United Nations
Educational, Scientific and
Cultural Organization

International
Hydrological
Programme

UNESCO-IHP Water Programme for Environmental Sustainability,
Climate Change and Human Impacts
on the Sustainability of Groundwater Resources:
Quantity and Quality Issues, Mitigation and Adaptation Strategies in Brazil

Integrated Environmental Assessment of Agricultural and Farming Production Systems in the Toledo River Basin (Brazil)

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Published in 2013 by the United Nations Educational,
Scientific and Cultural Organization

7, place de Fontenoy, 75352 Paris 07 SP, France

ISBN 978-92-3-001138-3

Cover design and illustrations: Pier Paolo Franzese

Printed by: UNESCO

Printed in English

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Background

Brazil has plenty of water resources but they are unevenly distributed across the country. In this context, groundwater plays a crucial role supplying towns, industries, and agricultural and farming systems. Climate variability and change as well as human activities could significantly impact Brazilian groundwater resources. The IPCC scenarios for temperature and rainfall in Brazil for the next 20-50 years show a significant warming across the country and a possible reduction of annual rainfall in portions of the north-eastern region and in the Amazon. In addition, there are risks of overexploitation and contamination of groundwater resources in vulnerable agricultural areas. The evaluation of these impacts and the definition of appropriate mitigation and adaptation measures are therefore much needed.

To address these issues, a UNESCO-IHP project involving Brazilian and Italian institutions was carried out. The main goals of the project entitled "UNESCO-IHP Water Programme for Environmental Sustainability, Climate Change and Human Impacts on the Sustainability of Groundwater Resources: Quantity and Quality Issues, Mitigation and Adaptation Strategies in Brazil" were: (**a**) to understand the hydrologic relationships between control and response variables in groundwater systems under the impact of climate change and human activities; (**b**) to identify mitigation and adaptation measures for groundwater management under those impacts; (**c**) to evaluate hydrological adaptive and mitigation measures in terms of replicability, sustainability, impacts of both global and regional climate change, and equality in access to groundwater, both in quantitative and qualitative terms.

In this context, the present study aimed at performing an integrated environmental assessment of agricultural and farming production systems located in the Toledo River Basin (Paraná State, Brazil). Water, material, energy, and money resources invested in supporting such production systems were evaluated with the final goal of calculating a large set of multi-criteria indicators useful to describe the environmental performance and sustainability of the production systems at farm and basin level. Finally, three alternative scenarios were drawn to explore the sustainable use of resources according to different land uses, production levels, and management practices, paying special attention to water use.

Executive summary

In this study, the environmental performance and sustainability of soybean-corn intercrop and pig production systems in the Toledo River basin (Brazil) were explored. The main steps of the study were: **(a)** identification of the spatial and temporal boundaries of the investigated systems; (**b**) modeling of the selected agricultural and farming production systems by means of H.T. Odum's energy-symbolic language; (**c**) inventory of the main water, mass, energy, and money input flows to the production systems; (**d**) conversion of the quantified input flows by means of appropriate intensity factors according to different environmental assessment methods; (**e**) calculation of mass, water, energy, and emergy performance indicators at farm level; (**f**) calculation of ecological, water and carbon footprints generated by the investigated production processes; (**g**) upscaling of up-stream and down-stream indicators of environmental impacts and sustainability at basin level; (**h**) calculation of indicators of environmental performance and sustainability for three alternative scenarios at basin level.

An integrated assessment framework was implemented by using the following methods: Emergy Synthesis, Embodied Energy Analysis, Material Flow Accounting, Life Cycle Assessment, Ecological Footprint, Water Footprint, and Carbon Footprint.

The multi-criteria approach used in this study provided useful information about the interactions and use of natural capital, human-driven resources, and ecosystem services supporting agricultural and farming production systems in the Toledo River basin (Brazil). The outcomes of the study will support local managers and policy makers committed to develop management schemes and environmental policies based on the sustainable management of agroecosystems. In addition, the results of the study will provide a useful benchmark for future investigations.

All indicators were calculated at farm scale and then upscaled to basin level to assess the environmental load of alternative scenarios at regional level. The indicators of environmental performance highlighted the intensification process occurring in the basin over the last decades. The indicators of environmental sustainability showed an increased dependence on non-renewable resources (mainly imported from outside the region) supporting the intensive agricultural and farming systems located in the Toledo River basin. The scenario analysis showed the environmental support and impacts for three alternative options in terms of land use, production levels, and management practices. The assumptions made in Scenario A pointed out a possible reduction of the environmental impacts in the basin. The use of water, the manure concentration as well as the interaction between the increasing impact of human-dominated production activities and the effects of climate change in the region are also discussed in the study.

1. Introduction

The Toledo River basin is located in the south-western portion of the state of Paraná and has an area of about 92 km^2 (Winter et al., 2005). Underlain by the Guarani aquifer, the Toledo River basin has a very high potential for groundwater use. The basin is characterized by intensive agricultural and farming production processes, among which the most important are soybean-corn and pig production systems. Most of the manure produced by pig production systems is used to fertilize soil with little or no treatment. Such a practice generates a set of environmental impacts due to the excess of manure produced in this region. Soybean-corn production systems are frequently fertilized with manure and they represent an important cropping system in the Toledo River basin. These crops are also related to the pollution of groundwater due to a massive use of agrochemicals. Moreover, the lower reach of the Toledo River crosses the urban area of the city of Toledo that is experiencing a fast population growth. Both agricultural and farming production systems are related to a massive use of groundwater and water pollution phenomena. Over time, the cumulative application of manure and agrochemicals as well as the urban sprawl can lead to severe groundwater pollution.

In this study, energy, material and water requirements of a selected farm integrating corn-soybean and pig production in Toledo River basin were assessed implementing the following steps:

1. Identification of the spatial and temporal boundaries of the investigated systems;
2. Modeling of the selected agricultural and farming production systems by means of Odum's energy-symbolic language;
3. Inventory of the main water, mass, energy, and money input flows;
4. Conversion of the quantified input flows by using appropriate intensity factors according to different environmental assessment methods;
5. Calculation of mass, water, energy and emergy performance indicators at farm level;
6. Calculation of ecological, water, and carbon footprints generated by the investigated production processes;
7. Upscaling of up-stream and down-stream indicators of environmental impacts and sustainability at basin level;
8. Calculation of indicators of environmental performance and sustainability for alternative scenarios at basin level.

The integrated assessment framework was implemented by using the following methods: Emergy Synthesis, Embodied Energy Analysis, Material Flow Accounting, Life Cycle Assessment, Ecological Footprint, Water Footprint, and Carbon Footprint.

This framework provided a set of indicators able to describe the environmental performance and sustainability of the investigated systems in terms of yield, resource use and efficiency, local versus imported resource use, renewable versus non-renewable resource use, environmental load, sustainability, interaction with and dependence on local environment, and intensity of water and land use.

Indicators calculated at farm scale were upscaled to basin level to assess the impacts of alternative scenarios at regional level. Special attention was paid to water use supporting agricultural and farming production systems. The relationship between the increasing impact of human-dominated activities and climate change are also discussed in the study.

1.1 Toledo River Basin

The Toledo River basin is located in the south-western portion of the state of Paraná, covering an area ranging from 24°43' to 24°47' South latitude and from 53°33' to 53°45' West longitude. The Toledo River has a length of about 27 km and it is the most important river of the town of Toledo. Its water represents an important resource, exploited to supply 40% of the population of the town of Toledo (Winter et al., 2005; Tomm, 2001).

The Toledo River basin is a sub-basin of the São Francisco Verdadeiro River and it is part of the larger Paraná III hydrographic basin. The Toledo River basin accounts for only 4.2% of the area of Paraná state but it is considered to play an important role, also because of its contribution to the reservoir of the Itaipu Binacional dam. Moreover, the Toledo River basin is underlain by the Guarani aquifer, showing a very high potential for groundwater use. The multiple use of water in this area can cause conflict between energy generation, farming systems, agricultural activities and urban sprawl (PNMA II, 2002).

The area of the Toledo River basin is about 9,290 ha and it has a population of approximately 550 inhabitants. The basin comprises 195 farms, of which 47 include pig production activities (Winter et al., 2005). The soybean-corn production is very important for the local economy but it also contributes to water pollution problems due to the high use of agrochemicals. The population of Toledo municipality is 116,774 inhabitants while the total cropped area covers about 75,000 ha (IBGE, 2009). The local economy is based on agriculture and livestock farming. The main crops are: soybean, wheat, corn, beans, rice, cassava, castor bean, peanut, cotton, sugarcane, and tobacco. The main livestock products are poultry and pork (Tomm, 2001).

The total area cropped with soybean in Toledo municipality covers 65,300 ha with a harvest of 206,634 tons of soybeans in 2008 (IBGE, 2009). Figure 1 shows an example of cropping system integrated with several pig farms (stables) located very close to the Toledo River basin.

Figure 1. Aerial photography showing cropping systems integrated with pig farms located very close to the Toledo River basin. (Source: Google Maps).

1.2 Pig production system

Pig production is an important economic activity in Brazil with a herd of 35 million heads, representing the fourth largest producer worldwide (3 million tons per year), the fourth largest exporter (600,000 tons per year), and the sixth largest consumer (11-13 kg inhabitant^{-1} year^{-1}). Pig production is mainly concentrated in the southern part of Brazil (IBGE, 2006; Miele and Waquil, 2007).

Pig production has dramatically changed in the last three decades, shifting from a small-subsistence model to a larger number of intensive farming systems. This trend towards industrial feeding operations has been driven by the reduction of production and logistic costs for both farmers and meat processors (Kunz et al., 2009; FAO, 2006). However, this model is causing several environmental problems associated with a higher concentration of animals as well as a higher dependence on external resources (Cavalett et al., 2006, 2010). An additional trend in meat production is the migration of production operations from developed to developing countries, basically due to: lower operating costs, greater availability of feed, land, and water as well as less restrictive environmental policies in comparison to Europe (EU-nitrate directive) or USA (EPA–CAFO rules) (Kunz et al., 2009; FAO, 2005).

In Brazil, effluent disposal in superficial waters is covered by federal regulations (CONAMA, 2005) which are very restrictive for animal wastewater. However, the regulation for effluents disposal through land applications is more flexible and differs according to different regions. At present, there is no regulation for water reuse.

Around 12,000 pig producers are located in the Parana III hydrographic basin. They produce 1.4 million animals, with 6,000 heads butchered per day (PNMA II, 2002). The Toledo River basin hosts 47 farms producing about 11,000 pig heads per year. Such an amount of pigs produces approximately 150,000 liters of manure per day (Winter et al., 2005). An average pig produces a daily amount of manure equivalent to about 10 human beings. This way, the pig population of the basin has an impact in terms of manure production equivalent to a population of 110,000 inhabitants, while the actual population of the basin accounts for only 550 inhabitants. Figure 2 shows a picture of a pig production system located in the Toledo river basin.

Figure 2. Pig production system located in the study area of the Toledo River basin (Source: Parthenope University of Naples, Italy).

The storage of liquid manure and its application to soil is the predominant manure management practice in Brazil and other countries. This is due to simplicity and low management cost as well as the possible reduction of the costs related to the replacement of chemical fertilizers by manure nutrients (Kunz et al., 2009). The main disadvantage of land manure application is the fact that manure transportation is not economically viable for distances beyond a few kilometers (Seganfredo and Girotto, 2004).

Taking into consideration the UN recommendation of manure spread of 170 kg of nitrogen per hectare per year (European Council Regulation, 1999), in the Toledo basin it would be necessary to have about 780 ha to dispose of the produced manure avoiding environmental problems. This figure highlights the problem of lack of available land for manure spread since 72% of the farms located in the basin have less than 20 ha of land (Winter et al., 2005). Moreover, according to the Brazilian Forestall Law, all the farms in this area of Brazil must preserve at least 20% of the area with original forest. The resulting lack of available land determines the accumulation of manure in soil and water with the related environmental problems. In the Toledo River basin 84% of farms have a creek, 63% have spring water, and 47% have some area with original forest. The riparian forest accounts for about 4% of the basin area (Tomm, 2001).

There is a set of potential environmental impacts involved in pig production due to its rapid expansion. These impacts (increasing atmospheric emissions of ammonia, nitrous oxide and methane as well as decrease in water quality) can be noted in all segments of the supply chain, from grain and animal production to processing, distribution and consumption. Because of the large amount of waste generated by pig production and its impact on air, soil, and water resources, animal production has been highly debated by both local and regional governments (Kunz et al., 2009; Sharpley et al., 2002; Pereira et al., 2008).

The effects of manure on water are caused by the excess of nitrogen and phosphorus. The effects on air are due to toxic gas emissions (ammonia, nitrous oxide, and methane) and unpleasant odors to human population. There are also negative influences caused by intensive pig production on animal and vegetal biodiversity (Pereira et al., 2008). In addition, because of the great variety of soils, plant fertilizer requirements, agronomic practices and manure composition, land application of manure has shown the potential to promote an imbalance in soil-plant nutrient absorption capacity (Seganfredo, 1999).

The intensification of pig production in recent decades by using less area and specific diets is based on the massive use of fossil energy in all production processes such as installations, feed, medicaments, and transport. The huge concentration of pig farms in some areas, together with coal extraction and the wide use of agrochemical, has created a severe threat to the Guarani aquifer, the biggest water source of South America (Pinheiro Machado Filho et al., 2001).

The inadequate management of pig manure can also contribute to raising emissions in the atmosphere. For example, each molecule of N_2O has a potential contribution to global warming effects equivalent to 296 molecules of CO_2 (IPCC, 2006). Another crucial issue related to pig production is the direct and indirect use of water. For instance, according to a conservative estimation, at least 3.5 liters of water are needed per pig per day only as cleaning water (Pinheiro Machado Filho et al., 2001).

1.3 Soybean-corn production system

In the past three decades soybean has become one of the main agricultural commodities in Brazil. Next to the United States, Brazil is the second largest producer and exporter of soybean worldwide (FAO, 2007). The National Supply Company (CONAB) estimated Brazil's harvest to be approximately 57.1 million tons in 2008/09. During this harvest period about 21.7 million hectares were cultivated for soybean production in the whole country (CONAB, 2009), a land area equal to the size of Great Britain.

The rapid expansion of soybean production in Brazil has been stimulated mainly by the industrial demand for a cheap, high-protein ingredient for animal feed in Brazil and Europe. About 80% of the soybean produced worldwide is used by livestock industry (Gelder and Dros, 2005). The grain is used to supply intensive meat and dairy production, feeding the ever-growing demand for cheap meat. The animal feed industry is expecting an average increase in world consumption of meat from 38.2 kg per capita per year in 2005 to 42.6 kg by 2020 (Gomes et al., 2008).

Soybean is a very important crop in the Toledo region. In 2008, the area cultivated with soybean in the Toledo region was 65,300 ha with a harvest of 206,634 tons of soybean (IBGE, 2009). Soybean is produced in the region during the summer season while corn and wheat are cultivated in the same area in the other seasons. Corn is a feed for pig production while soybean is mostly sold to the market or exchanged with soybean crusher for soy meal to be used as a pig feed ingredient. Intensive agricultural practices for soybean production rely on direct and indirect use of fossil fuels (diesel, machinery, fertilizers, and agrochemicals). The massive use of non-renewable resources generates high pressure on the local agroecosystem, jeopardizing the sustainability of soybean production (Pengue, 2005; Ortega at al., 2005; Cavalett and Ortega, 2009).

Figure 3 shows the soybean and corn production systems located in the study area of Toledo River basin.

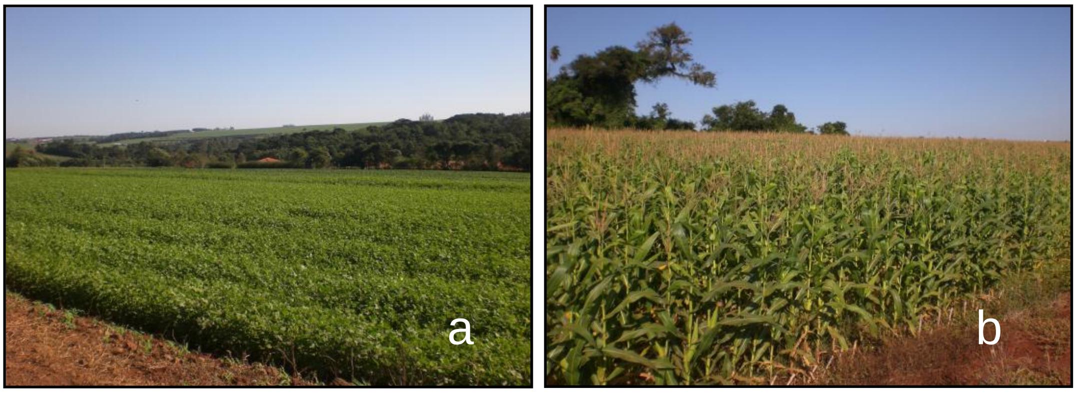

Figure 3. Soybean (a) and corn (b) field in the study area of Toledo River basin (Source: Parthenope University of Naples, Italy).

1.4 Problems related to water use in the Toledo River basin

In recent years, several interruptions to the water supply occurred in the town of Toledo because of the low water quality caused by pig manure pollution. The chemical pollution in the Toledo River (mainly due to widespread use of agrochemicals) also caused some interruptions in the water supply to the population of the town of Toledo (Nieweglowski, 2006).

The Rio Sao Francisco Verdadeiro hydrographic basin (which includes the Toledo River as a sub-basin) has been cited as the most polluted among those debouching into the reservoir of the Iguaçu dam. This basin pollutes the lake of the Iguaçu dam with up to 60,000 tons of sediment per year (Nieweglowski, 2006).

2. Methodology

Sustainability can be analyzed from an environmental, social or economic perspective. Moreover, sustainability can be assessed at different scales. At each scale, specific questions can be posed. Natural and human economies are self-organizing systems, where processes are linked and therefore affect each other at multiple scales. Investigating the behavior of a single process and merely seeking the maximization of only one parameter (energy efficiency, production cost, jobs, etc.) is unlikely to provide sufficient insights to properly inform policy making. Instead, several methods can be selected and applied at different scales by developing an integrated assessment framework. Each method can supply a piece of information about system performance at an appropriate scale, highlighting different perspectives and concerns complementary to each other. Integration supplies a deeper understanding of the overall picture and it is characterized by an "added value" that could not be achieved by means of a single crtiterion approach. The choice of a proper set of methods is therefore of crucial importance (Buonocore et al., 2012; Häyhä et al., 2011; Ulgiati et al., 2006; 2010).

The rationale underlying different methodologies for evaluating resource production and consumption as well as the need for integration of different approaches towards a comprehensive assessment framework was discussed by Ulgiati et al. (2006; 2008; 2011a,b). In this study an integrated assessment framework was implemented by using the following methods: a) Emergy Synthesis, b) Embodied Energy Analysis, c) Material Flow Accounting, d) Life Cycle Assessment, e) Ecological Footprint, f) Water Footprint, and g) Carbon Footprint. The selected methods have different scientific backgrounds and frames of attention and they account for the direct and indirect environmental support required to generate and make available natural and human-driven resources invested in the production process under investigation.

In this study, the investigated systems were treated as a "black box" and an inventory of all the input and output flows was firstly performed on its local scale. This inventory formed a common basis for all subsequent assessments carried out in parallel to ensure the maximum consistency of basic assumptions and input data (Annexes 1, 2, and 3). The outcome of such an integrated assessment framework was a set of multi-criteria indicators calculated at multiple scales and describing different aspects of the system performance and sustainability as well as different environmental problems and concerns.

Evaluating alternative scenarios, regarding different possible uses of natural and economic resources, necessarily requires the adoption of a multi-criteria approach. There is no single "optimal" solution to all problems. Only an assessment based on several complementary methods can highlight the inevitable trade-offs characterizing alternative scenarios, thus enabling a wiser selection of the option embodying the best compromise in light of the existing economic, social, technological, and environmental conditions.

In the next paragraphs we provide a brief description of each evaluation method used in this study.

2.1 Emergy Theory, Accounting and Evaluation Method

Emergy Synthesis (Odum, 1988, 1994, 1996, 2007) is an energy evaluation method rooted in irreversible thermodynamics (Prigogine, 1947; de Groot and Mazur, 1962) and systems thinking (von Bertalanffy, 1968). It aims at calculating indicators of environmental performance accounting for both natural and economic resources used up within ecosystem and human-dominated processes (Brown and Ulgiati, 1999, 2004a,b; Buonocore et al., 2012; Cavalett et al., 2006, 2010; Franzese et al. 2005, 2008a,b, 2009a,b).

According to the emergy theory, different forms of energy, materials, human labor, and economic services are all evaluated on the common basis of biosphere by converting them into equivalents of only one form of energy, the solar kind, expressed as solar equivalent Joule (seJ). To be more specific, emergy is defined as ‘‘the total amount of available energy of one kind (most often of the solar kind) that is used up directly or indirectly in a process to deliver an output product, flow, or service’’ (Odum, 1996).

Emergy accounting measures the past and present environmental support to a process, and it allows us to explore the interplay of natural ecosystem and human activities. The concept of self-organization provides a framework for understanding how systems utilize incoming emergy sources to develop new organizational states over time. Processes of energy transformation throughout the biosphere build order, degrade energy in the process, and cycle information in a network of hierarchically organized systems of ever-increasing spatial and temporal scales. Understanding this relationship between energy and the cycles of materials and information provides insight into the complex relations of society and biosphere (Brown and Ulgiati, 2004a,b).

The emergy method is deeply rooted in the concept of resource quality, i.e. the awareness that different energy forms have a different ability to do useful work even when their heat content is the same. Such an ability (or quality) is an intrinsic feature of the resource and derives from the characteristics of the process that generated the resource itself. This also applies to the different materials used in a process even when their masses are the same. The quality of a resource depends on its physical-chemical characteristics, which in turn depend on the work performed by nature to make it via the complex pattern of natural process. Instead of only looking at what can be extracted from a resource (exergy), the emergy evaluation method focuses on what it takes for biosphere to make and for societies to process a given resource. Odum (1988, 1994, 1996) pointed out that in all systems a greater amount of low-quality energy must be dissipated in order to generate a product containing a smaller amount of higher energy quality, thus generating an energy-based hierarchy of resources and products. The ratio of the available energy previously used up to make a product to the actual energy content of such a product provides a measure of the hierarchical position of the item within the thermodynamic scale of the biosphere (a kind of production cost of the item measured in ‘‘biosphere currency’’). Such a ratio is expressed as solar equivalent Joules per Joule (seJ J^{-1}) or per gram (seJ g^{-1}), termed transformity and specific emergy, respectively. The more energy previously used up, the higher the product’s transformity, and the product therefore corresponds to a higher position in the energy hierarchy (Odum, 1996). Insofar as natural or economic dynamics select the optimum process capable of generating a given product, the amount of required input emergy decreases to the minimum emergy demand for its production. According to such a selection driven perspective, transformity translates into an energy scaling ratio to indicate quality and hierarchical position of different resources in the hierarchy of biosphere.

Other emergy indicators and ratios can be calculated to evaluate the use of resources in production processes. For example, the Renewability index (%R) is the percentage of renewable emergy used by the system; the Emergy Yield Ratio (EYR) is the ratio between the total emergy inflow and the emergy purchased from outside the system; the Environmental Loading Ratio (ELR) is the ratio between imported plus local non-renewable emergy and the local renewable one; the Empower Density (ED) is the ratio between the total input emergy and the area of investigation over time. Odum (1996) and Brown and Ulgiati (2004b) provided a detailed explanation of the emergy accounting procedures for a variety of systems as well as a careful discussion about the meaning of the emergy-based indicators. The updated emergy baseline for biosphere of $15.83 \cdot 10^{24}$ seJ yr^{-1} (Brown and Ulgiati, 2004b) was used in this study and all the emergy intensity factors (specific emergy and solar transformity factors) were updated to this baseline.

2.2 Embodied Energy Analysis

Total input heat flow must always be equal to total output heat flow for isothermal systems, according to the First Law of Thermodynamics. Environmental as well as economic concerns may motivate us to investigate the consequences of releasing into the environment a resource characterized by a higher temperature than the environmental temperature. To address these aspects, a careful description and quantification of input and output heat flows is needed. However, it must be remembered that the energy invested in the overall production process is no longer available to the final user of the product as it has been used up and is no longer contained in the final product. The actual energy content of the product (measured as combustion enthalpy, HHV, LHV) differs from the total input energy because of the losses in all steps of the production processes leading to the final product (Ulgiati et al., 2003).

The Embodied Energy Analysis (EEA) has been defined as the process of determining the energy required directly and indirectly to allow a system to produce a product or service (IFIAS, 1974). The Gross Energy Requirement (GER) method accounts for the amount of fossil energy (also referred to as commercial energy) required directly and indirectly to make a good or service (Slesser, 1978; Smil, 1991; Herendeen, 1998; Franzese et al., 2009b). The GER method is concerned with the depletion of fossil fuels and it focuses on the availability and use of fossil and fossil-equivalent energy invested to produce a product or service. Direct use of fossil fuels refers to oil, lubricants, and electricity, while indirect use of fossil fuels is related to structures, machinery, fertilizers, pesticides, and chemicals, among others.

In the GER method, all inputs to the process are multiplied by an energy intensity factor accounting for the amount of fossil resources directly and indirectly required to make them available. The total of such fossil and fossil-equivalent energy requirement represents the GER of the process while the ratio between the GER of the process and the amount of generated product provides the GER of the product (usually expressed in MJ per kg). Renewable resources provided for free by nature (without using any fossil energy to make them available) are not accounted for by the GER method. Human labor and economic services are also not included in most GER evaluations (Franzese et al., 2009b).

2.3 Material Flow Accounting

The Material Flow Accounting (MFA) method (Schmidt-Bleek, 1993; Hinterberger and Stiller, 1998) is aimed at evaluating the environmental disturbance associated with the withdrawal or diversion of material flows from their natural ecosystemic pathways. When expanding the scale of investigation, we realize that each flow of matter supplied to a process has been extracted and processed elsewhere. Additional matter is moved from place to place, processed and then disposed of to supply each input to the process.

Sometimes a huge amount of rock must be excavated per unit of metal or chemical element actually delivered to the final user. Most of this rock is then returned to the mine site, but its stability is lost and several chemical compounds become soluble with rainfall, thus affecting the environment in unexpected ways. There are therefore two main aspects of the material balance to be considered: 1) when addressing the input side, we must account for the total input mass supporting a process, thus indirectly measuring how the process affects the environment by withdrawing resources (Bargigli et al., 2005); and 2) when focusing on the product side, we must be sure that economically and environmentally significant matter flows have not been neglected.

In this method, appropriate material intensity factors (kg $unit^{-1}$) are multiplied by each input to the process, accounting for the total amount of abiotic matter, biotic matter, water, and air directly or indirectly required to make each input available to the process. The resulting material demands of the individual inputs are then added up for each environmental compartment (biotic and abiotic matter, water, and air), and assigned to the system's output as a quantitative measure of its cumulative environmental burden from that compartment (often referred to as "Ecological Rucksack").

2.4 Life Cycle Assessment

Life Cycle Assessment (LCA) is used worldwide to assess material and energy flows to and from a production process. LCA is a method for determining the environmental impacts of a product or service during its entire life cycle or, as in the case of this study, from production of raw material inputs to their use in the agricultural/farming production systems. LCA is a cooperative effort performed by many investigators throughout the world (many working in the industrial sectors) to follow the fate of resources from initial extraction and processing of raw materials to final disposal. This effort is converging towards standard procedures and common frameworks to allow a consistent comparison of final results. The International Standard Office provided a very detailed investigation procedure for environmental management based on LCA and for a comparable quality assessment (ISO 14040, 2006; ISO 14044, 2006). The approach used in this study follows the ISO 14040-14044 standards and the current state of the art of LCA methodology.

A typical LCA study consists of the following stages: (1) goal and scope definition; (2) detailed life cycle inventory (LCI) analysis with compilation of data on energy and resource use and emissions in the environment throughout the life cycle; (3) assessment of the potential impacts related to the quantified forms of resource use and environmental emissions; (4) interpretation of the results from the previous phases of the analysis in relation to the objectives of the study (ISO 14040, 2006; ISO 14044, 2006).

In this study, the software package SimaPro® (PRé Consultants B.V.) and CML 2 Baseline 2000 v2.05 method were used for the environmental impact assessment of corn, soybean, and pig production systems. The following environmental impact categories were evaluated: Abiotic depletion (ADP); Acidification (AP); Eutrophication (EP); Global warming potential (GWP); Ozone layer depletion (ODP); Human toxicity (HTP); Fresh water aquatic ecotoxicity (FWAET); Marine aquatic ecotoxicity (MAET); Terrestrial ecotoxicity (TET); and Photochemical oxidation (POP).

2.5 Ecological Footprint

The Ecological Footprint methodology was developed in the early 1990s by the academics Mathis Wackernagel and William Rees in Canada (Wackernagel and Rees, 1996). The Ecological Footprint (EF) is an accounting tool based on two fundamental concepts: sustainability and carrying capacity. This method makes possible an estimation of resource consumption and waste assimilation for a given population in terms of equivalent productive land area. Since the land area owned or controlled by a population is usually a limited and identifiable quantity, it can be compared to its actual EF. This method can be applied to people, populations, products, firms, regions or countries.

The difference between the available land and the actual EF, termed “ecological deficit”, shows the dependence of a population on natural capital and ecosystem services purchased from outside the area. The rationale for representing impacts upon the environment in units of area is that biologically productive land area produces or absorbs flows of several materials utilized by our society. The different uses of land areas are often mutually exclusive and are therefore in competition for the finite area of productive land in the world.

The EF combines several environmental impacts into a single area measure. Conceptually, EF can include biological and energy resources, pollution, land use, waste disposal, and provision of natural habitats. EF does not seek to include social issues such as income distribution, education and criminality, nor economic issues such as inflation, GDP, and unemployment. EF is therefore not a comprehensive measure of sustainable development as it only includes a limited range of environmental concerns. There are six classes of land usually considered for EF calculation: 1) crop; 2) carbon dioxide absorption; 3) building area; 4) fishing; 5) grazing; and 6) forest.

In this study, the area used to produce 1 kg of output (crop land class) was added to the area necessary to absorb the CO_2 equivalent (CO_2 absorption land class) due to the use of the inputs (from the LCA). The cumulative area requirement of the system's output was then computed as the ecological footprint of the output measured in global hectares (gha).

2.6 Water Footprint

The Water Footprint (WF), introduced in 2002, is a young concept and water footprint assessment is a method still under development. The water footprint is an indicator of freshwater use that looks at both direct and indirect water use. The water footprint can be regarded as a comprehensive indicator of freshwater resources appropriation, next to the traditional and restricted measure of water withdrawal. The water footprint of a product is the volume of direct and indirect freshwater used to produce the product, measured over the full supply chain. It is a multi-dimensional indicator, showing water consumption volumes by source and polluted volumes by type of pollution. All components of the total water footprint are specified geographically and temporally. Blue water footprint refers to consumption of blue water resources (surface and ground water) along the supply chain of a product. "Consumption" refers to loss of water from the available ground-surface water body in a catchment area, which happens when water evaporates, returns to another catchment area or to the sea, or it is incorporated into a product. Green water footprint refers to consumption of green water resources (rainwater stored in soil as soil moisture). Grey water footprint refers to pollution and is defined as the volume of freshwater required to assimilate the load of pollutants based on existing ambient water quality standards (Hoekstra et al., 2009).

The water footprint method has been used in several studies, for instance in the "Value of Water Research Report Series" published by the UNESCO-IHE Institute for Water Education (Delft, the Netherlands) in collaboration with the University of Twente (Enschede, the Netherlands), and Delft University of Technology (Delft, the Netherlands) (Mekonnen and Hoekstra, 2010; Aldaya and Hoekstra, 2009; Aldaya and Llamas, 2008; Bulsink et al., 2009; Hoekstra, 2008; Gerbens-Leenes et al., 2008a,b).

Since, in this study, special attention was paid to water resources use, the Water Footprint method was applied to evaluate water resources use in corn, soybean, and pig production systems in the Toledo River basin. Proper information about water footprints of communities and businesses can help to understand how a more sustainable and equitable use of fresh water resources can be achieved. The Water Footprint thus offers a wider perspective on how a consumer or producer relates to the use of freshwater. WF is a volumetric measure of water consumption and pollution. WF is not a measure of the severity of local environmental impact by water consumption and pollution. The local environmental impact of a certain amount of water consumption and pollution depends on the vulnerability of the local water system, and on the number of water consumers and polluters that are supplied by the same system. Water footprint accounts give spatiotemporally explicit information on how water is appropriated for various human purposes, thus also informing the discussion about sustainable and equitable water use.

Blue water resources are generally scarcer and have higher opportunity cost than green water, thus suggesting a main focus on accounting for blue water footprint only. On the other hand, green water resources are also limited and thus scarce, giving a reason for accounting for green water footprint as well. Besides, green water can be substituted by blue water and sometimes – particularly in agriculture – the other way around as well, so that a complete picture can be obtained only by accounting for both of them. The argument for including green water use is that the historical engineering focus on blue water has led to the undervaluation of green water as an important production factor (Hoekstra et al., 2009). The idea of calculating the grey water footprint was introduced to express water pollution in terms of a polluted volume, so that it can be compared with water consumption, also expressed as a volume (Hoekstra et al., 2009). If one is interested in water pollution and in comparing the relative claims of water pollution and water consumption on the available water resources, it is relevant to take into account the grey footprint in addition to the blue water footprint.

The blue water footprint is an indicator of consumption of blue water, i.e. fresh surface or groundwater. The term "consumptive water use" refers to one of the following three cases: (**a**) water evaporates; (**b**) water is incorporated into the product, and (**c**) water does not return to the same catchment area (e.g., it is returned to another catchment area or to the sea) or in the same period (e.g., it is withdrawn in a scarce period and returned in a wet period).

The green water footprint is the volume of rainwater consumed during the production process. This is particularly relevant for agricultural and forestry products (products based on crops or wood), where it refers to the total rainwater evapotranspiration (from fields and plantations) plus the water incorporated into the harvested crop or wood.

The grey water footprint of a process is an indicator of the degree of freshwater pollution that can be associated with the process. It is defined as the volume of freshwater that is required to assimilate the load of pollutants based on existing ambient water quality standards. Accordingly, it is calculated as the volume of water that is required to dilute pollutants to such an extent that the quality of the ambient water remains above agreed water quality standards. When a waste flow deals with more than one form of pollution, as it is generally the case, the grey water footprint is determined by the pollutant that is the most critical: i.e., the one that is associated with the largest pollutant-specific grey water footprint. For the purpose of finding an overall indicator of water pollution, the grey water footprint based on the critical substance is sufficient.

Water footprint studies highlight two aspects of water resources management. First, data on water footprints of products, consumers, and producers inform the discourse about sustainable, equitable, and efficient freshwater use and allocation. Freshwater is scarce; its annual availability is limited. It is relevant to know who receives which portion and how water is allocated over various purposes. For example, rainwater used for bioenergy cannot be utilized for food production. Second, water footprint accounts help to estimate environmental, social, and economic impacts at local and catchment level. Environmental impact assessment should include a comparison of each water footprint component to available water at relevant locations and time (accounting for environmental water requirements).

The water footprint was calculated in this study using the methodology described in Hoekstra et al. (2009). Hoekstra et al. (2009) points out that frameworks like MFA and LCA consider the use of various types of environmental resources and look at different types of impacts on the environment. In contrast, ecological footprint, water footprint, and embodied energy analyses take the perspective of one particular resource or impact. In this study we have implemented and applied an extended LCA assessment, integrating different footprints and evaluation methods in a consistent conceptual analytical framework.

2.7 Carbon Footprint

The Carbon Footprint is a subset of the Ecological Footprint and of the more comprehensive Life Cycle Assessment (LCA). The Carbon Footprint is the measure of the amount of greenhouse gases, measured in units of carbon dioxide, produced by human activities. Carbon Footprint can be measured for an organization, event, product or person, and is usually expressed in tons (or kg) of CO_2 equivalents per kg of product.

The Carbon Footprint can be broken down into primary and secondary footprint. The primary footprint is the sum of direct emissions of greenhouse gases from burning fossil fuels for energy consumption and transportation. The secondary footprint is the sum of indirect emissions of greenhouse gases generated during the life cycle of the production process.

In this study, the Carbon Footprints of corn, soybean and pig production systems were calculated as the category "Global Warming Potential" (GWP). Both primary and secondary Carbon footprints were also considered in the LCA.

2.8 System boundaries, functional units, and allocation

System boundaries, defined as cradle-to-gate, include raw materials and emissions of crop cultivation and pig production.

Functional units were defined as 1 kg of corn, 1 kg of soybean and 1 kg of live pig meat. The main inputs and outputs of the soybean-corn intercrop production system were accounted for 1 ha of an average farm located in the Toledo basin (Annexes 1 and 2). In the same way, the main inputs and outputs of the pig production system were accounted for an average pig farm located in the Toledo River basin and producing 650 pig heads per year. The farmed animals are usually delivered to the processing industry with an average weight of 110 kg after 120 days in the rearing system (Annex 3). Inputs and outputs were referred to 1 kg of live pig meat produced.

According to LCA methodology, allocation is required for multi-product processes. Other methods, such as material flow accounting, embodied energy analysis and ecological footprint, also require allocation procedures. In this study, the criterion of economic allocation based on the market value of the process output was applied, as suggested in the ISO 14040-14044 documents for LCA (ISO 14040, 2006; ISO 14044, 2006). However, even if the co-products (corn stover, soybean straw, and pig manure) play an important role within the integrated farm, no environmental impacts were allocated to these co-products since they do not have any economic (market) value.

Delimitations of the study:

- Materials and energy used in farm buildings construction were excluded from this study.
- Production, use, and emissions from vaccines and other pig medicines were not considered in this study due to lack of knowledge about the environmental impacts of these chemicals.
- Disinfectants, washing detergents, and other minor stable inputs were also not taken into account.
- The components of pig feed indicated as other minerals corresponding to 3% (in mass) were considered as salt (NaCl) or generic chemicals (in LCA) because of simplification and lack of data for several specific components of this fraction: salt, natural and synthetic amino acids, limestone, enzymes, phosphate, soy oil, mix of vitamins, and mix of micronutrients.

3. Results and Discussion

The main water, material, energy, and money flows required by an average farm integrating corn, soybean and pig production were evaluated by developing an integrated environmental assessment framework. The data used to implement the inventory of the production systems (Annexes 1, 2, and 3) were obtained from field interviews to farmers, literature review and statistical books. Statistical data have been checked against those obtained from interviews with farmers during the field work.

Input raw amounts (inventory), presented in Annex 1, 2, and 3, were multiplied by suitable intensity factors specific to different evaluation methods and converted into water, mass, energy, money and emergy units to account for their total (direct and indirect) amounts. Finally, indicators of environmental performance (intensity factors) and sustainability were calculated for the investigated processes. The set of multi-criteria indicators was calculated at farm level and then upscaled to basin level to assess the environmental impacts of alternative scenarios at regional scale. The results obtained by using different assessment methods are presented in the following paragraphs.

3.1 Emergy Synthesis

Figure 4 shows the energy systems diagram drawn to model the investigated systems. Such a symbolic model, drawn according to a standardized energy systems language (Odum, 1996), was used as a basis to develop the quantitative inventory of input and output flows. The symbolic model shows in a pictorial way the system boundary, main driving forces, producers, consumers, storages, and interactions among the system's components. According to Odum (1996), driving forces and system's components were drawn from left to right in order of increasing energy quality (*i.e.*, increasing transformity) to provide a reference to the energy hierarchy characterizing the investigated systems.

Based on the systems diagram, input flows supporting agricultural and farming production systems were identified, quantified, and converted to emergy units by means of suitable emergy intensity factors. Finally, a set of emergy-based indicators were calculated to explore the environmental performance and sustainability of the investigated production activities.

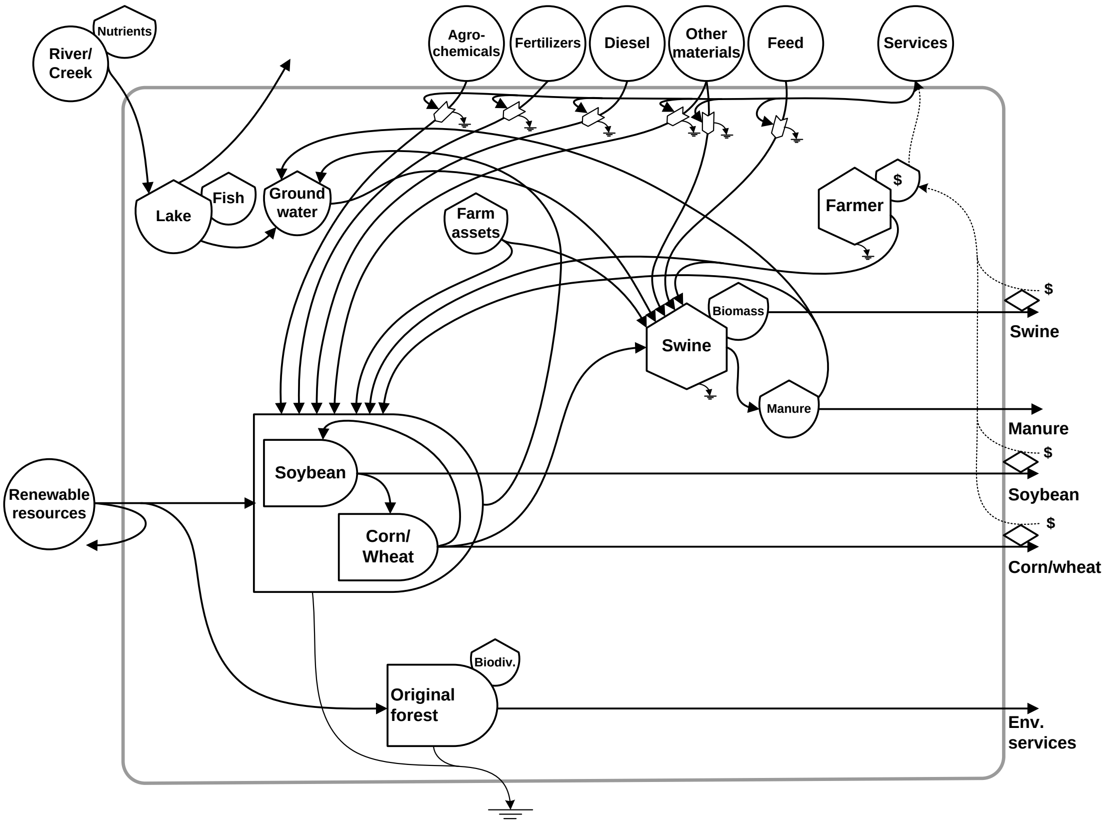

Figure 4. Energy systems diagram of a typical farm in the Toledo River basin (Brazil) integrating swine and soybean-corn production systems.

The input emergy flows invested to support the production systems were assessed by multiplying the raw data input flows by their specific emergy intensity factors (obtained from literature after an accurate evaluation of their conformity to the investigated process). Then, the emergy flows to the process (renewable and non-renewable resources from nature, purchased resources from outside the system, labor and services from human economy) were added to account for the total emergy supporting the process over the spatial and temporal frame of investigation. Finally, several emergy-based indicators for each production system were calculated. Tables 1, 2, and 3 show the emergy evaluation for corn, soybean, and pig production systems, respectively.

Table 1. Emergy evaluation of the corn production system.

Note	Description of flow	Flow	Unit ha^{-1} yr^{-1}	Emergy intensity (seJ $unit^{-1}$)	Reference for emergy intensities	Emergy (seJ ha^{-1} yr^{-1})
1	Sunlight	5.77E+13	J	1.00E+00	By definition	5.77E+13
2	Rain	5.52E+10	J	3.06E+04	Brown and Ulgiati, 2004b	1.69E+15
3	Deep heat	1.00E+10	J	1.02E+04	Odum, 1996	1.02E+14
4	Topsoil loss	4.07E+09	J	1.24E+05	Brown and Ulgiati, 2004b	5.05E+14
5	Limestone	2.14E+08	J	2.72E+06	Brown and Ulgiati, 2004b	5.82E+14
6	Agrochemicals	1.02E+01	kg	2.49E+13	Brown and Ulgiati, 2004b	2.53E+14
7	Seeds	1.79E+01	kg	1.15E+12	This study	2.05E+13
8	Organic fertilizer	1.03E+03	kg	1.13E+11	Castellini et al., 2006	1.17E+14
9	Nitrogen fertilizer	8.16E+01	kg	6.38E+12	Brown and Ulgiati, 2004b	5.21E+14
10	Phosphorus fertilizer	6.40E+01	kg	6.55E+12	Brown and Ulgiati, 2004b	4.19E+14
11	Potassium fertilizer	1.27E+02	kg	2.92E+12	Brown and Ulgiati, 2004b	3.71E+14
12	Fuel	2.14E+09	J	1.11E+05	Brown and Ulgiati, 2004b	2.36E+14
13	Machinery (steel)	2.85E+00	kg	1.13E+13	Brown and Ulgiati, 2004b	3.22E+13
14	Local labor	9.50E+00	USD	3.70E+12	Coelho et al., 1999	3.51E+13
15	Services	8.21E+02	USD	3.70E+12	Coelho et al., 1999	3.04E+15
	Output					
16	Corn	6.90E+03	kg	1.15E+12	This study	7.92E+15*
		1.13E+11	J	7.00E+04	This study	7.92E+15

*According to emergy algebra the total input emergy was accounted for by avoiding double counting among the renewable emergy flows.

Results in Table 1 show that the main emergy flows contributing to corn production system were Services from human economy (38% of the total emergy input), chemical potential of rain (21%), and limestone (7%).

Table 2. Emergy evaluation of the soybean production system.

Note	Description of flow	Flow	Unit ha^{-1} yr^{-1}	Emergy intensity (seJ $unit^{-1}$)	Reference for emergy intensities	Emergy (seJ ha^{-1} yr^{-1})
1	Sunlight	5.77E+13	J	1.00E+00	By definition	5.77E+13
2	Rain	5.52E+10	J	3.06E+04	Brown and Ulgiati, 2004b	1.69E+15
3	Deep heat	1.00E+10	J	1.02E+04	Odum, 1996	1.02E+14
4	Topsoil loss	4.61E+09	J	1.24E+05	Brown and Ulgiati, 2004b	5.72E+14
5	Limestone	1.22E+08	J	2.72E+06	Brown and Ulgiati, 2004b	3.32E+14
6	Agrochemicals	1.05E+01	kg	2.49E+13	Brown and Ulgiati, 2004b	2.60E+14
7	Seeds	6.50E+01	kg	2.06E+12	This study	1.34E+14
8	Organic fertilizer	1.03E+03	kg	1.13E+11	Castellini et al., 2006	1.17E+14
9	Nitrogen fertilizer	0.00E+00	kg	6.38E+12	Brown and Ulgiati, 2004b	0.00E+00
10	Phosphorus fertilizer	6.00E+01	kg	6.55E+12	Brown and Ulgiati, 2004b	3.93E+14
11	Potassium fertilizer	6.00E+01	kg	2.92E+12	Brown and Ulgiati, 2004b	1.75E+14
12	Fuel	1.85E+09	J	1.11E+05	Brown and Ulgiati, 2004b	2.05E+14
13	Machinery (steel)	2.50E+00	kg	1.13E+13	Brown and Ulgiati, 2004b	2.83E+13
14	Local labor	9.18E+00	USD	3.70E+12	Coelho et al., 1999	3.40E+13
15	Services	5.80E+02	USD	3.70E+12	Coelho et al., 1999	2.15E+15
	Output					
16	Soybean	3.00E+03	kg	2.06E+12	This study	6.19E+15*
		5.96E+10	J	1.04E+05	This study	6.19E+15

*According to emergy algebra the total input emergy was accounted for by avoiding double counting among the renewable emergy flows.

Results in Table 2 show that the main contributions to soybean production system in terms of emergy flows were Services from the human economy (34% of the total emergy input), chemical potential of rain (27%), and topsoil loss by erosion (9%).

Table 3. Emergy evaluation of the pig production system.

Note	Description of flow	Flow	Unit kg_{pig}^{-1}	Emergy intensity (seJ $unit^{-1}$)	Reference for Emergy intensities	Emergy (seJ kg_{pig}^{-1})
1	Sunlight	7.06E+07	J	1.00E+00	By definition	7.06E+07
2	Rain	6.75E+04	J	3.06E+04	Brown and Ulgiati, 2004b	2.07E+09
3	Deep heat	1.22E+04	J	1.02E+04	Odum, 1996	1.25E+08
4	Water (groundwater)	6.47E+04	J	4.28E+05	Bastianoni et al., 2001	2.77E+10
5	Corn	1.84E+00	kg	1.05E+12	This study	1.93E+12
5	Soy meal	3.90E-01	kg	2.98E+12	Cavalett and Ortega, 2009	1.16E+12
5	Other minerals	6.88E-02	kg	1.68E+12	Odum, 1996	1.16E+11
6	Electricity	5.53E+03	J	2.77E+05	Odum, 1996	1.53E+09
7	Local labor	1.44E-01	USD	3.70E+12	Coelho et al., 1999	5.31E+11
8	Services	1.22E+00	USD	3.70E+12	Coelho et al., 1999	4.51E+12
	Output					
9	Pig meat	1.00E+00	kg	8.28E+12	This study	8.28E+12*
		9.21E+06	J	8.99E+05	This study	8.28E+12

*According to emergy algebra the total input emergy was accounted for by avoiding double counting among the renewable emergy flows.

Results in Table 3 show that the main emergy flows contributing to pig production system were Services from the human economy (55% of the total emergy input), pig feed components (39%), and farmer labor (6%).

Tables 4, 5, and 6 summarize the different categories of emergy flows and emergy-based indicators calculated for corn, soybean, and pig production systems, respectively. Results in Tables 4, 5, and 6 were calculated with and without accounting for input Labor and Services (L&S) to provide results from both an integrated assessment including the feedback from the economy, and a pure biophysical accounting. The discussion of the results is performed considering the emergy-based indicators including the input Services from the economy.

Table 4. Emergy flows and emergy-based indicators of the corn production system.

Flow/Indicator	Corn (with L&S)	Corn (without L&S)	Unit
Renewable resources from nature (R)	1.79E+15	1.79E+15	seJ ha^{-1} yr^{-1}
Non-renewable resources from nature (N)	5.05E+14	5.05E+14	seJ ha^{-1} yr^{-1}
Purchased inputs from outside the system (F)	2.55E+15	2.55E+15	seJ ha^{-1} yr^{-1}
Labor and services from human economy (L&S)	3.07E+15	---	seJ ha^{-1} yr^{-1}
Total emergy (U)	7.92E+15	4.85E+15	seJ ha^{-1} yr^{-1}
Solar Transformity	7.00E+04	4.28E+04	seJ J^{-1}
Emergy Yield Ratio	1.41	1.90	
Environmental Loading Ratio	3.42	1.71	
Emergy Investment Ratio	2.45	1.11	
Renewability	22.6%	37.0%	
Empower Density	7.92E+11	4.85E+11	seJ m^{-2} yr^{-1}

Table 5. Emergy flows and emergy-based indicators of the soybean production system.

Flow/Indicator	Soybean (with Labor & Services)	Soybean (without L&S)	Unit
Renewable resources from nature (R)	1.79E+15	1.79E+15	seJ ha^{-1} yr^{-1}
Non-renewable resources from nature (N)	5.72E+14	5.72E+14	seJ ha^{-1} yr^{-1}
Purchased inputs from outside the system (F)	1.64E+15	1.64E+15	seJ ha^{-1} yr^{-1}
Labor and services from human economy (L&S)	2.18E+15	---	seJ ha^{-1} yr^{-1}
Total emergy (U)	6.19E+15	4.01E+15	seJ ha^{-1} yr^{-1}
Solar Transformity	1.04E+05	6.72E+04	seJ J^{-1}
Emergy Yield Ratio	1.62	2.44	
Environmental Loading Ratio	2.45	1.24	
Emergy Investment Ratio	1.62	0.70	
Renewability	29.0%	44.7%	
Empower Density	6.19E+11	4.01E+11	seJ m^{-2} yr^{-1}

Table 6. Emergy flows and emergy-based indicators of the pig production system.

Flow/Indicator	Pig meat (with Labor & Services)	Pig meat (without L&S)	Unit
Renewable resources from nature (R)	2.19E+09	2.19E+09	seJ kg_{pig}^{-1}
Non-renewable resources from nature (N)	2.77E+10	2.77E+10	seJ kg_{pig}^{-1}
Purchased inputs from outside the system (F)	3.21E+12	3.21E+12	seJ kg_{pig}^{-1}
Labor and services from human economy (L&S)	5.05E+12	---	seJ kg_{pig}^{-1}
Total emergy (U)	8.28E+12	3.24E+12	seJ kg_{pig}^{-1}
Solar Transformity	8.99E+05	3.51E+05	seJ J^{-1}
Emergy Yield Ratio	1.00	1.01	
Environmental Loading Ratio	3780	1476	
Emergy Investment Ratio	276	107	
Renewability	0.03%	0.07%	
Empower Density	6.77E+14	2.65E+14	seJ m^{-2} yr^{-1}

The Solar Transformity (total emergy invested into the process divided by the energy content of the product) calculated for pig meat ($8.99 \cdot 10^5$ seJ J^{-1}) was much higher than for corn ($7.00 \cdot 10^4$ seJ J^{-1}) and soybean ($1.04 \cdot 10^5$ seJ J^{-1}), indicating that the pig production system requires a higher global environmental support to produce one Joule of product. These results confirmed how pig production occupies a higher position within the energy hierarchy of the whole production chain due to its feature as an animal production system.

The Emergy Yield Ratio (EYR = U/F) is a measure of the ability of a process to exploit and make available local resources by investing outside resources. It provides a measure of the appropriation of local resources by a process, which can be read as a potential additional contribution to the economy, generated by investing resources already available. The higher this value the more able is the process to exploit and make available resources from nature per unit of investment from economy. The EYR for corn and soybean were 1.41 (Table 4) and 1.62 (Table 5), while the pig production showed an EYR of 1.00 (Table 6). The lowest possible value of the EYR is one, which indicates that the emergy converging to generate the yield does not differ significantly from the emergy invested from outside the system to drive the process. The latter is not usefully exploiting any local resource. Therefore, processes with EYR equal to one or only slightly higher do not provide significant net emergy to the economy and only transform resources that are already available from previous processes. In so doing they act as consumer processes more than creating new opportunities for the system's growth.

The Environmental Loading Ratio (ELR = (N+F) / R) is designed to compare the amount of non-renewable and purchased emergy flows (N+F) to the amount of locally renewable emergy (R). In the absence of investments from outside, the renewable emergy that is locally available would have driven the growth of a mature ecosystem consistent with the constraints imposed by the environment and characterized by an ELR=0. Instead, the non-renewable imported emergy drives a different site development, whose distance from the natural ecosystem can be indicated by the ELR. The higher this ratio, the bigger the distance of the development from the natural process that could have developed locally without non-renewable investment from outside. In a way, the ELR is a measure of the disturbance to the local environmental dynamics, generated by the development driven from outside sources. The ELR for pig production system indicates that the non-renewable fraction of the total emergy is 3,780 times higher than the renewable part (Table 6), while the same indicator for corn and soybean was 3.42 and 2.45 (Tables 4 and 5).

The Renewability indicator shows that the pig production system was supported by a very small contribution of renewable resources (0.03%). For this reason it could be considered like an industrial activity that is supported almost exclusively by human-driven economic resources coming from outside the system. The intensification of pig production over the last decades using smaller areas and industrial feed stuffs has been based on the massive use of fossil energy in all steps of the production chain. This is also reflected by the very high ELR and unitary value of the EYR calculated for the pig production system (Table 6). In contrast, the soybean production subsystem showed a renewability of 29.0% (Table 5), meaning that 71% of the inputs supporting the process were related to non-renewable sources of emergy. The same indicator calculated for corn production system was even lower: 22.6% (Table 4).

The Emergy Investment Ratio (EIR = F / (R+N)) indicates the proportion of purchased resources from the economy in relation to the free resources from nature used by the production system. The EIR value calculated for pig production system (276) was much higher than the value calculated for corn (2.45) and soybean (1.62) production systems (Tables 4, 5, and 6). For example, this figure shows that the pig production system uses 276 times more resources purchased from the economy than free resources from environment. The soybean production showed itself to be the system that uses the lowest proportion of purchased resources between all evaluated systems.

The Empower Density (ED = U/area per time) measures the amount of emergy invested per unit of area over time. ED may suggest land as a limiting factor for a process or, in other words, may suggest the need for a given amount of support land around the system, for it to be sustainable. The ED of the pig production system ($6.77 \cdot 10^{14}$ seJ m^{-2} $year^{-1}$) was much higher than the ED of the soybean ($6.19 \cdot 10^{11}$ seJ m^{-2} $year^{-1}$), and corn ($7.92 \cdot 10^{11}$ seJ m^{-2} $year^{-1}$) production systems (Tables 4, 5, and 6), proving how the pig production subsystem is much more intensive in the use of resources per unit of area than the investigated agricultural crops.

3.2 Embodied Energy Analysis

The embodied energy demand was evaluated by first quantifying the raw data input flows to the production systems, and then multiplying the input flows by their specific oil equivalent factors (obtained from literature after an accurate evaluation of their conformity to the investigated process). Then, the embodied energy demand for each input flow was added to account for the total energy demand of the process. The ratio between the total energy demand and generated product made possible the calculation of the energy intensity factor for each product (energy demand per kg of product). This indicator quantifies the contribution of the investigated process to fossil energy resources depletion. Tables 7, 8, and 9 show the Embodied Energy Analysis for corn, soybean and pig production systems, respectively.

Table 7 shows that about 0.05 kg of crude oil equivalent was necessary to produce 1 kg of corn. The total energy demand of the inputs was $1.36 \cdot 10^{10}$ J ha^{-1} $year^{-1}$ (Table 7). The total energy content of the corn output was $1.13 \cdot 10^{11}$ J ha^{-1} $year^{-1}$. These figures translate into an Energy Return on Investment (EROI) of 8.3 (about 8 joules of corn were produced per joule of fossil fuel invested in the production process). The main contributions to the corn production system in terms of embodied energy were nitrogen fertilizer (44% of the total energy demand), fuel (18%) and limestone (16%) (Table 7).

Table 8 shows that about 0.05 kg of crude oil equivalent was used to produce 1 kg of soybean. The total energy demand of the inputs was $5.83 \cdot 10^{9}$ J ha^{-1} $year^{-1}$ (Table 8). The total energy content of the soybean output was $5.96 \cdot 10^{10}$ J ha^{-1} $year^{-1}$. These figures translate into an EROI of 10.2 (about 10 joules of soybean were produced per joule of fossil fuel invested in the production process). The main contributions to the soybean production system were fuel (37%), limestone (22%) and phosphorous fertilizer (14%) (Table 8).

Table 7. Embodied energy analysis of the corn production system.

Note	Description of flow	Flow	Units	Oil equivalent (kg oil unit^{-1})	Reference for oil equivalent	Total oil demand (kg oil equiv.)	Total energy demand (J)
1	Sunlight	5.77E+13	J	*	*	*	*
2	Rain	1.12E+07	kg	*	*	*	*
3	Deep heat	1.00E+10	J	*	*	*	*
4	Loss of topsoil	1.50E+04	kg	*	*	*	*
5	Limestone	3.50E+02	kg	0.15	Boustead and Hancock, 1979	5.27E+01	2.21E+09
6	Agrochemicals	1.02E+01	kg	1.43	Estimated from Ulgiati, 2001	1.45E+01	6.08E+08
7	Seeds	1.79E+01	kg	0.05	This study	8.93E-01	3.74E+07
8	Organic fertilizer	1.03E+03	kg	*	*	*	*
9	Nitrogen fertilizer	8.16E+01	kg	1.75	Estimated from Ulgiati, 2001	1.43E+02	5.98E+09
10	Phosphorus fertilizer	6.40E+01	kg	0.32	Estimated from Ulgiati, 2001	2.05E+01	8.58E+08
11	Potassium fertilizer	1.27E+02	kg	0.22	Estimated from Ulgiati, 2001	2.80E+01	1.17E+09
12	Fuel	4.81E+01	kg	1.23	Estimated from Ulgiati, 2001	5.92E+01	2.48E+09
13	Machinery (steel)	2.85E+00	kg	1.91	Estimated from Ulgiati, 2001	5.44E+00	2.28E+08
14	Local labor	4.78E+00	h	*	*	*	*
15	Services	8.21E+02	USD	*	*	*	*
	Output						
16	Corn	6.90E+03	kg	0.05	This study	3.24E+02	1.36E+10

(*) No oil equivalent factor was associated with this item within the scale of investigation.

Table 8. Embodied energy analysis of the soybean production system.

Note	Description of flow	Flow	Units	Oil equivalent (kg oil unit^{-1})	Reference for oil equivalent	Total oil demand (kg oil equiv.)	Total energy demand (J)
1	Sunlight	5.77E+13	J	*	*	*	*
2	Rain	1.12E+07	kg	*	*	*	*
3	Deep heat	1.00E+10	J	*	*	*	*
4	Loss of topsoil	1.70E+04	kg	*	*	*	*
5	Limestone	2.00E+02	kg	0.15	Boustead and Hancock, 1979	3.01E+01	1.26E+09
6	Agrochemicals	1.05E+01	kg	1.43	Estimated from Ulgiati, 2001	1.50E+01	6.27E+08
7	Seeds	6.50E+01	kg	0.09	This study	5.85E+00	2.45E+08
8	Organic fertilizer	1.03E+03	kg	*	*	*	*
9	Nitrogen fertilizer	0.00E+00	kg	1.75	Estimated from Ulgiati, 2001	0.00E+00	0.00E+00
10	Phosphorus fertilizer	6.00E+01	kg	0.32	Estimated from Ulgiati, 2001	1.92E+01	8.04E+08
11	Potassium fertilizer	6.00E+01	kg	0.22	Estimated from Ulgiati, 2001	1.32E+01	5.53E+08
12	Fuel	4.16E+01	kg	1.23	Estimated from Ulgiati, 2001	5.12E+01	2.14E+09
13	Machinery (steel)	2.50E+00	kg	1.91	Estimated from Ulgiati, 2001	4.78E+00	2.00E+08
14	Local labor	4.62E+00	h	*	*	*	*
15	Services	5.80E+02	USD	*	*	*	*
	Output						
16	Soybean	3.00E+03	kg	0.05	This study	1.39E+02	5.83E+09

(*) No oil equivalent factor was associated with this item within the scale of investigation.

Table 9 shows that about 0.22 kg of crude oil equivalent was used to produce 1 kg of live pig meat. The total energy demand of the inputs was $9.13 \cdot 10^6$ J kg_{pig}^{-1} (Table 9). The total energy content of the pig meat output was $9.21 \cdot 10^6$ J kg_{pig}^{-1}. These figures translate into an EROI of approximately 1.0 (i.e., one joule of pig meat was produced per joule of fossil fuel invested in the production process).

Table 9. Embodied energy analysis of the pig production system.

Note	Description of flow	Flow	Units	Oil equivalent (kg oil unit^{-1})	Reference for oil equivalent	Total oil demand (kg oil equiv.)	Total energy demand (J)
1	Sunlight	7.06E+07	J	*	*	*	*
2	Rain	6.75E+04	J	*	*	*	*
3	Deep heat	1.22E+04	J	*	*	*	*
4	Water (groundwater)	1.31E+01	kg	1.43E-04	Boustead and Hancock,1979	1.87E-03	7.84E+04
5	Corn	1.84E+00	kg	0.05	This study	8.63E-02	3.61E+06
5	Soy meal	3.90E-01	kg	0.08	Cavalett and Ortega, 2009	3.12E-02	1.31E+06
5	Other minerals	6.88E-02	kg	1.43	Estimated from Ulgiati, 2001	9.85E-02	4.12E+06
6	Electricity	5.53E+03	J	6.97E-08	Biondi et al., 1989	3.85E-04	1.61E+04
7	Local labor	7.22E-02	h	*	*	*	*
8	Services	1.22E+00	USD	*	*	*	*
	Output						
9	Pig meat	1.00E+00	kg	0.22	This study	2.18E-01	9.13E+06

(*) No oil equivalent factor was associated with this item within the scale of investigation.

As expected, the most important contributions for pig production system in terms of embodied energy were the components of pig feed (99% of total inputs). These results are in accordance with those obtained by Angonese et al. (2006) for pig production system in Southern Brazil.

3.3 Material Flow Accounting

Local mass flows to the production systems were quantified and multiplied by appropriate material intensity factors (obtained from literature after an accurate evaluation of their conformity to the investigated process) to calculate the total material demand on a larger scale and the relative material intensities of the products. In so doing, the environmental disturbance generated by the withdrawal of resources over the production systems was assessed. Tables 10, 11, and 12 show the material flow accounting for corn, soybean, and pig production systems, respectively.

Results in Table 10 show that 1.82 kg of abiotic material, 1.77 kg of water, 0.02 kg of air (used in chemical reactions), and 0.09 kg of biotic materials were used to produce 1 kg of corn. The total material flow demand resulted in 3.7 kg per kg of corn. The main inputs to the abiotic impact factor in corn production system were topsoil loss by erosion (77% of the total inputs), potassium fertilizer (11%) and limestone (5%). The main inputs to the water impact factor were topsoil loss by erosion (36% of the total inputs), limestone (28%) and phosphorous fertilizer (12%). The main inputs to the air impact factor were phosphorous fertilizer (70%), limestone (18%) and potassium fertilizer (8%). The main inputs to the biotic impact factor were topsoil loss by erosion (91% of the total inputs) and organic fertilizer (8%). It is important to remark that scientific literature usually provides poor data on the biotic impact factor as this impact factor is not considered in most studies.

Results in Table 11 show that 4.25 kg of abiotic material, 3.49 kg of water, 0.03 kg of air, and 0.24 kg of biotic materials were used to produce 1 kg of soybean. The total material flow demand resulted in 8 kg per kg of soybean produced. The main inputs to the abiotic impact factor in the soybean production system were topsoil loss by erosion (88% of the total inputs), potassium fertilizer (5%), and limestone (3%). The main inputs to the water impact factor were topsoil loss by erosion (49% of the total inputs), limestone (19%), and phosphorous fertilizer (13%). The main inputs to the air impact factor were phosphorous fertilizer (80%), limestone (12%), and potassium fertilizer (4%). The main inputs to the biotic impact factor were topsoil loss by erosion (93% of the total inputs) and organic fertilizer (7%).

Results in Table 12 show that 4.99 kg of abiotic material, 22.36 kg of water, 0.08 kg of air, and 0.17 kg of biotic materials were needed to produce 1 kg of pig meat. The total material flow demand resulted in 27.6 kg per kg of pig meat produced. The main inputs to the abiotic impact factor in pig meat production system were corn (67% of the total inputs) and soy meal (29%) used as feed stuffs, and direct water use (3%). The main inputs to the water impact factor were direct water use (76 % of the total inputs), corn (15%) and soy meal used as feed (9%). The main inputs to the air impact factor were soy meal (41%) and corn (40%) used as feed, and direct water use (17%). The main input to the biotic impact factor was the corn used as feeding stuffs.

The material flow demand was much higher in the pig production than in the corn and soybean production systems. This is because the pig production system is a more intensive production process relying on external material resources. Agrochemicals use and topsoil loss are other important material indicators in agricultural production systems. Soybean production uses about 3.49 g of agrochemicals and 5.7 kg of topsoil per kilogram of soybean produced. Corn production uses about 1.47 g of agrochemicals and 2.2 kg of topsoil per kilogram of corn produced (Tables 10 and 11).

Table 10. Material flow accounting of the corn production system.

Note	Description of flow	Flow	Units	MIF abiotic (kg unit^{-1})	Mass Abiotic (kg)	MIF water (kg unit^{-1})	Mass Water (kg)	MIF air (kg unit^{-1})	Mass Air (kg)	MIF biotic (kg unit^{-1})	Mass Biotic (kg)	Ref. for MIF
1	Sunlight	5.77E+13	J	*	*	*	*	*	*	*	*	
2	Rain	1.12E+07	kg	*	*	*	*	*	*	*	*	
3	Deep heat	1.00E+10	J	*	*	*	*	*	*	*	*	
4	Loss of topsoil	1.50E+04	kg	0.66	9.90E+03	0.30	4.50E+03	0.00	0.00E+00	0.04	6.00E+02	By definition
5	Limestone	3.50E+02	kg	1.66	5.81E+02	9.70	3.40E+03	0.06	2.10E+01	0.00	0.00E+00	Wurbs et al., 1996
6	Agrochemicals	1.02E+01	kg	1.10	1.12E+01	0.00	0.00E+00	0.00	0.00E+00	0.00	0.00E+00	Our calculations based on literature data
7	Seeds	1.79E+01	kg	4.71	8.41E+01	4.94	8.82E+01	0.05	8.93E-01	0.24	4.28E+00	This study
8	Organic fertilizer	1.03E+03	kg	0.20	2.07E+02	0.75	7.75E+02	0.00	0.00E+00	0.05	5.17E+01	Our calculations based on literature data
9	Nitrogen fertilizer	8.16E+01	kg	1.10	8.98E+01	0.00	0.00E+00	0.00	0.00E+00	0.00	0.00E+00	Our calculations based on literature data
10	Phosphorus fertilizer	6.40E+01	kg	3.44	2.20E+02	23.30	1.49E+03	1.29	8.26E+01	0.00	0.00E+00	Wurbs et al., 1996
11	Potassium fertilizer	1.27E+02	kg	11.32	1.44E+03	10.60	1.35E+03	0.07	8.90E+00	0.00	0.00E+00	Wurbs et al., 1996
12	Fuel	4.81E+01	kg	1.36	6.54E+01	9.70	4.66E+02	0.02	9.14E-01	0.00	0.00E+00	Wurbs et al., 1996
13	Machinery (steel)	2.85E+00	kg	9.32	2.65E+01	81.90	2.33E+02	0.77	2.20E+00	0.00	0.00E+00	Wurbs et al., 1996
14	Local labor	4.78E+00	h	*	*	*	*	*	*	*	*	
15	Services	8.21E+02	USD	*	*	*	*	*	*	*	*	
	Output											
16	Corn	6.90E+03	kg	1.82	1.25E+04	1.77	1.22E+04	0.02	1.16E+02	0.09	6.52E+02	This study

(*) No material intensity factor (MIF) was associated to this item within the scale of investigation.

Table 11. Material flow accounting of the soybean production system.

Note	Description of flow	Flow	Units	MIF abiotic (kg unit^{-1})	Mass Abiotic (kg)	MIF water (kg unit^{-1})	Mass Water (kg)	MIF air (kg unit^{-1})	Mass Air (kg)	MIF biotic (kg unit^{-1})	Mass Biotic (kg)	Ref. for MIF
1	Sunlight	5.77E+13	J	*	*	*	*	*	*	*	*	
2	Rain	1.80E+07	kg	*	*	*	*	*	*	*	*	
3	Deep heat	1.00E+10	J	*	*	*	*	*	*	*	*	
4	Loss of topsoil	1.70E+04	kg	0.66	1.12E+04	0.30	5.10E+03	0.00	0.00E+00	0.04	6.80E+02	By definition
5	Limestone	2.00E+02	kg	1.66	3.32E+02	9.70	1.94E+03	0.06	1.20E+01	0.00	0.00E+00	Wurbs et al., 1996
6	Agrochemicals	1.05E+01	kg	1.10	1.15E+01	0.00	0.00E+00	0.00	0.00E+00	0.00	0.00E+00	Our calculations based on literature data
7	Seeds	6.50E+01	kg	4.71	3.06E+02	4.94	3.21E+02	0.05	3.25E+00	0.24	1.56E+01	This study
8	Organic fertilizer	1.03E+03	kg	0.20	2.07E+02	0.75	7.75E+02	0.00	0.00E+00	0.05	5.17E+01	Estimative
9	Nitrogen fertilizer	0.00E+00	kg	1.10	0.00E+00	0.00	0.00E+00	0.00	0.00E+00	0.00	0.00E+00	Our calculations based on literature data
10	Phosphorus fertilizer	6.00E+01	kg	3.44	2.06E+02	23.30	1.40E+03	1.29	7.74E+01	0.00	0.00E+00	Wurbs et al., 1996
11	Potassium fertilizer	6.00E+01	kg	11.32	6.79E+02	10.60	6.36E+02	0.07	4.20E+00	0.00	0.00E+00	Wurbs et al., 1996
12	Fuel	4.16E+01	kg	1.36	5.66E+01	9.70	4.03E+02	0.02	7.90E-01	0.00	0.00E+00	Wurbs et al., 1996
13	Machinery (steel)	2.50E+00	kg	9.32	2.33E+01	81.90	2.05E+02	0.77	1.93E+00	0.00	0.00E+00	Wurbs et al., 1996
14	Local labor	4.62E+00	h	*	*	*	*	*	*	*	*	
15	Services	5.80E+02	USD	*	*	*	*	*	*	*	*	
	Output											
16	Soybean	3.00E+03	kg	4.25	1.27E+04	3.49	1.05E+04	0.03	9.63E+01	0.24	7.32E+02	This study

(*) No material intensity factor (MIF) was associated to this item within the scale of investigation.

Table 12. Material flow accounting of the pig production system.

Note	Description of flow	Flow	Units	MIF abiotic (kg unit^{-1})	Mass Abiotic (kg)	MIF water (kg unit^{-1})	Mass Water (kg)	MIF air (kg unit^{-1})	Mass Air (kg)	MIF biotic (kg unit^{-1})	Mass Biotic (kg)	Ref. for MIF
1	Sunlight	7.06E+07	J	*	*	*	*	*	*	*	*	
2	Rain	6.75E+04	J	*	*	*	*	*	*	*	*	
3	Deep heat	1.22E+04	J	*	*	*	*	*	*	*	*	
4	Water (groundwater)	1.31E+01	kg	0.01	1.31E-01	1.30	1.70E+01	0.00	1.31E-02	0.00	0.00E+00	Wurbs et al., 1996
5	Corn	1.84E+00	kg	1.82	3.34E+00	1.77	3.25E+00	0.02	3.07E-02	0.09	1.73E-01	This study
5	Soy meal	3.90E-01	kg	3.67	1.43E+00	4.94	1.93E+00	0.08	3.12E-02	0.00	0.00E+00	Cavalett and Ortega, 2009
5	Other minerals	6.88E-02	kg	1.24	8.53E-02	2.30	1.58E-01	0.02	1.38E-03	0.00	0.00E+00	Wurbs et al., 1996
6	Electricity	1.54E-03	kWh	2.09	3.21E-03	5.86	9.00E-03	0.37	5.68E-04	0.00	0.00E+00	Hinterberger and Stiller, 1998. Modified.
7	Local labor	7.22E-02	h	*	*	*	*	*	*	*	*	
8	Services	1.22E+00	USD	*	*	*	*	*	*	*	*	
	Output											
9	Pig meat	1	kg	4.99	4.99E+00	22.36	2.24E+01	0.08	7.70E-02	0.17	1.73E-01	This study

(*) No material intensity factor (MIF) was associated to this item within the scale of investigation.

3.4 Life Cycle Assessment

The Life Cycle Inventory developed in this study was based on the calculation procedures reported in Annex 1, 2, and 3. The items considered in this study were:

- Emissions from manufacturing and application of fertilizers, limestone, herbicides, pesticides, fungicides, and insecticides in agricultural systems.
- Emissions from manufacturing of diesel used in agricultural operations.
- Emissions from manufacturing of machinery (tractors, implements, harvesters) used in agricultural operations.
- Emissions from manufacturing of the pig feed components (simplified as corn, soy meal, and chemicals in general), electricity, and water used in the pig production system.
- Local emissions of N_2O from nitrogen fertilizers and N_2O and CO_2 from urea.
- Local emissions of CO_2 from limestone.
- Local emissions of CO_2 from diesel in motor vehicles used in agricultural operations.
- Local emissions of NH_3 and N_2O from manure management and CH_4 from enteric fermentation and manure management in the pig production system.
- Local emissions of nitrogen, phosphorous, and potassium from manure spread in agricultural soils were not accounted for due to lack of data on these emissions and also to avoid double accounting with the manure emissions in the pig production systems.

The results from the life cycle inventory made possible the assessment of different environmental impact categories by means of the CML 2 Baseline 2000 v2.05 method. This calculation step was performed using the software package SimaPro® (PRé Consultants B.V.). Tables 13, 14 and 15 show the environmental impact indicators calculated for corn, soybean, and pig production systems. The functional unit considered in this LCA is one kg of output.

In Figure 5, the relative contribution of different inputs to the corn production system is depicted. Fertilizers were responsible for the vast majority of the environmental impacts in all the categories except in global warming potential (GWP) and ozone depletion potential (ODP). In terms of GWP, the local emissions (i.e., N_2O and CO_2 from nitrogen fertilizer and limestone use, and CO_2 from diesel used in the agricultural operations) played a crucial role. However, in terms of ODP, the use of agrochemicals (insecticides, fungicides, herbicides and pesticides) was the main source of impact.

Table 13. Absolute impact scores after the characterization of the corn production system.

Impact category [a]	Local emissions	Limestone	Fertilizers	Agrochemicals	Diesel	Machinery	Total
Abiotic depletion	0.00E+00	1.50E-04	2.75E-04	3.48E-04	3.31E-04	3.43E-05	1.14E-03
Acidification	0.00E+00	5.76E-05	9.17E-04	3.93E-04	8.46E-05	1.68E-05	1.47E-03
Eutrophication	0.00E+00	8.73E-06	1.12E-03	1.39E-04	1.23E-05	9.01E-06	1.29E-03
Global warming	7.56E-02	6.57E-02	4.13E-02	4.19E-02	7.05E-03	4.14E-03	2.36E-01
Ozone layer depletion	0.00E+00	4.54E-09	3.98E-09	1.04E-07	6.41E-09	3.81E-10	1.19E-07
Human toxicity	0.00E+00	2.00E-03	3.72E-02	6.94E-02	5.31E-03	8.82E-03	1.23E-01
Fresh water aquatic ecotoxicity	0.00E+00	7.13E-04	1.37E-02	1.48E-02	1.13E-03	2.52E-03	3.29E-02
Marine aquatic ecotoxicity	0.00E+00	1.50E+00	3.43E+01	2.91E+01	5.05E+00	4.83E+00	7.48E+01
Terrestrial ecotoxicity	0.00E+00	1.94E-05	2.79E-04	2.54E-04	3.01E-05	2.71E-05	6.10E-04
Photochemical oxidation	0.00E+00	1.11E-05	3.74E-05	2.38E-05	4.80E-06	1.52E-06	7.86E-05

Note: [a]Abiotic depletion units are kg Sb_{eq}; Acidification units are kg SO_{2eq}; Eutrophication units are kg $PO_4^{-3}{}_{eq}$; Global warming units are kg CO_{2eq}; Ozone layer depletion units are kg CFC-11_{eq}; Human ecotoxicity units are kg 1,4-DB_{eq}; Fresh water aquatic ecotoxicity units are kg 1,4-DB_{eq}; Marine aquatic ecotoxicity units are kg 1,4-DB_{eq}; Terrestrial ecotoxicity units are kg 1,4-DB_{eq}; and Photochemical oxidation units are kg C_2H_4.

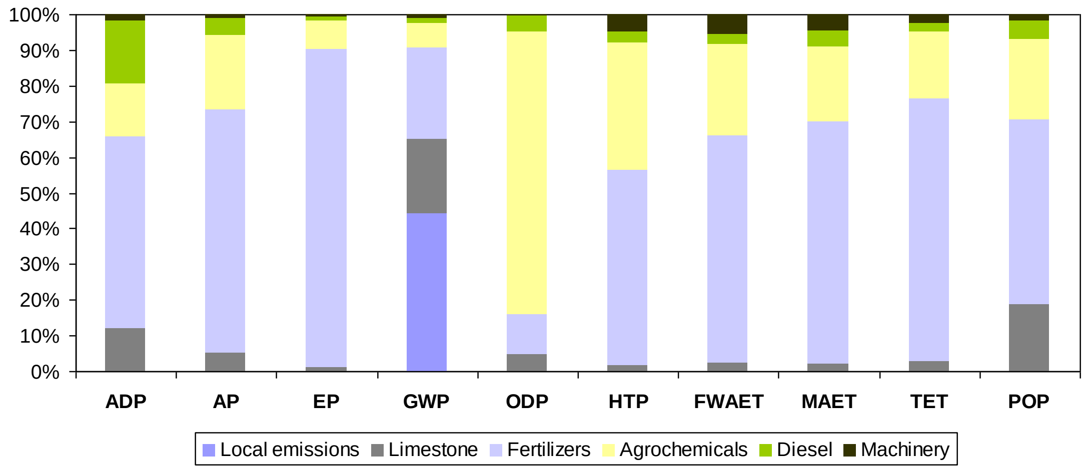

Figure 5. Contribution of different inputs to the impact categories for corn production system.

In Figure 6, the relative contribution of different inputs to the soybean production system is depicted. Fertilizers were responsible for the vast majority of the environmental impacts in the acidification (AP) and eutrophication (EP) impact categories while the use of agrochemicals (insecticides, fungicides, herbicides, and pesticides) was responsible for the majority of the environmental impacts in ozone layer depletion potential (ODP) and human ecotoxicity potential (HTP). The main causes for global warming potential (GWP) were local emissions (CO_2 released from limestone use and from diesel use in the agricultural machinery operations) and the limestone manufacturing process. For the other environmental impact categories, fertilizers and agrochemicals were responsible for most of the contribution to the environmental impacts.

Table 14. Absolute impact scores after the characterization of the soybean production system.

Impact category [a]	Local emissions	Limestone	Fertilizers	Agrochemicals	Diesel	Machinery	Total
Abiotic depletion	0.00E+00	1.14E-04	5.09E-04	1.39E-04	1.67E-04	1.71E-05	9.45E-04
Acidification	0.00E+00	4.38E-05	5.76E-04	1.74E-04	4.25E-05	8.31E-06	8.44E-04
Eutrophication	0.00E+00	6.65E-06	5.68E-04	5.14E-05	6.16E-06	4.43E-06	6.37E-04
Global warming	1.05E-01	5.00E-02	6.08E-02	1.67E-02	3.54E-03	2.06E-03	2.38E-01
Ozone layer depletion	0.00E+00	3.45E-09	7.52E-09	5.47E-08	3.22E-09	1.91E-10	6.91E-08
Human toxicity	0.00E+00	1.52E-03	4.72E-02	3.07E-02	2.67E-03	4.33E-03	8.64E-02
Fresh water aquatic ecotoxicity	0.00E+00	5.43E-04	1.42E-02	5.76E-03	5.70E-04	1.24E-03	2.23E-02
Marine aquatic ecotoxicity	0.00E+00	1.14E+00	3.69E+01	1.15E+01	2.54E+00	2.37E+00	5.45E+01
Terrestrial ecotoxicity	0.00E+00	1.48E-05	4.19E-04	1.06E-04	1.51E-05	1.33E-05	5.68E-04
Photochemical oxidation	0.00E+00	8.44E-06	2.35E-05	1.01E-05	2.41E-06	7.51E-07	4.53E-05

Note: [a]Abiotic depletion units are kg Sb_{eq}; Acidification units are kg SO_{2eq}; Eutrophication units are kg $PO_4^{-3}{}_{eq}$; Global warming units are kg CO_{2eq}; Ozone layer depletion units are kg CFC-11_{eq}; Human ecotoxicity units are kg 1,4-DB_{eq}; Fresh water aquatic ecotoxicity units are kg 1,4-DB_{eq}; Marine aquatic ecotoxicity units are kg 1,4-DB_{eq}; Terrestrial ecotoxicity units are kg 1,4-DB_{eq}; and Photochemical oxidation units are kg C_2H_4.

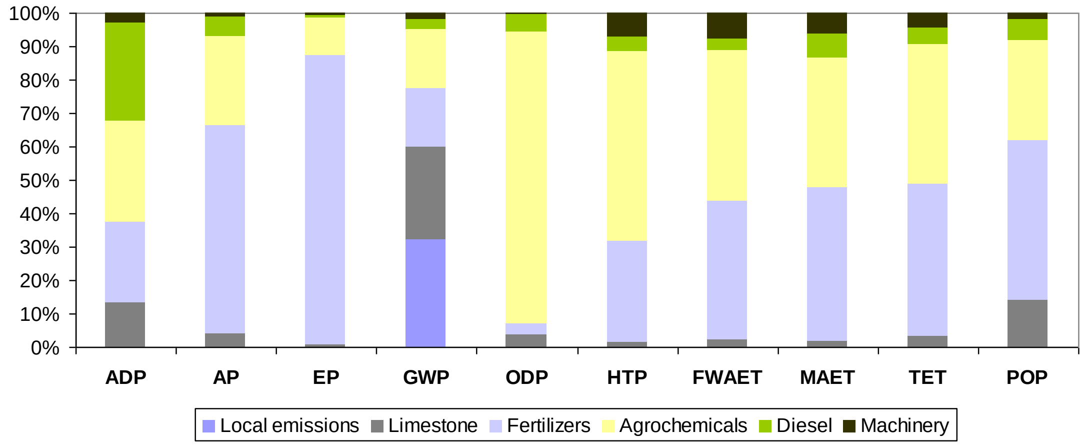

Figure 6. Contribution of different inputs to the impact categories for soybean production system.

In Figure 7, the relative contribution of different inputs to the pig production system is depicted. Pig feed ingredients were responsible for the highest environmental impacts in most of the categories. However, local emissions (NH_3, N_2O, and CH_4 from manure management and enteric fermentation of pigs) caused the highest contribution in the acidification (AP) and global warming potential (GWP) impact categories. The corn used as pig feed was responsible for most of the impacts in the categories of abiotic depletion (ADP), ozone depletion potential (ODP), and marine, freshwater, and terrestrial ecotoxicities (MAET, FWAET, and TET). In the photochemical oxidation (POP) impact category, soy meal showed the highest contribution. In the eutrophication

(EP) impact category, local emissions and soy meal represented the highest contribution.

Table 15. Absolute impact scores after characterization for pig production system.

Impact category [a]	Local emissions	Feed - Corn	Feed - Soy meal	Feed - Minerals	Electricity	Water	Total
Abiotic depletion	0.00E+00	1.74E-03	5.50E-04	8.32E-05	8.91E-07	2.75E-05	2.40E-03
Acidification	8.96E-03	1.55E-03	1.45E-03	6.07E-05	3.11E-07	1.82E-05	1.20E-02
Eutrophication	1.96E-03	1.17E-03	1.92E-03	4.60E-05	8.86E-08	1.14E-05	5.11E-03
Global warming	1.01E+00	4.39E-01	5.28E-01	1.24E-02	3.31E-04	4.15E-03	2.00E+00
Ozone layer depletion	0.00E+00	1.27E-07	1.03E-08	7.45E-10	1.25E-11	1.95E-10	1.38E-07
Human toxicity	5.60E-04	1.59E-01	1.65E-01	2.26E-02	5.22E-05	2.32E-03	3.49E-01
Fresh water aquatic ecotoxicity	0.00E+00	4.10E-02	1.10E-02	9.19E-03	1.43E-05	2.27E-03	6.35E-02
Marine aquatic ecotoxicity	0.00E+00	1.00E+02	2.25E+01	1.93E+01	2.96E-02	4.32E+00	1.46E+02
Terrestrial ecotoxicity	0.00E+00	1.04E-03	9.41E-05	8.42E-05	6.08E-07	2.41E-05	1.25E-03
Photochemical oxidation	1.95E-04	8.33E-05	1.59E-03	2.81E-06	7.27E-08	1.27E-06	1.88E-03

Note: [a]Abiotic depletion units are kg Sb_{eq}; Acidification units are kg SO_{2eq}; Eutrophication units are kg $PO_4^{-3}{}_{eq}$; Global warming units are kg CO_{2eq}; Ozone layer depletion units are kg CFC-11_{eq}; Human ecotoxicity units are kg 1,4-DB_{eq}; Fresh water aquatic ecotoxicity units are kg 1,4-DB_{eq}; Marine aquatic ecotoxicity units are kg 1,4-DB_{eq}; Terrestrial ecotoxicity units are kg 1,4-DB_{eq}; and Photochemical oxidation units are kg C_2H_4.

Although water use showed a low contribution to the environmental impact indicators in the LCA, water resource use figured remarkably high in the pig production system as showed in the inventory data and by both the material flow accounting and water footprint results (Chapters 3.3 and 3.6). These results reinforce the necessity of a multi-criteria assessment framework to calculate a set of complementary indicators able to fully explore different aspects of process performance and sustainability.

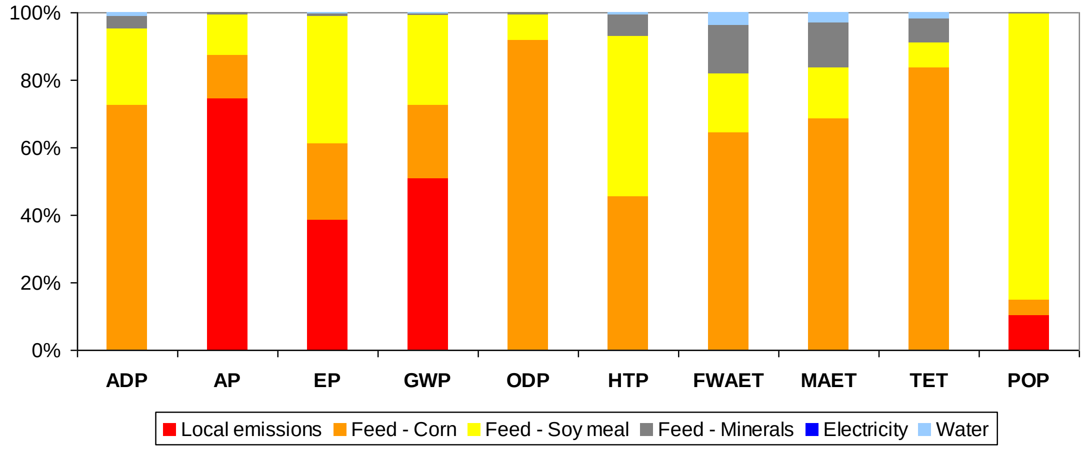

Figure 7. Contribution of different inputs to the impact categories for pig production system.

Figure 8 shows the comparative environmental impacts for corn, soybean and pig production systems. The environmental impact scores showed higher results for pig production in all the environmental impact categories compared to corn and soybean production. Corn production presented lower environmental impacts in comparison to soybean in all the categories except in the global warming potential (GWP). Results showed that high toxicity indicators were obtained in corn and soybean production systems due to the massive use of agrochemicals in these crop production systems.

The results obtained from this study pointed out that efforts in improving pig meat production should be mostly related to improvements in feed production due to its preponderance among the production inputs. The same conclusions were reached by Cederberg and Flysjö (2004). Proper feed production and consumption may lead to a lower amount of nutrients in manure per unit product. Low content of nitrogen in manure is a possible measure to reduce emissions of ammonia, methane, and nitrous oxide from the whole production chain. Crop rotation and low agrichemical use in the production of grains used as pig feed stuffs are other possible measures to reduce environmental impacts. Locally produced feeding stuffs reduce the environmental impacts from transport and increase the possibilities of beneficial integration of crop and swine production. New advanced techniques could be used for proper manure treatment and utilization in Brazil (Kunz et al., 2009). Such techniques (for instance, enhancement of solid-liquid separation using flocculants) are compatible with the new reality of Brazilian industrial swine production, which has emerged as a major competitor in the international market (Kunz et al., 2009).

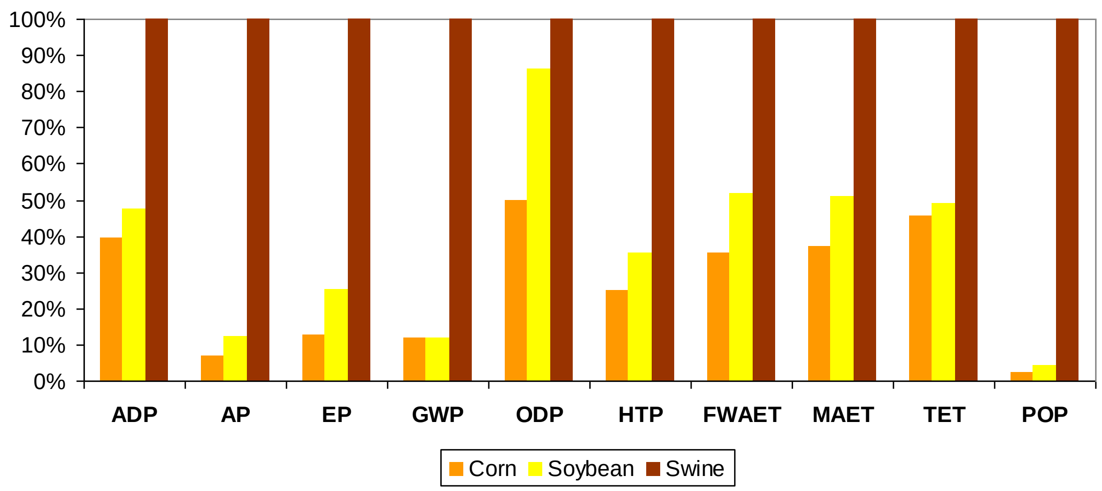

Figure 8. Comparison of environmental impact categories for corn, soybean, and swine production systems.

Careful planning for manure application in agricultural soils can also significantly reduce emissions from reactive nitrogen and provide savings in the use of chemical fertilizers, thus reducing the use of purchased non-renewable energy sources coming from outside the production area. An integrated farming system with proper balance between animals and fodder crops presents good opportunities to minimize nutrient loss and resource use while maintaining self-sufficiency of the production system.

3.5 Ecological Footprint

The calculation of the Ecological Footprint (EF) was based on the direct (or indirect in the case of pig feed ingredients in the pig production system) area required for growing soybean or corn crops and the forest area required to sequester CO_2 equivalent emitted by all inputs used in the production system. Tables 16, 17 and 18 show the ecological footprint calculations for corn, soybean, and pig production systems.

The total Ecological Footprint of corn production was $3.69 \cdot 10^{-4}$ gha/kg (Table 16). The direct agricultural area used in corn production accounted for 87% of the EF while the area necessary to absorb the carbon dioxide equivalent related to the inputs used in the corn production process was responsible for 13% of the EF.

Table 16. Ecological Footprint of the corn production system.

Description	Value	Unit	Reference
Cultivated area	1.45E-04	ha/kg	This study
Crop Yield Factor	2.21	gha/ha	Kitzes, 2009
Crop EF	**3.20E-04**	**gha/kg**	
Area to absorb theCO_2 equivalent related to the inputs use			
CO_2 equivalent inputs	1644	kg/ha	This study (LCA results)
Output (kg)	6.90E+03	kg/ha/	This study
Forest area CO_2 potential fixation	6600	kg CO_2/ha/yr	Wackernagel and Rees, 1996
Area to absorb the CO_2 equivalent	3.61E-05	ha/yr	
Forest Yield Factor	1.34	gha/ha	Kitzes, 2009
Forest EF	**4.84E-05**	**gha/kg**	
Total Ecological Footprint of corn	**3.69E-04**	**gha/kg**	

Table 17. Ecological Footprint of the soybean production system.

Description	Value	Unit	Reference
Cultivated area	3.33E-04	ha/kg	This study
Crop Yield Factor	2.21	gha/ha	Kitzes, 2009
Crop EF	**7.37E-04**	**gha/kg**	
Area to absorb the CO_2 equivalent related to the inputs use			
CO_2 equivalent inputs	707	kg/ha	This study (LCA results)
Output (kg)	3.00E+03	kg/ha	This study
Forest area CO_2 potential fixation	6600	kg CO_2/ha/yr	Wackernagel and Rees, 1996
Area to absorb the CO_2 equivalent	3.57E-05	ha/yr	
Forest Yield Factor	1.34	gha/ha	Kitzes, 2009
Forest EF	**4.78E-05**	**gha/kg**	
Total Ecological Footprint of soybean	**7.85E-04**	**gha/kg**	

The total Ecological Footprint of soybean production was 7.85·10^{-4} gha/kg (Table 17). The direct agricultural area used in soybean production was responsible for 94% of the EF while the area necessary to absorb the carbon dioxide equivalent related to the production inputs was responsible for 6% of the EF.

Concerning pig production, the total Ecological Footprint was 1.35·10^{-3} gha/kg (Table 18). Results show that the indirect agricultural area cropped to produce corn and soy meal-based feeding stuffs was responsible for 43% and 27% of the EF. The area necessary to absorb the carbon dioxide equivalent related to the inputs used in the pig production process was responsible for 30% of the EF.

Table 18. Ecological Footprint of the pig production system.

Description	Value	Unit	Reference
Cultivated area corn	2.66E-04	ha/kg	This study
Crop Yield Factor	2.21	gha/ha	Kitzes, 2009
Corn crop EF	**5.88E-04**	**gha/kg**	
Cultivated area soy meal	1.62E-04	ha/kg	
Crop Yield Factor	2.21	gha/ha	Kitzes, 2009
Soy meal crop EF	**3.59E-04**	**gha/kg**	
Area to absorb the CO_2 equivalent related to the inputs use			
CO2 equivalent inputs	1.997	kg/kg	This study (LCA results)
Output (kg)	1.00E+00	kg	This study
Forest area CO_2 potential fixation	6600	kg CO_2/ha/yr	Wackernagel and Rees, 1996
Area to absorb the CO_2 equivalent	3.03E-04	ha/yr	
Forest Yield Factor	1.34	gha/ha	Kitzes, 2009
Forest EF	**4.06E-04**	**gha/kg**	
Total Ecological Footprint of pig	**1.35E-03**	**gha/kg**	

Figure 9 shows the comparison of the Ecological Footprints calculated for corn, soybean and pig production systems. The results pointed out that the EF of pig production (1.35·10^{-3} gha kg^{-1}) is higher than the EF of corn (3.69·10^{-4} gha kg^{-1}) and soybean (7.85·10^{-4} gha kg^{-1}) productions, confirming the high intensity of pig production process.

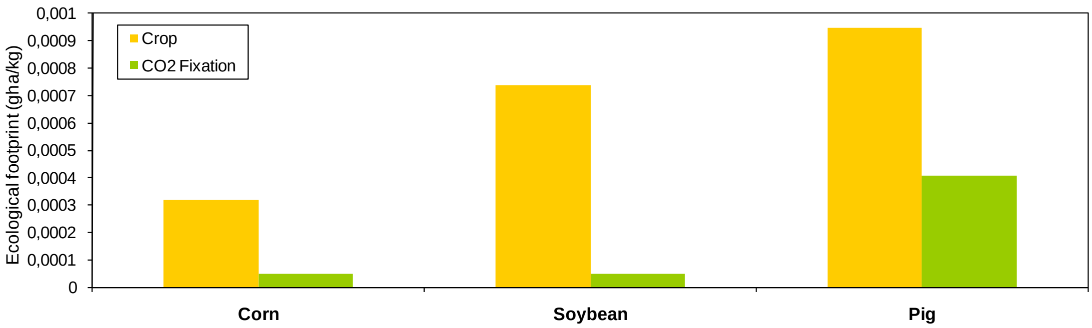

Figure 9. Comparison of the Ecological Footprint indicator of corn, soybean, and pig production systems.

3.6 Water Footprint

The calculation of the Water Footprint (WF) was based on three components: 1) green water footprint (consumptive use of rainwater); 2) blue water footprint (consumptive use of surface or groundwater); and 3) grey water footprint (volume of polluted water associated to the production of goods and services). The sum of these three components generates the total Water Footprint.

The green component for corn and soybean crops were obtained by adding the green water evapotranspiration over the growing period to water incorporated into the product (water content of the product). In the case of pig production, the green component was derived from the indirect green water footprints related to the main pig feed stuffs (corn and soy meal).

There was no blue water footprint in the corn and soybean production because no surface or groundwater was used for crop irrigation in the Toledo River basin. For the pig production system, the blue water footprint was calculated by taking into account drinking and service water used during pig production lifetime (Annex 3).

The grey component was calculated as the load of pollutants that enters the water system divided by the difference between the ambient water quality standard for that pollutant (the maximum acceptable concentration) and its natural concentration in the receiving water body. In the soybean and corn production systems the nitrogen emissions were related to the nitrogen from synthetic fertilizers and organic fertilizers (pig manure). In the pig production system the nitrogen emissions were related to the nitrogen from manure. The quantity of nitrogen that reaches free flowing water bodies was assumed to be 10% of the applied fertilization rate (Hoekstra et al., 2009). The total volume of water required per kg of nitrogen was calculated considering the volume of nitrogen leached and its maximum allowable concentration in free flowing surface water bodies. Due to the absence of local ambient water quality standards for nitrogen, we used the standard recommended by the US EPA for nitrate in water: 10 mg/liter (measured as N) (EPA, 2005). This limit was used to calculate the volume of freshwater required to assimilate the load of pollutants. Due to lack of available data on natural concentrations in receiving water bodies, the natural concentration was assumed to be zero. Tables 19, 20 and 21 show the water footprint calculated for corn, soybean and pig production systems.

The total Water Footprint of corn production was 937 liters per kilogram of corn (Table 19). Results in Table 19 show that the green water footprint (810 l kg^{-1}) was responsible for 86% of the total water footprint indicator while the grey water footprint (127 l kg^{-1})

was responsible for 14% of the total water footprint. There was no blue water footprint because no surface or groundwater was used for crop irrigation of corn in the Toledo River basin. The calculated green water footprint value for corn resulted much higher than that showed by Aldaya and Llamas (2008) for corn in Spain (around 400 m^3 per hectare). However, in the corn production system in Spain about 6000 m^3 per hectare of blue water resources were needed to complement green water use. By considering both green and blue water footprint the results obtained in this study are comparable to those obtained by Aldaya and Llamas (2008) for corn in Spain (927 l kg^{-1}).

The Water Footprints calculated for corn (Table 19) were also comparable to those calculated by Mekonnen and Hoekstra (2010) for corn production at global average. Mekonnen and Hoekstra (2010) obtained the following figures for corn production: green water footprint 947 l kg^{-1}; blue water footprint 81 l kg^{-1}; grey water footprint 194 l kg^{-1}. Total water footprint for corn production at global average was then 1,222 l kg^{-1} which is comparable to the value calculated for corn in the present study (937 l kg^{-1}). This is also because corn production systems in the Toledo River basin do not require the blue water component in the production process.

Table 19. Water Footprint for corn production system.

Description	Value	Unit	Ref.
Green WF			
Evaporation	8.10E+02	l/kg	See Annex 1
Incorporation	2.00E-01	l/kg	
Total WF green	8.10E+02	l/kg	
Blue WF			
Evaporation	0.00E+00	l/kg	
Incorporation	0.00E+00	l/kg	
Lost return	0.00E+00	l/kg	
Total WF blue	0.00E+00	l/kg	
Grey WF			
Nitrogen from fertilizers	8.16E+01	kg/ha/yr	See Annex 1
Nitrogen from organic fertilizer (manure)	5.82E+00	kg/ha/yr	See Annex 1
Total nitrogen leached[a]	8.74E+00	kg/ha/yr	
Nitrogen limit on environment[b]	1.00E+01	mg/l	EPA, 2005
Total WF grey	1.27E+02	l/kg	
Total WF	9.37E+02	l/kg	

[a] Nitrogen leaching to the water bodies estimated as 10% of total nitrogen used.
[b] By absence of local ambient water quality standards for nitrogen, the standard recommended by the US EPA for nitrate in water was used: 10 mg/liter (measured as N).

The total Water Footprint of soybean production was 1,880 liters per kilogram of soybean (Table 20). Results in Table 20 show that the green water footprint indicator (1,860 l kg^{-1}) was responsible for 99% of the total water footprint indicator while the grey water footprint (19.4 l kg^{-1}) was responsible for only 1% of the total water footprint. Also for soybean, there was no blue water footprint because no surface or groundwater was used for crop irrigation. The grey water footprint of the soybean production was lower than that of the corn because the soybean plant is able to assimilate nitrogen from atmosphere and no complement of nitrogen is necessary as synthetic fertilizers in this production system. Apparently, in the case of soybean production nitrogen is not the most critical pollutant. Due to the lack of available data on limits of phosphorous, potassium or agrochemicals residue emissions in local water bodies, it was not possible to perform a more accurate calculation of the grey water footprint component for soybean production.

Mekonnen and Hoekstra (2010) presented the following figures for soybean production at global average: green water footprint 2,037 l kg^{-1}, blue water footprint 70 l kg^{-1}, and grey water footprint 37 l kg^{-1}. Total water footprint for soybean production at global average was then 2,145 l kg^{-1}. These figures are comparable with the value calculated for soybean production system in the present study (Table 20).

Table 20. Water Footprint for soybean production system.

Description	Value	Unit	Ref.
Green WF			
Evaporation	1.86E+03	l/kg	See Annex 2
Incorporation	1.20E-01	l/kg	
Total WF green	1.86E+03	l/kg	
Blue WF			
Evaporation	0.00E+00	l/kg	
Incorporation	0.00E+00	l/kg	
Lost return	0.00E+00	l/kg	
Total WF blue	0.00E+00	l/kg	
Grey WF			
Nitrogen from fertilizers	0.00E+00	kg/ha/yr	See Annex 2
Nitrogen from organic fertilizer (manure)	5.82E+00	kg/ha/yr	See Annex 2
Total nitrogen leached[a]	5.82E-01	kg/ha/yr	
Nitrogen limit on environment[b]	1.00E+01	mg/l	EPA, 2005
Total WF grey	1.94E+01	l/kg	
Total WF	1.88E+03	l/kg	

[a] Nitrogen leaching to the water bodies estimated as 10% of total nitrogen used.

[b] in the absence of local ambient water quality standards for nitrogen, we have used the standard recommended by the US EPA for nitrate in water: 10 mg/liter (measured as N).

The total Water Footprint of pig production was 2,740 liters per kilogram of pig meat (Table 21). Results in Table 21 show that the green water footprint (2,390 l kg^{-1}) from the indirect inputs (corn and soy meal) used as pig feeding stuffs was responsible for 87% of the total water footprint while the blue footprint indicator (13.1 l kg^{-1}) was responsible for only 1% of the total water footprint. The blue water footprint refers to the direct groundwater used in the pig production while the grey water footprint refers to the water necessary for diluting the nitrogen leaching from the pig manure. The grey water footprint (332 l kg^{-1}) was responsible for 12% of the total water footprint. In this study it was assumed that only 10% of total nitrogen content in manure is emitted to the water bodies. If all the manure was released to the water bodies the grey water footprint would increase up to 3,318 l kg_{pig}^{-1} (an increase of 109% in the total water footprint indicator for this production system). Release of pig manure in water bodies is forbidden by Brazilian environmental legislation although this practice still occurs. In Figure 10 the water footprint components calculated for corn, soybean, and pig production are compared.

Table 21. Water Footprint for pig production system.

Description	Value	Unit	Ref.
Green WF			
Indirect from corn production	1.49E+03	l/kg_{pig}	See Annex 1
Indirect from soy meal production	9.08E+02	l/kg_{pig}	See Annex 2
Total WF green	2.39E+03	l/kg_{pig}	
Blue WF			
Evaporation	0.00E+00	l/kg_{pig}	
Incorporation	0.00E+00	l/kg_{pig}	
Lost return	1.31E+01	l/kg_{pig}	See Annex 3
Total WF blue	1.31E+01	l/kg_{pig}	
Grey WF			
Nitrogen leached from manure[a]	3.32E-03	kg/kg_{pig}	See Annex 3
Nitrogen limit on environment[b]	1.00E+01	mg/l	EPA, 2005
Total WF grey	3.32E+02	l/kg_{pig}	
Total WF	2.74E+03	l/kg_{pig}	

[a] Nitrogen leaching to the water bodies estimated as 10% of total present in manure produced.
[b] In the absence of local ambient water quality standards for nitrogen, we have used the standard recommended by the US EPA for nitrate in water: 10 mg/liter (measured as N).

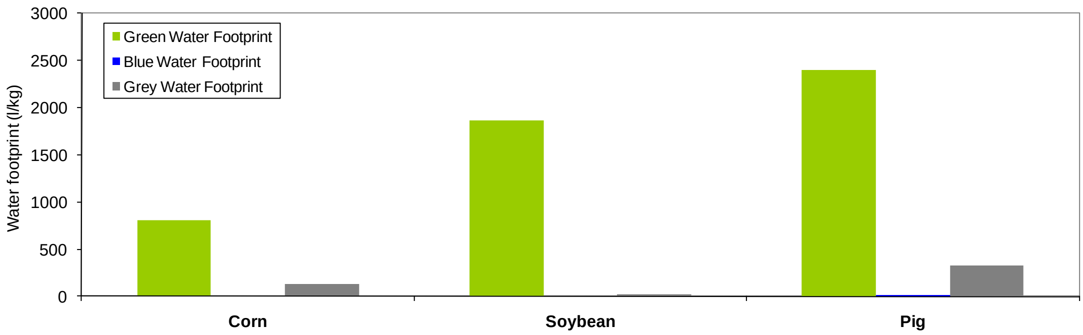

Figure 10. Comparison of the Water Footprint for corn, soybean, and pig production systems.

The indicators of water use calculated by applying the Water Footprint method were much higher than the water intensity factors calculated by means of the Material Flow Accounting (Tables 10, 11, and 12). This is because the Material Flow Accounting method evaluates direct and indirect water use corresponding only to the Blue Water Footprint component of a production process. Conventionally, statistics on water use focus on measuring water withdrawals and direct water use. Hoekstra et al. (2009) pointed out that the Water Footprint accounting method is characterized by a much broader perspective. First of all, Water Footprint measures both direct and indirect water use, where the latter refers to water use in the supply chain of a product. The Water Footprint thus links final consumers and intermediate businesses and traders to the water use along the whole production chain of a product. This is relevant because generally the direct water use of a consumer is small compared to its indirect water use, and the operational water use of a business is generally small if compared to the supply-chain water use. Consequently, the picture of the actual water requirement for a product can change radically. The Water Footprint method looks at water consumption (not only to withdrawal) also referring to the part of the water withdrawal that gets lost through evaporation (i.e., the part of the water withdrawal that does not return to the system from which it has been withdrawn). Summarizing, Water Footprint looks not only at blue water use (i.e., use of surface and ground water) but it also includes a green water footprint component (use of rainwater) and a grey water footprint component (polluted water).

Data used in the calculations of the present study were obtained from the closest meteorological station to the Toledo River basin. Since the green water footprint component is very important in the investigated production systems, it would be important to improve the quality of data on specific evapotranspiration measurements for the evaluated crops in the Toledo River basin. Site specific data on evapotranspiration in the Toledo River basin as well as standardized evapotranspiration measurements could improve water footprint calculations.

3.7 Carbon Footprint

The Carbon Footprint was assessed by using data from the LCA (GWP category). Table 22 and Figure 11 show the comparative results of Carbon Footprint for corn, soybean and pig production systems divided into primary (local emissions) and secondary (related to the inputs to the production process) Carbon Footprints.

Table 22. Comparison of the Carbon Footprints for corn, soybean and pig production systems.

Component	Corn	Soybean	Pig	Unit
Primary Carbon Footprint	0.11	0.08	1.01	kg CO_{2eq}/kg
Secondary Carbon Footprint	0.13	0.16	0.98	kg CO_{2eq}/kg
Total Carbon Footprint	0.24	0.24	2.00	kg CO_{2eq}/kg

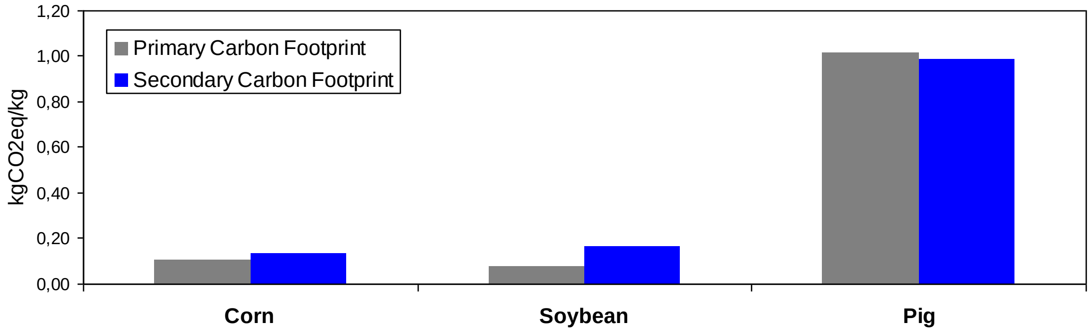

Figure 11. Comparison of the Carbon Footprints for corn, soybean and pig production systems.

Results in Table 22 show that corn and soybean production systems are characterized by the same Carbon Footprint: 0.24 kg of CO_2 equivalent is released per kg of generated products. Although the investigated corn production system shows higher primary Carbon Footprint than soybean, the soybean production system shows higher secondary Carbon Footprint than the corn system. This means that the corn production system has higher local emissions (probably due to higher emissions from nitrogen in chemical fertilizers) while the soybean production system uses more inputs in the production process. Finally, the pig production system showed the highest Carbon Footprint: about 2 kg of CO_2 equivalent released per kilogram of pig meat produced.

3.8 Performance and sustainability indicators: scenario analysis

The purpose of this section is to explore the environmental performance and sustainability of the investigated production systems at basin level through alternative scenarios based on multi-criteria assessment methods and indicators (Table 23).
The Toledo River basin has a total area of about 9,292 ha and a population of approximately 550 inhabitants. The land use is divided as follows: agricultural area 6,460 ha (69.5%); pasture 160 ha (1.7%); water 29 ha (0.3%); original forest 1,116 ha (12.0%); urban area 1,528 ha (16.4%). In the agricultural area of this basin 11,000 pigs per year are also farmed. In the scenario analysis the soybean-corn intercrop was assumed to occupy the entire agricultural area of the Toledo River basin since it is the main crop activity in the basin.

Indicators calculated at farm level were upscaled at basin level to assess the environmental impacts at regional scale focusing on three main scenarios:

- **Base Scenario:** this scenario is based on the current land uses listed above and on the inputs supporting corn, soybean and pig production systems in the Toledo River basin as detailed in Annexes 1, 2, and 3.

- **Scenario A:** this scenario considers a decrease of 50% in pig production in the Toledo basin and substitution of the agricultural area by original forest until the basin area reaches 20% of forest area, as it is requested by the Brazilian forest law. Scenario A is also based on the following assumptions: (**a**) the use of more appropriate soil management techniques reduces soil loss by 50% compared to the Base Scenario; (**b**) appropriate measures for water savings reduce water use in pig production by 50%; (**c**) appropriate manure management techniques reduce local emissions of N_2O, NH_3, and CH_4 from manure by 50%; (**d**) biological pest control reduces agrochemicals use in corn and soybean production systems by 50%.

- **Scenario B:** this scenario considers an increase of 50% in pig production in the Toledo River basin and the spreading of the agricultural area over the remaining original forest until the latter decreases to only 5% of the total basin area. Scenario B is also based on the following assumptions: (**a**) without using appropriate soil management techniques soil loss increases by 50% compared to the Base Scenario; (**b**) due to lack of proper water management, water use in pig production system increases by 50%; (**c**) inappropriate manure management techniques increase local emissions of N_2O, NH_3, and CH_4 from pig manure by 50%; (**d**) more resistant agricultural pests will increase the use of agrochemicals by 50% in both corn and soybean production systems.

Table 23 shows selected environmental indicators calculated to draw and evaluate the three alternative scenarios for the Toledo River basin. In line with the best option suggested by Scenario A, all indicators decrease in Scenario A compared to the Base Scenario and Scenario B. This highlights the crucial role played by the assumption made in Scenario A in terms of the environmental performance and sustainability of the investigated production systems.

A comparison among a large set of multi-criteria indicators calculated for three alternative scenarios (Base Scenario, Scenarios A, and B) is shown through a radar diagram in Figure 12. To enable the comparison among indicators with different orders of magnitude, a normalization procedure was applied. Indicators were normalized from Table 23 by dividing all the values of Scenarios A and B by the corresponding value of the Base Scenario.

Table 23. Environmental indicators selected to draw three alternative scenarios for the Toledo River basin.

Indicator	Base Scenario	Scenario A	Scenario B	Units per year
Energy input	1.36E+14	1.13E+14	1.59E+14	Joule
Abiotic resources	1.69E+08	8.70E+07	2.64E+08	kg
Water resources	1.73E+08	1.10E+08	2.51E+08	kg
Air resources	1.46E+06	1.25E+06	1.66E+06	kg
Biotic resources	9.15E+06	4.35E+06	1.47E+07	kg
Emergy input	1.01E+20	8.11E+19	1.21E+20	seJ
Ecological footprint	3.33E+04	2.86E+04	3.77E+04	global ha
Green water footprint	7.51E+10	6.53E+10	8.39E+10	Liter
Blue water footprint	1.58E+07	3.96E+06	3.56E+07	Liter
Grey water footprint	6.42E+09	5.19E+09	7.65E+09	Liter
Agrochemicals use	1.33E+08	5.89E+07	2.20E+08	g
Soil loss	2.07E+08	9.14E+07	3.42E+08	kg
Abiotic depletion	6.71E+04	5.25E+04	8.22E+04	kg Sb eq
Acidification	8.07E+04	5.62E+04	1.11E+05	kg SO_2 eq
Eutrophication	5.95E+04	4.75E+04	7.26E+04	kg PO_4 eq
Global warming (Carbon Footprint)	1.76E+07	1.36E+07	2.21E+07	kg CO_2 eq
Ozone layer depletion (ODP)	5.56E+00	2.88E+00	8.64E+00	kg CFC-11 eq
Human toxicity	6.65E+06	4.52E+06	8.99E+06	kg 1.4-DB eq
Fresh water aquatic ecotoxicity	1.71E+06	1.24E+06	2.21E+06	kg 1.4-DB eq
Marine aquatic ecotoxicity	4.05E+09	3.04E+09	5.13E+09	kg 1.4-DB eq
Terrestrial ecotoxicity	3.86E+04	2.93E+04	4.85E+04	kg 1.4-DB eq
Photochemical oxidation	5.81E+03	3.80E+03	7.99E+03	kg C_2H_4

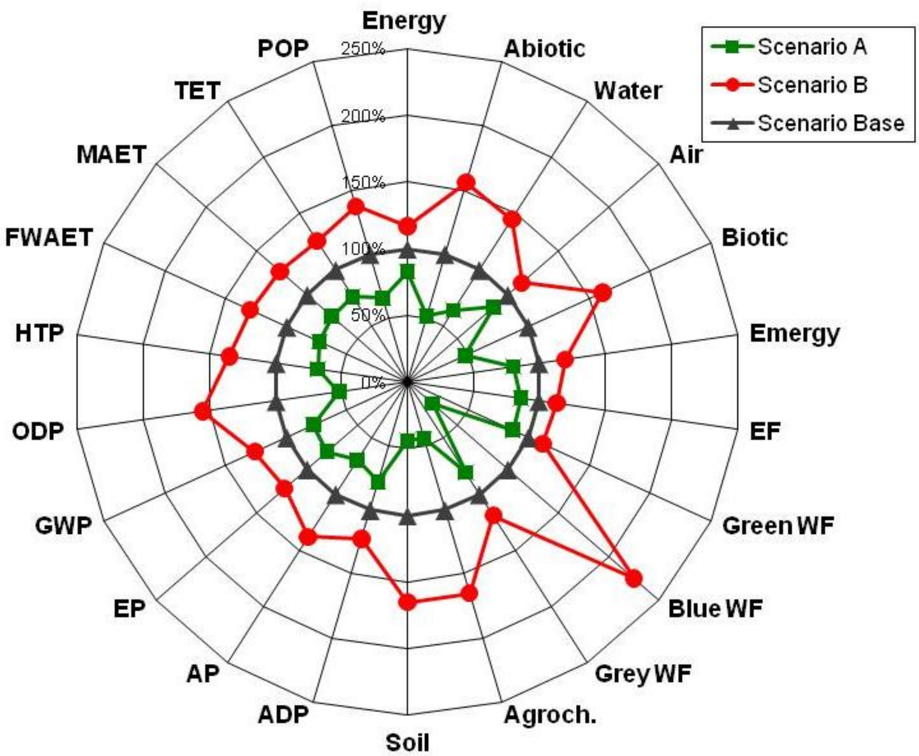

Figure 12. Comparison among three alternative scenarios: Base Scenario, Scenario A, and Scenario B.

Considering that a wider area means a higher environmental impact, Scenario A shows a smaller impact compared to Scenario B and Base Scenario. Such an outcome can be explained by considering that the assumptions made in Scenario A involve not only a lower direct consumption of inputs but also lower indirect emissions as well as indirect consumption of energy, material and environmental support.

Results of different scenarios may differ depending on goal, boundaries, time scale and different management schemes, thus suggesting different optimization procedures. Ulgiati et al. (2003) pointed out that assessing a process performance on different scales offers significant ways to refine the analysis and improve the process.

Agrochemicals use and soil loss are important mass flow indicators for agricultural production systems. The figure of 133 tons of agrochemicals used every year in the Toledo River basin (Base Scenario) proves the intensity of agrochemical use in the basin, indicating its high contribution to environmental problems and water pollution in the region. The Toledo River basin plays an important role in water and sediment contribution to the reservoir of the Itaipu Binacional dam. The topsoil loss due to agricultural activities in the basin is about 207,000 tons per year. This amount of topsoil loss becomes sediment into the dam decreasing its life span. This highlights the interaction between agricultural production systems in the Toledo River basin and other important economic sectors in Brazil (e.g., electricity generation). Therefore, proper soil management techniques are urgently needed not only to preserve the ability of agroecosystems to provide goods and services but also to avoid potential negative feedback on other productive sectors.

The total emergy is a measure of environmental support (work done by nature) provided to productive systems. In principle, the higher the imported non-renewable emergy use, the less sustainable is the system. In this regard, the emergy theory suggests that high-transformity products should be properly used to reinforce (amplify) the process by feeding back high-quality emergy to the lower (low-transformity) levels of the system. An appropriate use of environmental support increases sustainability. The demand for environmental support, here measured by the emergy intensity indicator, appears to be a fundamental performance category, suggesting patterns for appropriate use of products. In the Base Scenario, the emergy-based indicators show that soybean, corn and pig production systems require an environmental support of $1.01 \cdot 10^{20}$ seJ year^{-1}. If this emergy flow could be provided only by renewable resources, an area equivalent to 56,364 ha would be necessary. This value is about 6.1 times higher than the total area of the basin considering all land uses.

The Ecological Footprint indicator shows that the area required to produce the inputs used in the production process and to assimilate the wastes produced by the three production systems is equivalent to 33,300 hectares. This area is about 3.6 times higher than the total area of the basin. Ecological Footprint is a measure of the “ecological deficit” showing the dependence of the Toledo basin on ecosystem services generated outside its political boundary. This is an important indication of unsustainability as there is strong competition for using the limited area of productive land in the world.

An important environmental benefit of biomass production should be the carbon neutrality between carbon absorption and emissions: the carbon emitted by utilizing biomass should be balanced by the carbon absorbed in the photosynthetic growing of biomass, thus having a carbon neutral balance. On investigating the entire production chain, it most often emerges that this condition is not satisfied. The Life Cycle Assessment showed that the Carbon Footprint (global warming potential) of the three production systems (corn, soybean, and pig) upscaled to the basin level is equivalent to the emissions of 17,600 tons of CO_2 per year (Base Scenario). Through better management practices assumed in Scenario A, it would be possible to reduce the Carbon Footprint by 22% compared to the present situation (Base Scenario). However, in the case of Scenario B the Carbon Footprint would increase by 26% compared to the current situation. In the same way, in Scenario A, acidification and eutrophication would decrease by 20% and 30% compared to the Base Scenario.

It is worth noting that, while the global warming potential (Carbon Footprint) is related to global biosphere processes and climate change aspects, the acidification and eutrophication potentials are mainly related to local regional-scale impacts generated on the sites where the process occurs.

The indicator of water resource use calculated in the Material Flow Accounting shows that the amount of water directly and indirectly used for soybean, corn, and pig production systems in the Toledo River basin (Base Scenario) is equivalent to the water supplying a city of 3,314 inhabitants (considering an average water use of 143 liters person^{-1} day^{-1} in urban areas of Brazil). This figure is more than six times higher than the population living in the Toledo River basin.

The Water Footprint indicators show that the total water required by the investigated processes (green and blue water) and the water used for wastes dilution (grey water) at the Toledo River basin level is equal to 82 million m^3 per year (Base Scenario). Considering an average water use of 143 liters person^{-1} day^{-1}, the amount of water directly and indirectly used for soybean, corn, and pig production systems at the Toledo basin level is equivalent to the water supply for a city of 1.5 million inhabitants. This figure highlights the huge impact of the three production systems on local water resources. Results in Table 23 show how the water footprint (green, blue, grey) is a crucial factor when upscaling the production processes at basin level. In addition, the high value of the green water footprint also points out the potentially high impact on biodiversity due to reallocation of green evaporative flows from natural vegetation to productive vegetation. Massive losses of original forest can heavily affect such a regime shift. Grey water footprint is also an important component due to the high load of agrochemicals on water bodies. Hoekstra et al. (2009) pointed out that grey water footprint can be reduced to zero by preventing the application of chemicals to agricultural fields. Grey water can be lowered substantially by applying less chemicals and adopting better techniques and timing of application (so that less chemicals are drained into water systems by leaching and runoff).

Agriculture is often focused on maximizing land productivity, which makes sense when land is scarce and freshwater is very abundant. Instead, when water is the limiting factor, maximizing water productivity becomes a crucial goal. This implies applying less irrigation in a more efficient way and harvesting a higher yield per volume of water evaporated. Because blue water originates from surface or groundwater, it has a larger effect on the environment than green water use. The world's blue water resources are limited. Once we subtract from the total annual blue water flow the flows in remote areas as well as flood flows and environmental flow requirements, we are left with a limited volume of available blue water.

Local impacts may occur due to overexploitation or pollution of surface or groundwater bodies or due to land use change. Environmental impacts at the river basin level may occur when several exploitations and waste flows are added up causing downstream impacts on aquatic and terrestrial ecosystems next to the river.

Mekonnen and Hoekstra (2010) presented a study that quantifies the green, blue and grey water footprint of global crop production in a spatially-explicit way for the period 1996-2005. The study showed that corn production is responsible for 10% of the total world water footprint while soybean production is responsible for 5% of the total world water footprint.

In the Base Scenario, considering the land uses at basin level, agricultural crops are responsible for 96% of the total Water Footprint in the Toledo River basin while pig production system is responsible for only 4% of the total Water Footprint. This proportion is very similar to the results obtained for the Guadiana River basin (Spain) by Aldaya and Llamas (2008), where agricultural activities accounted for 95% of the total Water Footprint.

Mekonnen and Hoekstra (2010) showed that the water footprint of crop production in the Paraná River basin (the biggest hydrological basin that includes the Toledo River basin) is as follows: green water footprint $237 \cdot 10^{12}$ l year^{-1}, blue water footprint $3.2 \cdot 10^{12}$ l year^{-1}, and grey water footprint $9.4 \cdot 10^{12}$ l year^{-1}. The total water footprint in the Paraná River basin is $250 \cdot 10^{12}$ liters per year. If we divided the water footprint of the crops in the Paraná River basin by its area ($8.8 \cdot 10^{7}$ ha) and the water footprint of the crops (corn and soybean) in the Toledo River basin by its area ($9.3 \cdot 10^{3}$ ha), the comparative results show that the green water footprint per unit of area calculated for Toledo River basin is 2.9 times higher than the green water footprint in the Parana River basin. In addition, the grey water footprint per unit of area calculated in the Toledo River basin is 6.1 times higher than in the Parana River basin. It was not possible to compare the blue water footprint components because there is no blue water use in the Toledo River basin. These figures highlight the higher intensity in water use per unit area in the Toledo River basin since they are much higher than the average water footprint calculated for agricultural activities in the whole region of Paraná River basin.

All these results prove the high intensity of materials, energy, emergy, and water use due to agricultural and pig production activities in the Toledo River basin. The use of these natural resources is exceeding the carrying capacity of the Toledo basin and is sustained by eroding the stocks of natural resources at an unsustainable rate. Water Footprint indicators in river basins can facilitate a more efficient allocation and use of water resources, also providing a transparent interdisciplinary framework for policy formulation.

It is important to notice that double counting may occur when evaluating green and grey water footprint components at the basin level. The double counting in green water footprint may occur when corn or soybean produced locally is used in pig production systems. In this case, the indirect green water resources from corn and soy meal (from soybean) produced locally should not be double counted. Double counting in grey water may occur when pollution from pig manure is accounted for in pig production systems and also in crop production systems when the manure is used as organic fertilizer in the same crop production.

The application of an integrated multi-criteria assessment framework to alternative scenarios generated performance and sustainability indicators calling for a twofold optimization pattern: (**a**) to decrease the use of or replace those inputs affecting material, energy, emergy, and water flows as well as the ecological and carbon footprints; and (**b**) to decrease the use or avoid the misuse of the investigated products, thus indirectly decrease the input demand by controlling the end of the life cycle chain. Results on a local scale suggest that optimization strategies should be applied to the investigated processes by means of a more efficient use of input flows as well as by recycling wastes, by-products, and co-products, thus implementing so-called “zero-emission production patterns”. Process clustering oriented to maximize matter and energy flow exchanges (included wastes, by-products and co-products) within a production pattern could be a viable strategy to improve the environmental performance and sustainability in the long run. For example, a higher integration between agricultural activities and pig farming systems could generate significant savings of chemical fertilizers and feed stuffs at both farm and regional scales, reducing at the same time the environmental impacts of these production activities.

4. Conclusion

The multi-criteria assessment framework developed in this study provided useful information about the interactions and proper use of natural capital, human-driven resources, and ecosystem services supporting the management of agricultural and farming systems in the Toledo River basin (Brazil).

Quantifying the direct and indirect flows of water, matter, energy and money to and from the investigated systems made possible a deeper understanding of their production processes as well as a more detailed picture of their relationships with the surrounding environment. Indicators of environmental performance highlighted the intensification process occurring in the Toledo River basin over recent decades. The indicators of environmental sustainability showed an increased dependence on non-renewable resources, mainly imported from outside the system, supporting modern cropping and pig production systems. The input flows showing a high impact on performance and sustainability indicators were water and feeding stuffs used in the pig production and agrochemicals, fertilizers and topsoil used in the soybean-corn production systems.

The analysis of three alternative scenarios explored the potential environmental impacts associated with different options of natural resource management in the Toledo River basin. The assumptions made in Scenario A showed a possible improvement of the environmental performance and sustainability through a shift in land use and by applying proper environmental management practices.

The multi-criteria assessment framework implemented in this study and the related set of indicators provided a benchmark for future investigations as well as a useful support to local managers and policy makers committed to developing environmental policies based on sustainable management of agroecosystems. Better integration between agricultural and farming activities in the Toledo River basin is worth further investigation by means of both field and modeling studies. Crucial factors to investigate are the intensive use of water, agrochemicals and the concentration of manure, all related to the high intensity of agricultural and farming activities in the basin.

Acknowledgements

The authors wish to acknowledge the support of UNESCO-IHP in the framework of the project “Water Programme for Environmental Sustainability” - contract n. 4500080116. They are also grateful to Rafael González from the International Hydroinformatics Center (PTI Itaipu) for providing data and assistance to set up the case study.

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Annex 1. Calculation notes for corn production system

Note	Description	Value	Unit	References	Other estimates (if any)
1	**Sun**				
	Insolation	**1.86E+06**	**watt-hour/m2/yr**	http://eosweb.larc.nasa.gov/cgi-bin/sse/sse.cgi	
	Albedo	**14%**		http://eosweb.larc.nasa.gov/cgi-bin/sse/sse.cgi	
	Conversion	**3.60E+03**	**J/Wh**		
	*Insolation energy = (1-Albedo) * (Insolation) * (3600 J/kWh)*				
	Insolation energy	**5.77E+09**	**J/m2/yr**		
	Cropped area	**1.00E+04**	**m2/ha**		
	*Insolation energy = (Land area) * (Insolation)*				
	Insolation energy	**5.77E+13**	**J/ha/yr**		
2	**Rain**				
	Precipitation (Average years 1961-1990, Maringa city)	**1.80E+03**	**mm/yr or L/m2/yr**	http://eosweb.larc.nasa.gov/cgi-bin/sse/sse.cgi	
	Cropped area	**1.00E+04**	**m2/ha**		
	Density of water	**1.00E+00**	**kg/L**		
	*Mass of rain = (Precipitation) * (Area) * (Density)*				
	Mass of rain	**1.80E+07**	**kg/ha/yr**		
	Fraction of water that is evapotranspired	**62%**		www.inmet.gov.br	
	Mass of rain evapotranspired	**1.12E+07**	**kg/ha/yr**		
	*Free energy of water = (Evapotranspired water) * (Gibbs free energy of water)*				
	Gibbs free energy of water	**4.94E+03**	**J/kg**	Odum, 1996	
	Energy of rain	**5.52E+10**	**J/ha/yr**		
3	**Deep heat**				
	Heat flow through earth crust				
	Average heat flow per area	**1.00E+06**	**J/m2/yr**	Odum, 1996	
	Land area	**1.00E+04**	**m2/ha**		
	*Energy = (Land area) * (Heat flow per area)*				
	Energy	**1.00E+10**	**J/yr**		
4	**Soil loss**				
	Soil loss (eroded)	**1.50E+04**	**kg/ha/yr**	http://www.unicamp.br/fea/ortega/curso/planilha-complexo.htm	
	Ratio of the organic matter in the soil	**4%**		Organic matter in soil is reported in the range 3-6% of total soil weigh (Odum,1996)	
	*Organic matter in topsoil used up = (Mass of topsoil) * (% organic matter)*				
	Organic matter in topsoil used up	**6.00E+02**	**kg/ha/yr**		
	Water content in organic matter	**70%**		Average value	
	*Dry organic matter lost with erosion = (Organic matter) * (% Water content)*				
	Dry organic matter lost with erosion	**1.80E+02**	**kgdw/ha/yr**		
	Energy content of dry organic matter	**5.40E+03**	**Kcal/kgdw**	Odum, 1996	
	Energy = (kgdw/ha/yr) * (5400 Kcal/kgdw) * (4186 J/Kcal)				
	Energy content of dry organic matter	**4.07E+09**	**J/ha/yr**		
5	**Limestone**				
	Limestone use	**3.50E+02**	**kg/ha/yr**	Agrianual, 2010	Others: 413 kg/ha/yr (field work)
	Specific energy	**6.11E+05**	**J/kg**	Odum, 1996	
	*Energy demand = (Mass) * (Specific energy)*				
	Energy demand	**2.14E+08**	**J/ha/yr**		

6	**Agrochemicals**				
	Herbicides	**7.60E+00**	**kg/ha/yr**	Agrianual, 2010	
	Insecticides	**1.80E+00**	**kg/ha/yr**	Agrianual, 2010	
	Fungicides	**7.50E-01**	**kg/ha/yr**	Agrianual, 2010	
	Total	**1.02E+01**	**kg/ha/yr**		Others: 8,7 kg/ha/yr (field work)
7	**Seeds**				
	Mass of seeds used	**1.79E+01**	**kg/ha/yr**	From field work	
8	**Organic fertilizer**				
	Total organic fertilizer (pig manure) used	**1.03E+03**	**kg/ha/yr**	From field work	
	Nitrogen in manure	**5,82E+00**	**kg/ha/yr**	Cederberg and Flysjö, 2004	
	Phosphorous in manure	**2,02E+00**	**kg/ha/yr**	Cederberg and Flysjö, 2004	
	Potassium in manure	**2,36E+00**	**kg/ha/yr**	Cederberg and Flysjö, 2004	
9	**Nitrogen fertilizer**				
	NPK fertilizer used (8-20-20)	**3.20E+02**	**kg/ha/yr**	Agrianual, 2010	Others: 372 kg/ha/yr (8-30-20) (field work)
	% N	**8%**		Agrianual, 2010	
	*N = (Total fertilizer) * (%N)*				
	N use	**2.56E+01**	**kg N/ha/yr**		
	Urea fertilizer used	**1.20E+02**	**kg/ha/yr**	Agrianual, 2010	Others: 123 kg/ha/yr (field work)
	*N = (Total urea) * (28 gmol N/60 gmol urea)*				
	N use	**5.60E+01**	**kg N/ha/yr**		
	Total N use	**8.16E+01**	**kg N/ha/yr**		
10	**Phosphate fertilizer**				
	NPK fertilizer used (8-20-20)	**3.20E+02**	**kg/ha/yr**	Agrianual, 2010	Others: 372 kg/ha/yr (8-30-20) (Field work)
	% P_2O_5	**20%**		Agrianual, 2010	
	*P_2O_5 = (Total fertilizer) * (%P_2O_5)*				
	Total P_2O_5 use	**6.40E+01**	**kg P_2O_5/ha/yr**		
11	**Potassium fertilizer**				
	NPK fertilizer used (8-20-20)	**3.20E+02**	**kg/ha/yr**	Agrianual, 2010	Others: 372 kg/ha/yr (8-30-20) (Field work)
	% K_2O	**20%**		Agrianual, 2010	
	*K_2O = (Total fertilizer) * (%K_2O)*				
	K_2O used	**6.40E+01**	**kg K/ha/yr**		
	KCl fertilizer used	**1.00E+02**	**kg/ha/yr**	Agrianual, 2010	Others: 206 kg/ha/yr (Field work)
	*K = (KCl fertilizer) * (39 gmol K/74.5 gmol KCl)*				
	K used	**5.23E+01**	**kg K/ha/yr**		
	*K_2O = (kg K) * (94gmol K_2O/78gmol K)*				
	K_2O equivalent used	**6.31E+01**	**kg K_2O/ha/yr**		
	Total K_2O use	**1.27E+02**	**kg K_2O/ha/yr**		

12	**Fuels**				
	Hours of tractor (4x4 120cv) used	**1.05E+00**	**HM/ha/yr**	Agrianual, 2010	
	Average fuel use	**1.78E+01**	**L/hr**	Based on the tractor power	
	*Fuel consumption = (Hours used) * (consumption/hour)*				
	Fuel consumption	**1.86E+01**	**L/ha/yr**		
	Hours of tractor (4x2 65cv) used	**8.30E-01**	**HM/ha/yr**	Agrianual, 2010	
	Average fuel use	**9.62E+00**	**L/hr**	Based on the tractor power	
	*Fuel consumption = (Hours used) * (consumption/hour)*				
	Fuel consumption	**7.98E+00**	**L/ha/yr**		
	Hours of tractor (4x2 90cv) used	**1.00E+00**	**HM/ha/yr**	Agrianual, 2010	
	Average fuel use	**1.33E+01**	**L/hr**	Based on the tractor power	
	*Fuel consumption = (Hours used) * (consumption/hour)*				
	Fuel consumption	**1.33E+01**	**L/ha/yr**		
	Hours of harvester (180cv) used	**6.50E-01**	**HM/ha/yr**	Agrianual, 2010	
	Average fuel use	**2.66E+01**	**L/hr**	Based on the harvester power	
	*Fuel consumption = (Hours used) * (consumption/hour)*				
	Fuel consumption	**1.73E+01**	**L/ha/yr**		
	Total fuel use	**5.72E+01**	**L/ha/yr**		Others: 2 - 3 HM/ha/yr (Field work)
	Density of fuel	**8.40E-01**	**kg/L**		
	*Mass = (Volume) * (Density)*				
	Mass of fuel used	**4.81E+01**	**kg/ha/yr**		
	Specific energy of diesel	**4.45E+07**	**J/kg**	Boustead and Hancock, 1979	
	*Energy demand = (Mass) * (Specific energy)*				
	Energy demand	**2.14E+09**	**J/ha/yr**		
13	**Steel**				
	Tractors	**1.12E+00**	**kg/ha/yr**	See Annex 1a	
	Harvester	**1.07E+00**	**kg/ha/yr**	See Annex 1a	
	Agricultural Machinery	**6.62E-01**	**kg/ha/yr**	See Annex 1a	
	Total	**2.85E+00**	**kg/ha/yr**		
14	**Local labor**				
	Manpower	**1.25E+00**	**man-hour/ha/yr**	Agrianual, 2010	Others: 3 - 4.3 H-man/ha/yr (Field work)
	Tractor/harvester driver	**3.53E+00**	**man-hour/ha/yr**	Agrianual, 2010	
	Total	**4.78E+00**	**man-hour/ha/yr**		
	Labor cost per hour	**1.99**	**USD/h**	Agrianual, 2010	
	Labor cost per hectare	**9.50**	**USD/ha/yr**		
15	**Services**				
	Production cost (excluding labour)	**821.22**	**USD/ha/yr**	Agrianual, 2010	
16	**Corn output**				
	Average corn production	**6.900E+03**	**kg/ha/yr**	Agrianual, 2010	Others: 7605 - 11529 kg/ha/yr (Field work)
	Specific energy	**1.64E+07**	**J/kg**		
	*Energy demand = (Mass) * (Specific energy)*				
	Energy demand	**1.13E+11**	**J/ha/yr**		

Annex 1a: Calculation notes for agricultural machinery in corn production

Description	Weight (kg)	Life spam (h)	Hours used (h/ha/yr)	Ref. for hours used	Machinery used up (kg/ha/yr)
Tractor tires 90cv	3870	10000	1.00	Agrianual, 2010	0.39
Tractor tires 120cv	4920	10000	1.05	Agrianual, 2010	0.52
Tractor tires 65cv	2580	10000	0.83	Agrianual, 2010	0.21
Harvester	16400	10000	0.65	Agrianual, 2010	1.07
Moldboard plowing	3200	8000	0.40	Agrianual, 2010	0.16
Limestone sprayer	1203	8000	0.33	Agrianual, 2010	0.05
Seeder	1500	8000	0.65	Agrianual, 2010	0.12
Seed mixer	800	8000	0.10	Agrianual, 2010	0.01
Field cultivator	850	8000	0.50	Agrianual, 2010	0.05
Agrochemical sprayer	2140	8000	1.00	Agrianual, 2010	0.27

Annex 1b: Local emissions in corn production

Nitrogen application (urea)					
N_2O	1.325	% of N in fert. is conv. in N_2O	(IPCC, 2006)	1.08	kgN_2O/ha/yr
CO_2	0.2	kgC/kg_{urea}	(IPCC, 2006)	88.00	$kgCO_2$/ha/yr
Lime					
CO_2	0.13	kgC/kg_{lime}	(IPCC, 2006)	166.83	$kgCO_2$/ha/yr
Diesel					
CO_2			Stoichiometric value	152.10	$kgCO_2$/ha/yr

Annex 2. Calculation notes for soybean production system

Note	Description	Value	Unit	References	Other estimates (if any)
1	**Sun**				
	Insolation	**1.86E+06**	**watt-hour/m2/yr**	http://eosweb.larc.nasa.gov/cgi-bin/sse/sse.cgi	
	Albedo	**14%**		http://eosweb.larc.nasa.gov/cgi-bin/sse/sse.cgi	
	Conversion	**3.60E+03**	**J/Wh**		
	*Insolation energy = (1-Albedo) * (Insolation) * (3600 J/kWh)*				
	Insolation energy	**5.77E+09**	**J/m2/yr**		
	Cropped area	**1.00E+04**	**m2/ha**		
	*Insolation energy = (Land area) * (Insolation)*				
	Insolation energy	**5.77E+13**	**J/ha/yr**		
2	**Rain**				
	Precipitation (Average years 1961-1990, Maringa city)	**1.80E+03**	**mm/yr or L/m2/yr**	http://eosweb.larc.nasa.gov/cgi-bin/sse/sse.cgi	
	Cropped area	**1.00E+04**	**m2/ha**		
	Density of water	**1.00E+00**	**kg/L**		
	*Mass of rain = (Precipitation) * (Area) * (Density)*				
	Mass of rain	**1.80E+07**	**kg/ha/yr**		
	Fraction of water that is evapotranspired	**62%**		www.inmet.gov.br	
	Mass of rain evapotranspired	**1.12E+07**	**kg/ha/yr**		
	*Free energy of water = (Evapotranspired water) * (Gibbs free energy of water)*				
	Gibbs free energy of water	**4.94E+03**	**J/kg**	Odum, 1996	
	Energy of rain	**5.52E+10**	**J/ha/yr**		
3	**Deep heat**				
	Heat flow through earth crust				
	Average heat flow per area	**1.00E+06**	**J/m2/yr**	Odum, 1996	
	Land area	**1.00E+04**	**m2/ha**		
	*Energy = (Land area) * (Heat flow per area)*				
	Energy	**1.00E+10**	**J/yr**		
4	**Soil loss**				
	Soil loss (eroded)	**1.70E+04**	**kg/ha/yr**	http://www.fea.unicamp.br/docentes/ortega/livro/C17-EAnaliseAl-JM.pdf (pg 9)	
	Ratio of the organic matter in the soil	**4%**		Organic matter in soil is reported in the range 3-6% of total soil weigh (Odum,1996)	
	*Organic matter in topsoil used up = (Mass of topsoil) * (% organic matter)*				
	Organic matter in topsoil used up	**6.80E+02**	**kg/ha/yr**		
	Water content in organic matter	**70%**		Average value	
	*Dry organic matter lost with erosion = (Organic matter) * (1-Water content)*				
	Dry organic matter lost with erosion	**2.04E+02**	**kgdw/ha/yr**		
	Energy content of dry organic matter	**5.40E+03**	**Kcal/kgdw**	Odum, 1996	
	Energy = (kgdw/ha/yr) * (5400 Kcal/kgdw) * (4186 J/Kcal)				
	Energy content of dry organic matter	**4.61E+09**	**J/ha/yr**		
5	**Limestone**				
	Limestone use	**2.00E+02**	**kg/ha/yr**	Agrianual, 2010	Others: 1200 kg/ha/yr (Hirakuri, 2008); 413 kg/ha/yr (field work)
	Specific energy	**6.11E+05**	**J/kg**	Odum, 1996	
	*Energy demand = (Mass) * (Specific energy)*				
	Energy demand	**1.22E+08**	**J/ha/yr**		

6	**Agrochemicals**				
	Other chemicals	**1.10E+00**	**kg/ha/yr**	Agrianual, 2010	
	Herbicides	**5.45E+00**	**kg/ha/yr**	Agrianual, 2010	
	Insecticides	**2.95E+00**	**kg/ha/yr**	Agrianual, 2010	
	Fungicides	**9.60E-01**	**kg/ha/yr**	Agrianual, 2010	
	Total	**1.05E+01**	**kg/ha/yr**		Others: 7,14 kg/ha/yr (Hirakuri, 2008); 13,2 kg/ha/yr (Field work)
7	**Seeds**				
	Mass of seeds used	**6.50E+01**	**kg/ha/yr**	Agrianual, 2010	Others: 56 kg/ha/yr (Hirakuri, 2008); 82,3 kg/ha/yr (Field work)
8	**Organic fertilizer**				
	Total organic fertilizer (pig manure) used	**1.03E+03**	**kg/ha/yr**	From field work	
	Nitrogen in manure	**5,82E+00**	**kg/ha/yr**	Cederberg and Flysjö, 2004	
	Phosphorous in manure	**2,02E+00**	**kg/ha/yr**	Cederberg and Flysjö, 2004	
	Potassium in manure	**2,36E+00**	**kg/ha/yr**	Cederberg andFlysjö, 2004	
9	**Nitrogen fertilizer**				
	NPK fertilizer used (0-20-20)	**3.00E+02**	**kg/ha/yr**	Agrianual, 2010	
	% N	**0%**		Agrianual, 2010	
	*N = (Total fertilizer) * (%N)*				
	Annual N use	**0.00E+00**	**kg N/ha/yr**		
10	**Phosphate fertilizer**				
	NPK fertilizer used (0-20-20)	**3.00E+02**	**kg/ha/yr**	Agrianual, 2010	
	% P_2O_5	**20%**		Agrianual, 2010	
	*P = (Total fertilizer) * (%P_2O_5)*				
	Annual P_2O_5 use	**6.00E+01**	**kg P/ha/yr**		
11	**Potassium fertilizer**				
	NPK fertilizer used (0-20-20)	**3.00E+02**	**kg/ha/yr**	Agrianual, 2010	
	% K_2O	**20%**		Agrianual, 2010	
	*K = (Total fertilizer) * (%K_2O)*				
	Annual K_2O use	**6.00E+01**	**kg K/ha/yr**		
12	**Fuels**				
	Hours of tractor (4x4 120cv) used	**6.70E-01**	**HM/ha/yr**	Agrianual, 2010	
	Average fuel use	**1.78E+01**	**L/hr**	Based on the tractor power	
	*Fuel consumption = (Hours used) * (consumption/hour)*				
	Fuel consumption	**1.19E+01**	**L/ha/yr**		
	Hours of tractor (4x2 65cv) used	**4.50E-01**	**HM/ha/yr**	Agrianual, 2010	
	Average fuel use	**9.62E+00**	**L/hr**	Based on the tractor power	
	*Fuel consumption = (Hours used) * (consumption/hour)*				
	Fuel consumption	**4.33E+00**	**L/ha/yr**		
	Hours of tractor (4x2 90cv) used	**1.20E+00**	**HM/ha/yr**	Agrianual, 2010	
	Average fuel use	**1.33E+01**	**L/hr**	Based on the tractor power	
	*Fuel consumption = (Hours used) * (consumption/hour)*				
	Fuel consumption	**1.60E+01**	**L/ha/yr**		
	Hours of harvester (180cv) used	**6.50E-01**	**HM/ha/yr**	Agrianual, 2010	
	Average fuel use	**2.66E+01**	**L/hr**	Based on the harvester power	
	*Fuel consumption = (Hours used) * (consumption/hour)*				

	Fuel consumption	**1.73E+01**	**L/ha/yr**		
	Total fuel use	**4.95E+01**	**L/ha/yr**		Others: 2,95 HM/ha/yr (Hirakuri, 2008)
	Density of fuel	**8.40E-01**	**kg/L**		
	*Mass = (Volume) * (Density)*				
	Mass of fuel used	**4.16E+01**	**kg/ha/yr**		
	Specific energy of diesel	**4.45E+07**	**J/kg**	Boustead and Hancock, 1979	
	*Energy demand = (Mass) * (Specific energy)*				
	Energy demand	**1.85E+09**	**J/ha/yr**		
13	**Steel**				
	Tractors	**9.10E-01**	**kg/ha/yr**	See Annex 2a	
	Harvester	**1.07E+00**	**kg/ha/yr**	See Annex 2a	
	Agricultural machinery	**5.24E-01**	**kg/ha/yr**	See Annex 2a	
	Total	**2.50E+00**	**kg/ha/yr**		
14	**Local labor**				
	Manpower	**1.65E+00**	**man-hour/ha/yr**	Agrianual, 2010	Others: 4,3 HM/ha/yr (Field work)
	Tractor/harvester driver	**2.97E+00**	**man-hour/ha/yr**	Agrianual, 2010	
	Total	**4.62E+00**	**man-hour/ha/yr**		
	Labor cost per hour	**1.99**	**USD/h**	Agrianual, 2010	
	Labor cost per hectare	**9.18**	**USD/ha/yr**		
15	**Services**				
	Production cost (-labour)	**580.01**	**USD/ha/yr**	Agrianual, 2010	Others: 803 USD/ha/yr (Hirakuri, 2008); 705 USD/ha/yr (Field work)
16	**Output**				
	Average soybean production	**3.000E+03**	**kg/ha/a**	Agrianual, 2010	Others: 3000 kg/ha/yr (Hirakuri, 2008); 3595 kg/ha/yr (Field work)
	Specific energy	**1.99E+07**	**J/kg**		
	*Energy demand = (Mass) * (Specific energy)*				
	Energy demand	**5.96E+10**	**J/ha/a**		

Annex 2a: Calculation notes for agricultural machinery in soybean production

Description	Weight (kg)	Life spam (h)	Hours used (h/ha/yr)	Ref. for hours used	Machinery used up (kg/ha/yr)
Tractor tires 90cv	3870	10000	1.20	Agrianual, 2010	0.46
Tractor tires 120cv	4920	10000	0.67	Agrianual, 2010	0.33
Tractor tires 65cv	2580	10000	0.45	Agrianual, 2010	0.12
Harvester	16400	10000	0.65	Agrianual, 2010	1.07
Limestone sprayer	1203	8000	0.45	Agrianual, 2010	0.07
Seeder	1500	8000	0.67	Agrianual, 2010	0.13
Seed mixer	800	8000	0.10	Agrianual, 2010	0.01
Agrochemical sprayer	2140	8000	1.20	Agrianual, 2010	0.32

Annex 2b: Local emissions in soybean production

Nitrogen application (urea)					
N_2O	1.325	% of N in fert. is conv. in N_2O	(IPCC, 2006)	0.00	$kgN_2O/ha/yr$
CO_2	0.2	kgC/kg_{urea}	(IPCC, 2006)	0.00	$kgCO_2/ha/yr$
Lime			(IPCC, 2006)		
CO_2	0.13	kgC/kg_{lime}	(IPCC, 2006)	95.33	$kgCO_2/ha/yr$
Diesel					
CO_2			Stoichiometry	131.55	$kgCO_2/ha/yr$

Annex 3. Calculation notes for pig production system

Note	Description	Value	Unit	References	Other estimates (if any)
1	**Sun**				
	Insolation	**1.86E+06**	**watt-hour/m2/yr**	http://eosweb.larc.nasa.gov/cgi-bin/sse/sse.cgi	
	Albedo	**1.40E-01**		http://eosweb.larc.nasa.gov/cgi-bin/sse/sse.cgi	
	Conversion	**3.60E+03**	**J/Wh**		
	*Insolation energy = (1-Albedo) * (Insolation) * (3600 J/kWh)*				
	Insolation energy	**5.77E+09**	**J/m2/yr**		
	Cropped area	**8.74E+02**	**m2**	Angonese et al., 2006	
	*Insolation energy = (Land area) * (Insolation)*				
	Insolation energy	**5.04E+12**	**J/yr**		
	Insolation energy	**7.06E+07**	**J/kg pig**		
2	**Rain**				
	Precipitation (Average years 1961-1990, Maringa city)	**1.80E+03**	**mm/yr or L/m2/yr**	http://eosweb.larc.nasa.gov/cgi-bin/sse/sse.cgi	
	Cropped area	**8.74E+02**	**m2**	Angonese et al., 2006	
	Density of water	**1.00E+00**	**kg/L**		
	*Mass of rain = (Precipitation) * (Area) * (Density)*				
	Mass of rain	**1.58E+06**	**kg/yr**		
	Fraction of water that is evapotranspired	**62%**		www.inmet.gov.br	
	Mass of rain evapotranspired	**9.77E+05**	**kg/yr**		
	*Free energy of water = (Evapotranspired water) * (Gibbs free energy of water)*				
	Gibbs free energy of water	**4.94E+03**	**J/kg**	Odum, 1996	
	Energy of rain	**4.83E+09**	**J/yr**		
	Energy of rain	**6.75E+04**	**J/kg pig**		
3	**Deep heat**				
	Heat flow through earth crust				
	Average heat flow per area	**1.00E+06**	**J/m2/yr**	Odum, 1996	
	Land area	**8.74E+02**	**m2**	Angonese et al. 2006	
	*Energy = (Land area) * (Heat flow per area)*				
	Energy	**8.74E+08**	**J/yr**		
	Energy	**1.22E+04**	**J/kg pig**		
4	**Water (groundwater)**				
	Water use	**936000**	**L/yr**	From field work (Itaipu data)	
	Gibbs free energy of water	**4.94E+03**	**J/kg**	Odum, 1996	
	*Energy of water = (Consumption) * (Gibbs free energy of water)*				
	Energy	**4.62E+09**	**J/yr**		
	Energy	**6.47E+04**	**J/kg pig**		
	Water use	**1.31E+01**	**kg/kg pig**		
5	**Feed**				
	Total feed use	**1.64E+05**	**kg/yr**	Angonese et al., 2006	
	Pig feed composition			From field work	
	Corn - 80%	**1.31E+05**	**kg/yr**		
		1.84E+00	**kg/kg pig**		
	Soy meal - 17%	**2.79E+04**	**kg/yr**		
		3.90E-01	**kg/kg pig**		
	Other nutrients - 3%	**4.92E+03**	**kg/yr**		
		6.88E-02	**kg/kg pig**		

6	**Electricity**			
	Electricity use	**1.10E+02**	**kWh/yr**	Angonese et al., 2006
	Conversion factor	**3.60E+06**	**J/kWh**	
	Electricity use	**3.95E+08**	**J/yr**	
	Electricity use	**5.53E+03**	**J/kg pig**	
	Electricity use	**1.54E-03**	**kWh/kg pig**	
7	**Local labor**			
	Labor per year	**5.16E+03**	**man-hour/yr**	
	Labor cost per hour	**1.99**	**USD/h**	Anualpec, 2010
	Labor cost per hectare	**10261**	**USD/yr**	Anualpec, 2010
	Labor cost per hectare	**0.144**	**USD/kg pig**	
	Labor	**7.22E-02**	**man-hour/kg pig**	
8	**Services**			
	Production cost (-labour)	**87236**	**USD/yr**	Anualpec, 2010
	Production cost (-labour)	**1.220**	**USD/kg pig**	
9	**Output**			
	Meat production	**7.150E+04**	**kg/yr**	Angonese et al., 2006
	Specific energy	**9.21E+06**	**J/kg pig**	Angonese et al., 2006
	*Energy demand = (Mass) * (Specific energy)*			
	Energy demand	**6.59E+11**	**J/yr**	
	Manure	**4.212E+05**	**kg/yr**	Angonese et al., 2006
		5.89E+00	**kg/kg pig**	

Annex 3a: Parameters for pig production

Parameters	Value	Unit	Ref.
US Dollar/ Br Real	0.54		
Average number of pigs produced per year per farm	650	pigs	Angonese et al., 2006
Breeding time	120	days/year	Angonese et al., 2006
Pig weight after 120 days	110	kg/pig	Angonese et al., 2006

Annex 3b: Local emissions from manure management in the pig production

Ammonia[a]	14%	Of total N in manure	0.0056	$kgNH_3/kg_{pig}$
Nitrous oxide[a]	0.02	kg N in N_2O per kg N (after ammonia losses)	0.0009	kgN_2O/kg_{pig}
Methane [a] (entheric fermantation and manure management)	3.58	$kgCH_4$/pig/yr	0.0325	$kgCH_4/kg_{pig}$

[a]Based on data from Cederberg and Flysjö (2004).

Authors’ biographical sketch

Pier Paolo Franzese (Italian) has a permanent position as Senior Researcher in Ecology at Parthenope University of Naples, Italy. At the Faculty of Science and Technology of the same university, Dr. Franzese also holds the position of Assistant Professor of Environmental and Energy Assessment. After graduating with honours in Environmental Sciences, he achieved the title of International Ph.D. in “Crop Systems, Forestry and Environmental Science” with orientation in Environmental Science and label of Doctor Europaeus. Dr. Franzese is founder member of the International Ph.D. Programme “Environment, Resources, and Sustainable Development” hosted at Parthenope University where he also founded and is now directing the Laboratory of Ecodynamics and Sustainable Development.

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UNESCO-IHP Water Programme for Environmental Sustainability,
Climate Change and Human Impacts
on the Sustainability of Groundwater Resources:
Quantity and Quality Issues, Mitigation and Adaptation Strategies in Brazil

Integrated Environmental Assessment of Agricultural and Farming Production Systems in the Toledo River Basin (Brazil)

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