Maximum concentration permitted to agriculture (Hespanhol, 2014)			Unit
				EPA 40 Part 503	CONAMA 375/2006	CETESB P4230/1999	
pH ($CaCl_2$)	6.8	6.5	8.4	-	-	-	
Cationic Exchange Capacity	6.6	4.3	7.0	-	-	-	$cmolc/dm^3$
As	<0.01	<0.01	<0.01	75	41	75	mg/kg
Cd	<0.1	<0.1	<0.1	85	39	85	mg/kg
Cr	<0.1	<0.1	<0.1	3000	1000		mg/kg
Pb	<0.01	<0.01	<0.01	840	300	840	mg/kg
B	411	776	48	-	-	-	mg/kg
Zn	411	776	2560	7500	2800	7500	mg/kg
Cu	733	944	3220	4300	1500	4300	mg/kg
Fe	1864	3978	4355	-	-	-	mg/kg
Na	1228	1141	5500	-	-	-	mg/kg
Mn	783	990	505	-	-	-	mg/kg
S	8	4	13	-	-	-	g/kg
P	32	60	19	-	-	-	g/kg
Mg^{2+}	20	47	10	-	-	-	g/kg
Ca^{2+}	25	38	15	-	-	-	g/kg
K^+	5	4	30	-	-	-	g/kg
Organic C	279	142	181	-	-	-	g/kg
Inorganic C	183	163	280	-	-	-	g/kg
Recalcitrant matter	314	281	481	-	-	-	g/kg
Total organic matter (combustion)	795	526	793	-	-	-	g/kg
Organic matter	481	245	312	-	-	-	g/kg
Total N	27	41	50	-	-	-	g/kg
C/N (Organic C and Total N)	10	4	4	-	-	-	-
C/N (Total C and Total N)	17	8	9	-	-	-	-
Fixed minerals (ashes)	205	474	207	-	-	-	g/kg
Insoluble fixed minerals	31	122	41	-	-	-	g/kg
Soluble fixed minerals	174	352	166	-	-	-	g/kg
Humidity loss at 60-65 ^{0}C	52	26	96	-	-	-	%
Humidity loss at 65-110 ^{0}C	57	42	97	-	-	-	%

The separated solids are rich in P and N, enhanced by struvite crystals ($MgNH_4.PO_4.6H_2O$) formation (Rahman et al., 2014) in effluent lagoon due to pH ~ 8.5 (see Table 1). After submitted to pyrolysis, the organic fertilizer maximizes the slow nutrient release properties and C-refractory properties (Bergier et al., 2014b).

Despite the modest improvements in the sustainability indexes of the rural system driven by distributed renewable biogas (Buller et al., 2015a), the recycling of water can reach about 50%, whereas the recycling of N, P, and K (in grain production to swine feed) is virtually 58%, 5% and 48%, respectively (Buller et al., in preparation).

The importance to implement urban-to-rural feedback loops

Urban systems obey universal scaling relations with population size, characterizing rates of innovation, wealth creation, patterns of consumption and human behavior as well as properties of urban infrastructure. To sustain continued growth of urban systems, major innovations or adaptations must arise at an accelerated rate (Bettencourt et al., 2007). The increase in world annual agricultural yields (Cassidy et al., 2013) to sustain people in cities by 2050 must be at least 2.4%, though major crops are increasing at a rate around or below half of this value (Ray et al., 2013). Conversely, it has been shown that planetary boundaries (Liu et al., 2015; Rockstrom et al., 2009) limit food production boosted by HAFR rather than the population growth (Kahiluoto et al., 2014). Earth will be fine in the long run, but the prospects are, however, less clear for humanity (Frank and Sullivan, 2014) in particular due to HIGCC. An immediate return to the sustainable planetary boundaries (Liu et al., 2015; Rockstrom et al., 2009) would lead to widespread starvation and a decrease in the current human population. Whereas dietary changes to vegetarian and other sources of proteins, reduction of losses across the food supply chains, and efficient recycling of nutrients can make a substantial contribution (Cassidy et al., 2013; Kahiluoto et al., 2014). Therefore, the internal rural and urban-to-rural loop depicted in Figure 3 is of crucial importance because urban sewage treatment is not commonplace, particularly in developing countries. In Brazil, for instance, more than 60% of the municipalities did not adequate by 2014 to the Federal Policy on solid wastes, in which nutrient recycling is a primordial regulatory aspect.

Here we propose that similar systemic solution given to the distributed agroforestry-livestock industry fits to urban areas because they arise from the same root. Taking SGO as an example, 22,000 people (confined) in the city of SGO may daily produce about 11 metric ton of feces and 22 to 44 m^3 of urine, expending about 132 to 176 m^3 of groundwater for flushing. The location of SGO wastewater treatment facility is show in Figure 4. The system is composed of two (open) anaerobic lagoons and a larger aerobic lagoon. The anaerobic lagoon reduces the C content by emitting CH_4 and CO_2 to the atmosphere. The effluent reaches the aerobic lagoon where N and P are processed. It is noticeable, however, the eutrophication of the aerobic lagoon, that delivers eutrophic waters with cyanobacteria downstream at a hydroelectric reservoir (Figure 5). For this reason, hydroelectric dams may not be totally considered clean energy because the land-use in the surrounding terrestrial landscape must be taken into account (Bergier et al., 2014a). The redesign of the wastewater treatment station system of SGO (including rainstorm collector/storage at people houses for bath use, which also helps amending city flood) with biodigesters to efficiently produce and collect biogas, can generate power to self-use and to the Municipality City Hall, schools, city illumination or several other public services. Moreover, fertigated areas in the surroundings of the wastewater treatment plant would produce e.g. timber. Accordingly to the urban-to-rural required loop (Figure 3), the separated digested solids rich in recalcitrant organic C and nutrients (NPK) can further be returned to farmlands following FAO recommendations (Pescod, 1992) or in the form of biochar after pyrolysis. That measure of reconnecting rural and urban recycling can thus substantially improve overall human sustainability at local, regional and global level if widely adopted.

CONCLUSION

By means of engineering innovation, it is possible and economically viable to reestablish sustainable internal rural and urban-to-rural feedback loops of water and nutrient recycling with renewable power. Actual fossil resources should be spent in new infrastructure for supporting an emerging renewable economy based on ecosystem services recovery, renewable energy and organic fertilizers that altogether reduce water and carbon footprints. Sustainability involves socioeconomic and environmental gains and cooperative (distributed) schemes can bring together small, medium and large interests in a synergic and more sustainable system. Governments should then incentive distributed arrangements for power, food and goods, grounded on innovative solutions as those reported herein.

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