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Review

Energy Analysis, and Carbon and Water Footprint for Environmentally Friendly Farming Practices in Agroecosystems and Agroforestry

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Abstract: Agriculture accounts for 5% of the entire energy used worldwide. Most of it is not in a renewable form, so it can be linked to greenhouse gas emissions. According to the Paris Agreement, on climate change, one of its major targets is the reduction of greenhouse gas emissions. Therefore, the agricultural production process must drastically change. Currently, the sustainable use of water is critical for any agricultural development. Agricultural production effects water quality and sufficiency, as well as, freshwater wetlands. Energy balance, carbon, and water footprint are crucial for sustainable agricultural production. Agroforestry systems are important in reducing high inputs of non-renewable energy and greenhouse gas emissions, along with better water use, leading to the most minimal influence on climate change. Energy analysis, carbon, and water footprint can be applied to agroforestry systems' production. An outline could be applied by adopting a modified—for agricultural production—life cycle assessment methodology to assess energy use, greenhouse gas emissions, and water consumption in agroforestry ecosystems.

Keywords: agrisilviculture; life cycle assessment; greenhouse gas emissions; energy analysis; environmental indicators

1. Introduction

Agroforestry ecosystems are land-use systems in which tree species are grown in conjunction with crops or grassland grazing or post-harvest grazing [1,2]. According to the FAO [3], there are three main types of agroforestry systems: (a) agrisilvicultural systems are a combination of crops and trees, (b) silvopastoral systems combine forestry and grazing of domesticated animals on pastures, rangelands, or on farms and (c) agrosilvopastoral systems are a combination of trees, animals and crops. The three different production components of agrosilvopastoral systems (trees, crops/grass, and animals) could be applied in the form of spatial arrangement or temporal sequence.

The major environmental benefits of agroforestry ecosystems are: increased soil fertility, reduced soil erosion, improved water quality, increased biodiversity, improved microclimate, and larger carbon sequestration [4–8]. From an ecological standpoint, agroforestry is a natural resource management system that sustains and enhances production for increased social, economic, and environmental benefits [9].

The application of agroforestry systems could minimize non-renewable energy inputs in agricultural production, reduce greenhouse gas emissions (GGE), and apply better water use during the production process [10–13]. The application of agroforestry could also increase the energy use efficiency (EUE) of production [14]. In the Paris Agreement on climate change, agroforestry was suggested as a measure in adapting to the negative consequences of climate change and reducing GGE [15,16].

Agroforestry ecosystems could be evaluated with environmental indicators based on energy use, yield, GGE, and water consumption of the production process. Finally, there is a possibility of applying a methodology of environmentally-friendly cultivation practices in agricultural production.

The scope of this review is to present how energy analysis, carbon and water footprint (CF and WF), and life cycle assessment (LCA) methods could assess the environmental impacts on agroforestry ecosystems and agroecosystems in general.

2. Energy in Agroecosystems

Worldwide, agriculture accounts for 5% of the total energy consumption [17]. Most of it is not in a renewable form, so it is essential to use it properly [18]. Extensive and intensive agriculture requires higher inputs of fertilizers, agrochemicals, agricultural machinery, seeds, and fuels, resulting in higher energy consumption and usually increased GGE [19]. Agricultural production could be analyzed from an energy standpoint, by the conversion of all inputs and outputs of production, into energy units [20–24].

Energy balance began to be discussed in the early 1970s when the global energy crisis made people aware that the quantity of solid fuels is limited [25]. The reflections were focused on production and use of energy. The lack of energy resources, and the subsequent side-effects, required precise planning and careful estimation of energy consumption [26].

According to the FAO [3], energy consumption in an agroecosystem leads to increased productivity and strengthened product safety. Application of energy is contributing in general in the economic growth of the rural sector. In the EU, agriculture, forestry, and other related activities are responsible for 2.78% of fossil fuel energy consumption [27].

In agroecosystems, human labor, application of fossil fuels, machinery, electricity for irrigation, and agrochemicals are considered as energy inputs [28]. Energy consumption for the production of fertilizers, chemical products, machinery and any other that was used in agricultural production is also included as energy inputs [28]. This complementary energy contributes to the maximization of output (production) per hectare [29].

Well-managed practices on agroforestry ecosystems, such as intercropping, could enhance both EUE of the production system and the added value of the agricultural products [30]. However, farming practices can negatively affect agroforestry ecosystems from an environmental point of view. Lin et al. [31] showed that the EUE in agroforestry did not differ from that of organic farming systems, probably because the tree components were not well-developed enough to have positive interactions with the cultivations.

Energy Analysis

Energy analysis is an approach of agroecosystems' production, which is based on the conversion of all inputs and outputs into energy units. According to this method, both the energy that flows into the agroecosystem and the energy outputs are calculated [28]. The evaluation of agroecosystems from an energy standpoint is crucial for minimizing energy inputs and improving environmental aspects of production [32]. Consequently, effective use of energy resources is vital, taking into account the need for increasing agricultural production [23,28,29]. Energy analysis is used for the estimation of energy efficiency and environmental resilience of the productive systems [33].

The methods vary accordingly to the location of the farm, the production period, the flows of energy, the materials that are taken into account and the energy equivalents [25]. Extensive information for the applied methodology is required to compare different energy analyses [25]. Energy analysis could provide alternative ways for input reduction and simultaneously could increase productivity [34].

Energy saving is environmentally necessary but insufficient for increasing net income. The combination of an economic and energy analysis of the production system contributes to the planning of more suitable strategies for agricultural management [35].

3. Greenhouse Gas Emissions and Water Use in Agroecosystems

Energy use in agriculture is directly linked to GGE. Greenhouse gases (GHGs) absorb and emit thermal radiation in the atmosphere within the infrared spectrum. The main GHGs are carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). The agricultural sector contributes to 22% of the GGE, which have a negative impact on the climate, while cultivation practices approach 20% of the annual global CO_2 emissions [17]. In the EU, GGE from agriculture reach 470.6 Mt of CO_2-equivalent per year, which equals 10% of the total GGE [36]. To achieve the climate targets, set out in the Paris Agreement in 2015, GGE must be drastically reduced, through the use of fossil fuels, as well as through the resources and cultivation practices applied [37]. Based on this process, the CF of the products should be estimated. The CF refers to the GGE of a product throughout the product's lifecycle [38]. Current policies on global agricultural production and especially in Europe, include methods of reducing total fossil fuel consumption to maintain high agricultural outputs (final products) [39]. The goal of reducing GGE up to 80–95% by 2050 [40,41] requires the streamlining of methods and techniques for the agroecosystems [42,43].

According to Baah-Acheamfour et al. [44], agroforestry systems could minimize GGE in agricultural production. Agroforestry could increase vegetative carbon, soil organic carbon stocks, and reduce CH_4 and N_2O emissions compared to cropland. Agroforestry ecosystems with tree components along with the simultaneous environmental friendly farming practices could demonstrate better results on carbon sequestration compared to grasslands and total GGE reduction compared to intensive monocultures [45]. Tree and crop management practices in agroforestry ecosystems could affect the total carbon sequestration of the system [46]. In some cases, CO_2 emissions reduction from forest fires is another aspect of well-managed agroforestry ecosystems [46]. Rigueiro-Rodríguez et al. [47] highlighted that the application of silvopastoral systems, along with goat grazing, could lead to a less flammable herbaceous layer. These systems could enhance CO_2 emissions reduction, especially if they include fast-growing tree components, such as poplar [48].

Given the essential role in food and energy supply, water is an important resource for sustainable agricultural development [49]. Agricultural production is greatly affecting the quality and sufficiency of water, as well as the freshwater wetlands [50]. Water pollution, due to the use of agrochemicals and the overconsumption of water, is a structural problem in many regions of the world [51,52], especially where intensive livestock production is indispensable [53,54]. With regards to agroforestry ecosystems, their application along with livestock components, such as silvopastoral systems, could improve water quality and reduce water consumption [9].

WF is a concept emerging from the issue of water sufficiency. WF expresses the amount of water consumed directly or indirectly (from the supply chain) to produce products and services [49].

3.1. The Concept of Carbon and Water Footprint

The concepts of CF and WF are of particular importance to management practices. These methods contribute to the reduction of GGE and the quantity of water required for production. For each product, CF is the sum of GHGs, which are emitted during production, use, and final disposal. The concept of WF expresses the amount of water consumed directly or indirectly to the production. WF is the sum of individual footprints known as green, blue and grey footprints. Green refers to the consumption of water stored in soil moisture from atmospheric deposition during the production. Blue refers to the consumption of surface or underground water bound during production. Grey refers to the volume of water polluted during agricultural production [49].

The issue of global warming is essential, as well as the CF and WF of products [17,55–57]. Wiedmann and Minx [58] recognized that the definitions of CF differ between researchers. The term "Climate Footprint" was proposed, which included all the GHGs covered by the Kyoto Protocol [59]. Despite the differences between the calculation, the CO_2-equivalent (CO_2-e) expresses the global warming from GGE and is used as a reference unit of CF. The CF improves the management of GGE by evaluating the production inputs [60–62]. The main factors which determine the amount of CF and WF of an agricultural product are the crop yield in relation to the inputs, the demand, the quality, and the impact of climatic conditions. The assessment of CF and WF of a product provides a context for both inputs and quantity of water consumed across the production process. Based on the assessment of CF and WF, consumers, traders, and food industries could contribute to more rational management of inputs and especially water inputs. Cultivation practices during the various stages of production, means of transport, and distribution systems are some of the variables that could optimize the management of inputs and minimize the CF and WF of the product. To summarize, the values of the WF are associated with the CF and energy demand [17].

3.2. Carbon and Water Footprint in Agroecosystems

The assessment of the life cycle of each crop species of an area is the basis on which CF and WF are calculated. The products with reduced CF and WF incorporate a series of advantages for both the production system and the consumer. Compared to conventional systems, the organic and integrated production systems reduce GGE and utilize the water resources in an optimal way [20–24,29,42]. Reduced GGE and rational management of water resources depend on farm area [23,34,63]. Therefore, a combination of the production system and farm location could contribute to the reduction of inputs and the reduction of production costs due to the implementation of possible energy savings [24]. The combination mentioned above could increase environmentally-friendly food production. Measuring and recording both CF and WF of food, allows the consumer: (a) to choose products which genuinely help to tackle climate change, (b) recognize the competitive advantage of a product in relation to similar products and (c) to promote the overall environmental benefits, highlighting the use of products with lower CF and WF.

Considering that the inputs with high CF are the fertilizers, fuel, and machinery for irrigation [64], producers should implement procedures to reduce these factors. This goal could be achieved by applying regulated nitrogen-release fertilizers in deeper soil layers [65]. These products restrict both the leaching in deeper soil layers and the N_2O emissions in the atmosphere [65]. In previous years, an attempt was made to produce nitrogen fertilizers with a reduced CF, focusing on the benefits for agriculture and the environment. Cultivation practices based on rational management of water and reduction of input losses could lead to cultivations resilient in dry climates, with lower GGE. In summary, climate change requires environment-friendly farming practices which reduce the CF and WF of the agricultural products. This characteristic acts as an added value to the agricultural products, which is also an expected purpose.

Agroforestry ecosystems concentrated on livestock production showed the largest CF [66]. Nevertheless, the tree components enhance carbon sequestration more compared to grasslands [67].

According to Ibidhi and Salem [68], the different types of agroforestry systems concentrated on livestock production (sheep) perform differently according to WF. Extensive agropastoral systems presented the highest WF (around 13,000 l kg^{-1} meat), followed by the agropastoral system (10,023 l kg^{-1} meat), and the agrosilvopastoral farming system which showed up the lowest WF (8654 l kg^{-1} meat) [68].

Although the indicator of WF is a commonly accepted method to assess water consumption, it is necessary to take into account the climate data and hydrological modeling, especially in regions with extreme conditions [69].

4. A Method for Measuring Energy Use, Carbon and Water Footprint—the Life Cycle Assessment

Life cycle assessment (LCA) is a methodology to investigate the environmental impact of products, taking into account all relevant impacts during production. LCA is a method to estimate the energy use in agriculture and to calculate CF and WF for the life cycle of the crop species, applied to the product, the process, and the farm level [28,70,71]. The real advantage of an LCA is the determination of environmental impacts related to a specific system, to locate life cycle phases for process improvements, create data, and compare alternatives for products, services, and processes [72]. The methodology of calculation of CF and WF requires an LCA of cultivated species with various production standards [73–75] with a detailed description of inputs and outputs. CF and WF refer to the calculation of GGE and the Water Use for a product. There is not a unique methodology for the calculation of CF [76]. The CF of a product should include all emissions during the life cycle [64]. The total emissions per unit of production are the CF (CO_2-equivalent kg^{-1}). WF in m^3 or l kg^{-1} is calculated according to the methodology of Hoekstra and Chapagain [77], Ababaei and Etedali [78]. WF of the cultivated species is calculated for long periods and different locations [56,79]. The results can be compared to the WF of other geographic regions and on a global scale.

A recent application of LCA, implemented in the reforested area of the Peruvian Amazon highlights the environmental benefits of a jam produced by fruits harvested from agroforestry ecosystems [80]. Although LCA methodologies are very useful to evaluate the environmental impacts of agricultural production, extensive research of all the environmental aspects should be carried out. Therefore, further accepted standardization is necessary to take place [81].

An outline could be applied by adopting a modified, for agricultural production, life cycle assessment (LCA) methodology to assess energy use [29,63,73,74,82,83], which could involve the five stages, as shown in Figure 1.

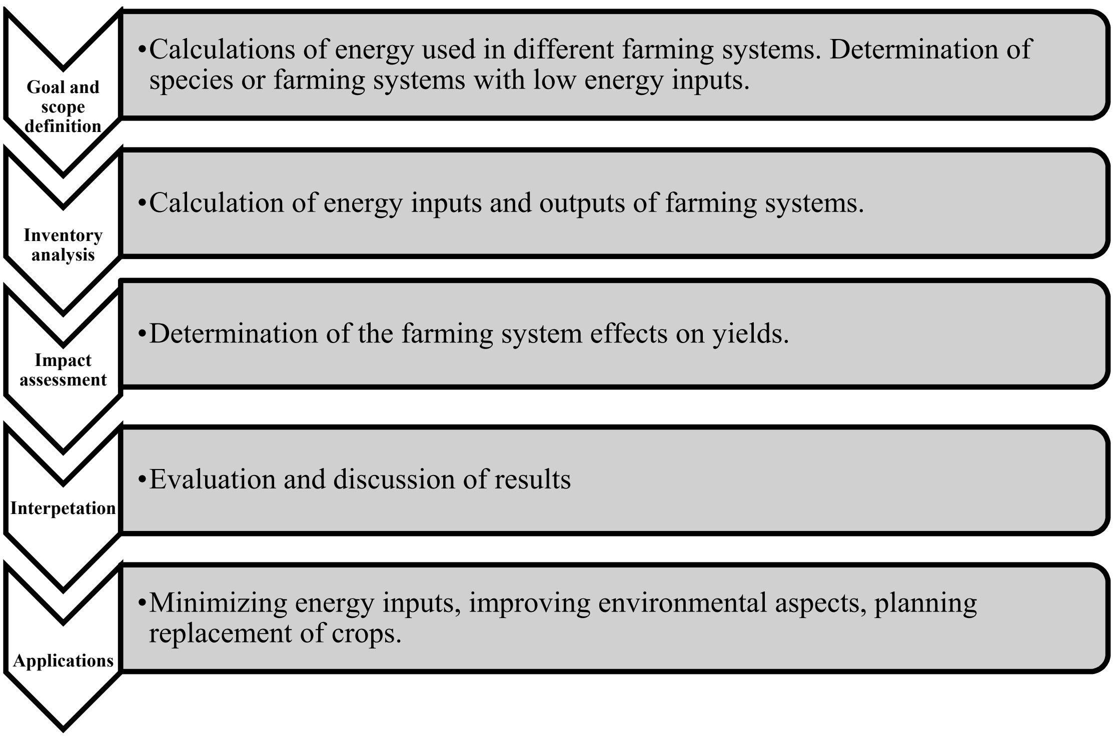

Figure 1. A modified for agriculture LCA with five stages.

In stage 1, the goals are calculating the energy used from the production components of the different farming systems and comparing them to determine the crop or farming system with low energy inputs. The functional unit is the product output per hectare. The system boundaries could start at the use of production factors, and end at the removal of the product. In stage 2, the energy inputs and outputs of production are estimated. In stage 3, the effects of the different production systems on yields are examined. In stage 4, the results are evaluated and discussed. In stage 5, a remodeling is applied according to the results, with the final goal of minimizing energy inputs, improving environmental aspects and replacing of crops.

The emissions of CO_2, CH_4, N_2O from fuels are calculated by their coefficients of CO_2-equivalent given by the IPCC [64,84]. Fertilizers and soil calculations are made according to the coefficients also given by IPCC [17,84] and EMEP / CORINAIR [85]. The WF of crops (m^3 kg^{-1}) is calculated by dividing the total volume of green and blue water used (m^3 yr^{-1}) by the quantity of the production (kg yr^{-1}) [86–88].

The calculation of CF and WF could help producers to reduce their GGE in an economically efficient way. The CF of a product can affect competitiveness by reducing the cost of products [89]. The production process varies in different countries or even regions since the type of energy used in each country leads to different CF and WF. Therefore, CF and WF could be adopted as a management evaluation tool for crop production.

In Table 1, it is shown that the CF of livestock is higher than that of fruit and vegetables. Firstly, this reflects the fact that animals and especially ruminants produce methane (CH_4), that is 25 times more powerful than CO_2, and secondly, it is a result of manure management, which also produces GHGs.

Table 1. The CF of selected food products (mean global prices from Chapagain and James [90]).

Food Product	kg $CO_{2\text{-eq}}$ kg^{-1}
Beef Meat	30.4
Eggs	4.81
Pork meat	4.36
Olive oil	3.9
Chicken	3.83
Rice	1.8
Legumes	1.13
Bread	0.98
Sugar	0.47
Potato	0.16
Tomato (open-field)	0.15
Apple	0.07

In Table 2, it is shown that the WF is undoubtedly higher in the production of meat products and, in general, animal production. Crop products, such as rice and corn cultivations, also have high WF.

Table 2. The WF of selected food products (mean worldwide prices from Hoekstra and Chapagain [77], Hoekstra [91], Hoekstra [92]).

Food Product	l of H_2O kg^{-1}
Beef Meat	15,415
Pork meat	5988
Chicken	4325
Rice	3400
Eggs	3265
Sugar beet	1500
Peach	1200
Corn	900
Apple	700
Potato	250
Tomato (open-field)	180

According to Tables 1 and 2, the high CF and WF of crop production is attributed to the increased inputs of intensive crop production and the mismanagement of water resources.

5. Conclusions

Agroforestry ecosystems could be evaluated with environmental indicators based on the energy use, the yield, the GGE, and the water consumption of the production process. There is a possibility of applying a methodology of environment-friendly cultivation practices in agricultural production.

Provided that an appropriate number of farms can be selected, comparisons could be made between different farming systems, species, and environments. This process could lead to more efficient rationalization of inputs. Products with reduced CF and WF contribute to the reduction of energy use while they continue to meet consumers' demands. The resilience of agricultural production on climate change could be stabilized by applying less intensive and carefully organized farming methods and techniques. The above agro-environmental indices are useful to decision makers seeking crop and farming systems to regulate the fragile balance between climate change and agricultural production.

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