Revista Brasileira de Ciência do Solo

Division - Soil Use and Management | Commission - Soil and Water Management and Conservation

Interconnections among rural practices and Food-Water-Energy Security Nexus in the Atlantic Forest biome

Gabriela Teixeira Duarte[(1)], Julia Camara Assis[(2)], Rafaela Aparecida da Silva[(3)] and Ana Paula Dias Turetta[(1,4)*]

[(1)] Empresa Brasileira de Pesquisa Agropecuária, Embrapa Solos, Rio de Janeiro, Rio de Janeiro, Brasil.
[(2)] Universidade Estadual Paulista "Júlio de Mesquita Filho", Instituto de Biociências, Departamento de Ecologia, Rio Claro, São Paulo, Brasil.
[(3)] Universidade Federal de Goiás, Departamento de Ecologia, Goiânia, Goiás, Brasil.
[(4)] Universidade Federal Rural do Rio de Janeiro, Departamento de Arquitetura e Urbanismo, Programa de Pós-Graduação em Desenvolvimento Territorial e Políticas Públicas, Seropédica, Rio de Janeiro, Brasil.

*** Corresponding author:**
E-mail: ana.turetta@embrapa.br

Received: January 29, 2021
Approved: August 02, 2021

How to cite: Duarte GT, Assis JC, Silva RA, Turetta APD. Interconnections among rural practices and Food-Water-Energy Security Nexus in the Atlantic Forest biome. Rev Bras Cienc Solo. 2021;45:e0210010.
https://doi.org/10.36783/18069657rbcs20210010

Editors: José Miguel Reichert and Ricardo Simão Diniz Dalmolin.

ABSTRACT: Global agricultural production is expected to double by 2050 due to both global population increase and changes in diets as a consequence of growing incomes. This also means more pressure on water resources, as agriculture accounts for 70 % of global water withdrawal and for energy production as the entire food supply chain accounts for about 30 % of total global energy consumption. Although there are ongoing discussions related to the sustainability of food, water, and energy sectors, integrating these sectors is still rare and challenging. We investigated the effects of agricultural practices on the Food, Water and Energy (F-W-E) nexus security systems by evaluating the results reported in scientific literature. Focusing on the Brazilian Atlantic Forest biome as a study case, our main goals were 1) to elucidate the impacts of rural conservation practices on food, water, and energy production based on literature analysis, 2) to propose F-W-E attributes and evaluate how they are addressed by rural practices. Our findings demonstrated, in general, a positive impact of agricultural conservation practices on F-W-E security attributes. Indeed, 76 % of the combination between a conservational practice with a F-W-E attribute was positive. Some agricultural practices, such as no tillage are very well documented (45 % of all combinations), especially regarding their effects on soil quality parameters. We found few results connecting agricultural practice and energy aspects. These results are key elements that corroborate with the agriculture multifunctionality approach, and the results can better guide the planning of strategies in the agricultural sector and subsidize decision making.

Keywords: soil functions, multifunctional agriculture, food security, water security, energy security.

INTRODUCTION

International organizations and governments are increasing their awareness of the challenges in securing human well-being and livelihoods in the face of current population growth rates and environmental degradation. Most scenarios considering non-intervention, or a business-as-usual perspective, project that food demand will increase from 59 up to 98 % between 2005 and 2050 (Valin et al., 2013). Indeed, global agricultural production is expected to double by 2050 due to both global population increase and changing diets due to growing incomes (Godfray et al., 2010; Tilman and Clark, 2015). This means increased demand for water resources, as agriculture is responsible for 70 % of global water withdrawal (Aquastat FAO, 2019), and for energy production, while the entire food supply chain consumes about 30 % of total global energy (FAO, 2011a).

Due to this complex scenario, food, water and energy (F-W-E) issues need to be addressed together and cannot be treated as a stand-alone problem. Applying a Nexus approach allows a systematic integration to address issues related to F-W-E security at various levels, generating different scenarios (Hellegers et al., 2008; Hoff, 2011; Rasul, 2014). This approach looks for ways to conceptualize and, if possible, quantify the links between F-W-E in a single structure capable of generating integrated assessments focused on food, water, and energy security (Flammini et al., 2014).

Some of the elements considered by F-W-E Nexus include: a) the three sectors have billions of people lacking access (quantity, quality or both); b) there is a growing global demand and resource constraints for all of them; c) different availability on a regional scale and variations in supply and demand; d) the strong interdependencies with climate change and with the availability of natural resources (Brazilian et al., 2011).

Additionally, besides the pressure for more water and energy, there is also a concern related to climate change effects on F-W-E production, specifically extreme events and natural disasters. These include more frequent droughts, floods, landslides, as well as outbreaks of animal and plant pests and diseases. Cumulative effects of decisions regarding land management, construction techniques, implementation of waste treatment infrastructure, as well as low investment in educational programs, poverty reduction, social integration, and others can be exposed by unexpected disasters (World Bank, 2010). Such combined decisions and unexpected natural events can have severe socio-economic and environmental consequences.

Adding to the impacts of climate change related disasters, there are the impacts related to conventional management practices in rural areas. These practices often correspond to the use of synthetic chemicals, fertilizers, tillage systems, monocultures, among other practices that aim to maximize the yield of a particular crop or set of crops. Although these conventional management practices have been used to feed the fast-growing human population, their negative impacts on the ecosystem services that sustain human well-being created the need to transition towards more sustainable management practices.

The adoption of an ecosystem approach to address agricultural food production is used to pursue sustainable intensification. This aims to enhance crop productivity by relying on ecosystem services that enable the reduction of external inputs (e.g., mineral fertilizer and pesticides) (Bommarco et al., 2013). Conservation agriculture (CA) implemented at the farm level is connected to reduced labor requirement, lower energy consumption, stable yields, and improved soil quality (FAO, 2011b). Conservation agriculture has the potential to optimize the use of agricultural resources through the integrated management of soil, water and biodiversity, also reducing the dependency on external inputs.

Therefore, these agricultural approaches affect three components embedded in any human livelihood and are susceptible to the cited pressures: food, water and energy security. As most of the food, water, and energy production occurs in rural landscapes, these areas face the most pressures to fulfill society's demands. In this respect, the F-W-E nexus perspective helps reach a better understanding of the intersectoral dimension of sustainability in rural landscapes (BMZ, 2018). However, how to target the nexus remains an open issue as its components are often treated in isolation (Liu et al., 2018).

Soil resources have been neglected, but they are fundamental for understanding the capacity of the land to produce food, capture water and generate energy (Hatfield et al., 2017). However, soil management practices play an important role to encompass key linkages in socio-ecological systems and enable changes in soil functions (Helming et al., 2018). In other words, it is possible and essential to improve rural landscape sustainability through agricultural management practices that improve the utilization of soil resources and increase ecosystem services provision (Turetta et al., 2016), related to F-W-E security. Some authors demonstrate that understanding soil functions and their correlations with food, water, and energy provision could be a platform to promote operational actions that simultaneously impact all three (Lal et al., 2017; Helming et al., 2018). That is, there are uncovered synergies and co-benefits between soil functions, management practices, and the F-W-E Nexus.

This study investigated the effects of agricultural practices on Food, Water and Energy (F-W-E) security through the evaluation of the results reported in scientific literature. Our main goals were to synthesize what has been published to elucidate the impacts of rural conservation practices on food, water, and energy production in the Atlantic Forest biome; and to evaluate how different attributes of the F-W-E Nexus have been addressed.

MATERIALS AND METHODS

We performed a literature review to assess research papers that link rural conservation practices and their impact on food, water, and energy production. The focus was on the Brazilian Atlantic Forest biome. The Atlantic Forest is the Brazilian biome with the greatest population density within the country, hosting 72 % of the population and contributing to 70 % of the Brazilian GDP (SOS Mata Atlântica, 2020). Thus, the demand for water, energy and food in this biome is high. The intensive use of land for agriculture, urbanization, and industrialization has led to high rates of deforestation, which result in the loss of many ecological functions, especially those related to the supply of F-W-E (Joly et al., 2014; Rezende et al., 2015).

Water provided within this biome is important for drinking and electricity production, as is the case, for example, of the Parana River watershed. The complex of reservoirs and dams within this biome provides energy to more than 60 % of the Brazilian population (Joly et al., 2014). The Atlantic Forest also provides food and other agricultural products. Brazil has three main regions for the development of agriculture, two of which encompass areas of the Atlantic Forest biome: one in the southeastern region, characterized by crops for exportation and vertically integrated agribusiness; and other in the south, with diversified agriculture, like cooperatives and contract agriculture (Chaddad, 2015).

Searching the articles

We searched the Web of Science database, using a combination of keywords with at least one rural conservation practice that follow the conservation agriculture principles stated by FAO (2011b), and one security aspect (F-W-E) restricted to terrestrial landscapes in rural, agricultural, mixed rural-urban or natural habitat regions, in the Atlantic Forest Biome, thus excluding strictly urban or marine landscapes (Table 1).

Table 1. Keywords used to search for articles that were investigating the impact of at least one rural conservation practice on one security within the Brazilian biome of interest

Keywords used in the research		
Rural conservation practices	**Security aspect**	**Location**
Spring protection / Headwater protection		
Riparian restoration		
No tillage		
Conventional crop / Conventional agriculture		
Minimum crop		
Organic crop / Organic Fertilization / Organic agriculture		
Green manure / Green fertilization	Water	
Crop rotation	Energy / power / hydropower	
Terrace	Food	Brazil
Level crop	Agricultural production	Atlantic Forest
Containment basin	Crop production	
Basic sanitation		
Rural tourism / Agritourism		
Agroforestry / Agroforestry		
Fallow		
Soil manage / Soil management		
Pasture rotation / rotational grazing		
Manure treatment		

Table 2. Groups of selected rural conservation practices and their description

Group[(1)]	Description[(1)]	Rural conservation practices
Soil management practices	Practices used to maintain the fertility and structure of the soil	No-tillage, minimum tillage, crop rotation, green fertilization, intercropping
Biological and water-related management practices	Practices that utilize the protective effects of plant covers to reduce erosion, thus conserving soil and water	Hedgerows, grass cover, Buffer strips, springs conservation
Engineering practices	Practices that control the movement of water over the soil surface with human-made structures	Terraces, contour bunds
System-related practices	Set of practices that increase ecological interactions and decrease the need for inputs from outside the system.	Agroforestry systems, organic systems, integrated crop-livestock-forest systems, rotational pastures

[(1)] Classifications were adapted from Xiong et al. (2018).

Rural practices groups

The second step was to organize the literature survey results adapting the framework proposed by Xiong et al. (2018) when they investigated the impact of agricultural practices on soil erosion and water runoff within Brazilian's landscapes (Table 2).

F-W-E attributes

Because food, water, and energy production can occur in one rural landscape and be consumed in another landscape, within their respective distribution systems, we limited the assessment presented in this study to only the provision systems that ensure the security of the three attributes.

It is important to highlight that we also restricted our evaluation according to the "stability" dimension of each security, i.e., the system's ability to provide food, water, or energy over time despite disturbances. Thus, the third step was to connect the papers surveyed with the F-W-E security attributes that were established based on the following statements:

- For food security, we assessed the capacity of rural systems to produce food. This production is directly related to ecosystem quality, including soil, plants, pollinators, and ecological processes that maintain food production throughout time.
- For water security, we assessed the capacity of the rural systems to impact the water quantity and quality provision to fulfill drinking and non-drinking purposes (such as irrigation).
- For energy security, we assessed the rural system performance regarding energy aspects.
- Each rural system was connected to F-W-E Nexus attributes. These attributes were created to demonstrate the interconnectedness of the F-W-E security nexus (Figure 1 and Table 3).

For each surveyed paper, we then attributed a positive, negative or neutral impact of the rural conservation practice on the respective security attribute, as proposed in table 3, when compared to sites without any conservation practice or under conventional practices. That is, if the rural conservation practice improved the related security attribute compared with conventional practices, it had a positive impact. If the security attribute decreased

Table 3. Select attributes for each element of the F-W-E Nexus, and their description, for which we could measure the impact of rural conservation practices

Attributes	Description	Security		
		Food	Water	Energy
Water quantity and quality	Influences the provision of clean water for drinking and non-drinking purposes, including the amount of water in reservoirs		X	X
Water efficiency	Reduction in the amount of water used in agricultural systems	X	X	
Water infiltration	Important for groundwater recharge		X	
Food productivity	Improvement of agricultural activities and more stable production of food through time	X		
Energy efficiency	This efficiency decreases the demand for energy in agricultural activities, and it can be used for other purposes in addition to reducing production costs	X		X
Energy from biofuels	Increases the diversity of energy sources			X
Soil quality	Addresses the multi-functionality of soils defined from an environmental perspective, including the promotion of plant growth and food production, in addition to protecting watersheds by regulating the infiltration and preventing water pollution	X	X	X
Soil erosion control	Despite being a component of soil quality, this attribute was kept separately as it increases the stability and nutrients of the soils for food production, decreases the amount of sediments in water bodies, and helps in the reservoir longevity	X	X	X

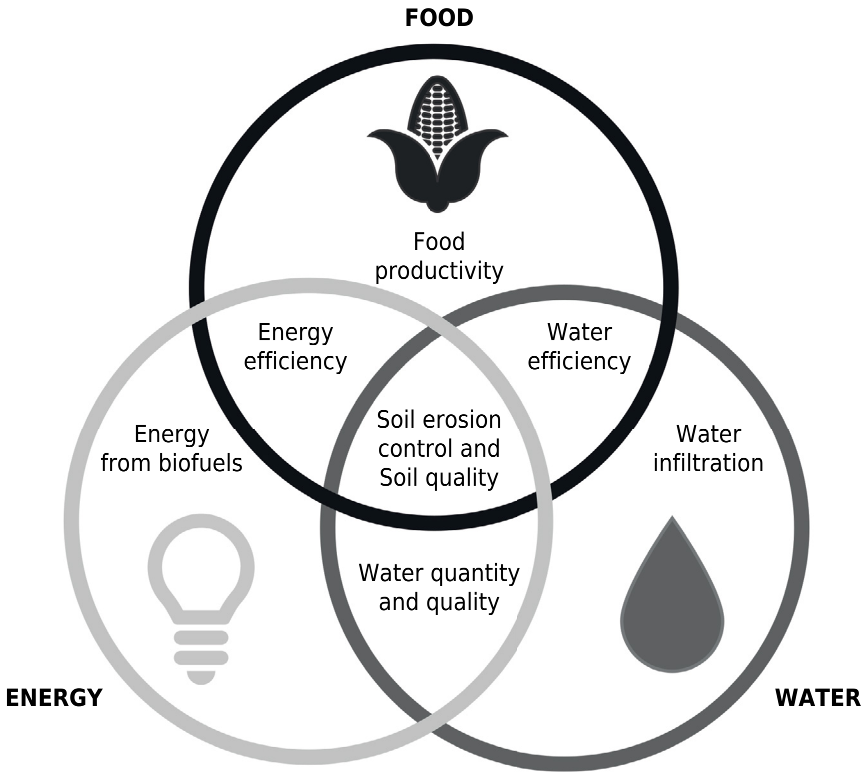

Figure 1. Linkages among attributes and F-W-E Nexus.

or had a lower value than the conventional practice, the conservation practice negatively impacted the area. If no significant change between conservation and conventional practices was reported, we considered the impact as neutral. We considered each relationship between one rural conservation practice and one F-W-E attribute as one independent combination between these variables.

RESULTS

A total of 105 studies met the established criteria, which generated 152 combinations between one rural practice and one F-W-E attribute. Of this total, 91 (60 %) combinations approached soil management practices, 35 combinations (23 %) corresponded to system-related practices, 21 (14 %) to biological and water-related management practices, and 5 (3 %) engineering practices (Figure 2).

Among the soil management practices, 68 (~75 %) combinations are related to no-tillage practices, that correspond to ~45 % of all combinations (Figure 2b). Most of the combinations within this practice group were related to soil quality (41 combinations) and soil erosion control (14 combinations) attributes. Between all combinations related to no-tillage, 75 % presented positive impact on one or more F-W-E security when compared to sites without any conservation practice or under conventional practices. Crop rotation was the second soil management practice with more reported combinations, with 11 in total (Figure 2b), with almost 64 % presenting positive impacts and 36 % neutral.

Combinations with system-related practices group were distributed along with all the F-W-E attributes (Figure 3). Most of them were combinations impacting food production and soil quality attributes, with 12 combinations (34 %) each. The agroecological systems and organic practices corresponded to, respectively, 46 and 40 % of the system-related practices combinations. Most of the studies regarding these two practices reported a positive impact on the F-W-E attributes, and only one study reported a negative impact on food production.

There was the same number of reported combinations of biological and water-related management practices group with soil erosion control, soil quality, and water quantity and quality attributes, each one representing 24 % of all combinations with this practice group. Almost all combinations reported (20 out of 21) a positive influence of this practice group on F-W-E attributes. The engineering practices group had the lowest number of reported combinations among our research, and all of them were related to the soil erosion control attribute.

As we defined attributes that can be related to one or more security, as exposed in table 3, we found 133 combinations with the attributes related to food security (Figure 3a), 126 related to water security (Figure 3b) and 177 related to energy security (Figure 3c). From these, 101 reported a positive influence on food security, 99 on water security and 91 on energy security. These correspond to 76, 79 and 78 % of all combinations with

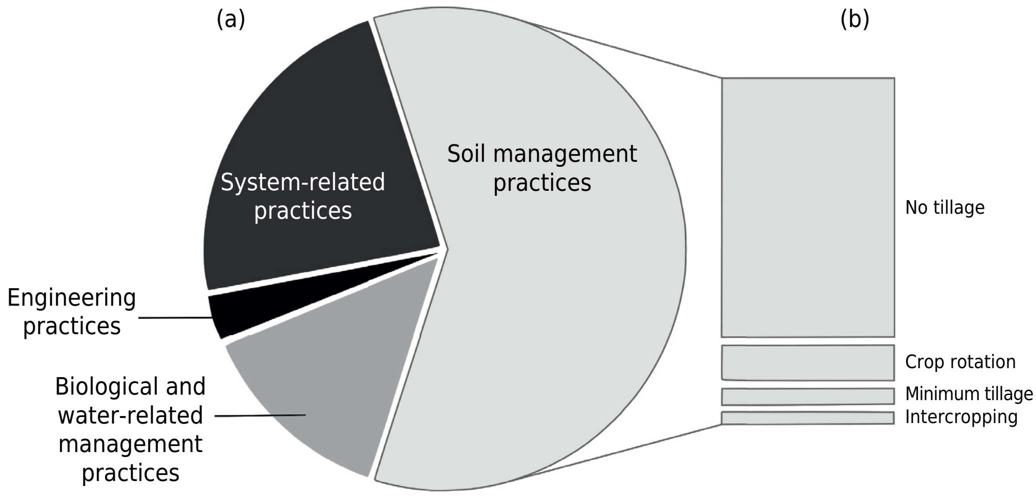

Figure 2. Proportions of combinations between rural practices and F-W-E attributes encountered in each rural practice group (a), and predominance of each practice within the soil management practices group in detail (b).

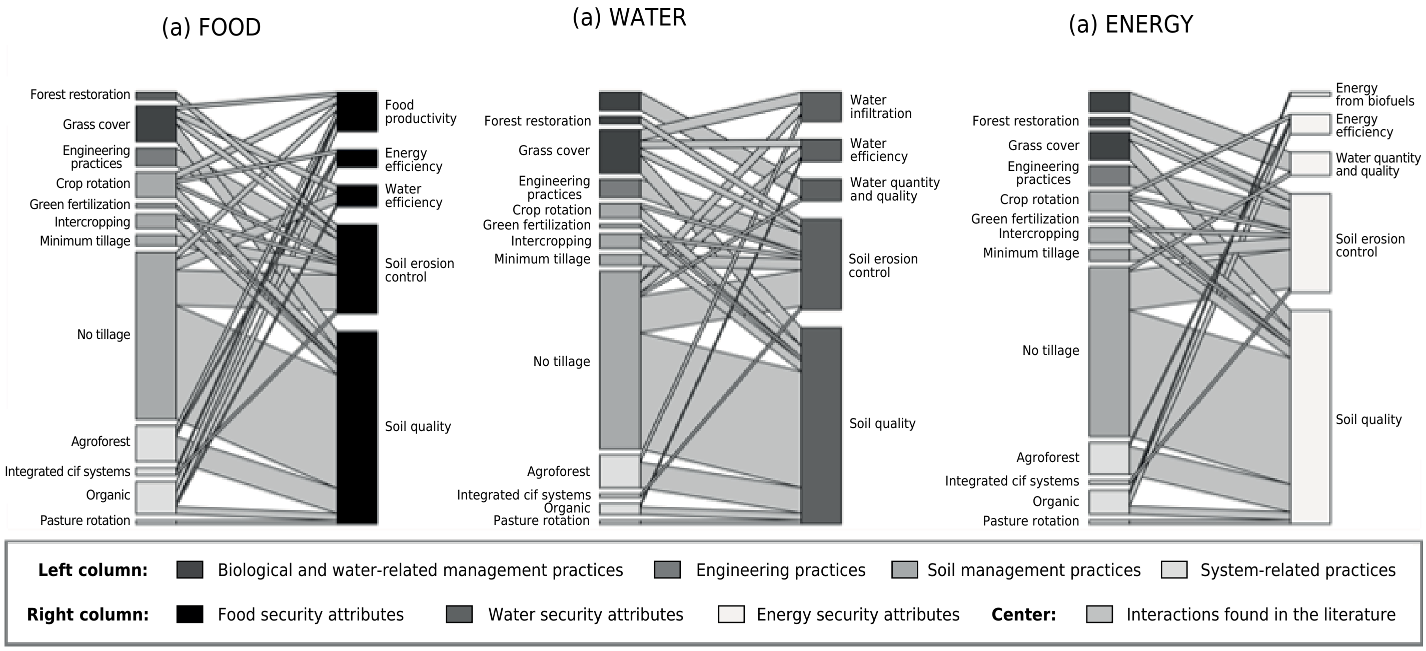

Figure 3. Linkages between rural practices (organized by groups; left column) and attributes of (a) food, (b) water and (c) energy security systems. The width of the links and bars represent the number of combinations identified in the literature.

the respective security systems. There were 27 (~18 %) reported combinations with a neutral impact and 9 (~6 %) with a negative impact.

Soil quality attribute appeared in most combinations, 70 (~46 %) in total, and encompasses a set of soil parameters connected to different soil functions. This attribute is correlated to all three security systems (Figure 3). Among all combinations, between one practice and this attribute, 74 % showed a positive effect on soil quality. The same goes for soil erosion control, which was part of 32 (~21 %) combinations in total, with 78 % of them being positive. However, without considering these two attributes (soil erosion control and soil quality), we were able to find only seven combinations of rural conservation practices specifically related to energy security (Figure 3c).

Indications for decision-making

According to our findings, soil management practices were the most studied conservation practices in the Atlantic Forest Biome, with a high rate of positive impact (~72 %) on Nexus F-W-E. This practice category should be encouraged and pursued throughout private and public lands due to their synergistic ability to impact the three securities. This is translated in figure 3, with the rural practices belonging to this group having the thickest interaction bars in the three representations of each security system.

For landscapes focused on food production and need to ensure food productivity, water, and energy efficiency, our results indicate that system-related practices are described as having a positive effect on these attributes. Specifically, we found that 61 % of the interactions (total of 18) between a system-related practice and one of these three attributes were indicated as positive, which means that the rural practice increased productivity or efficiency when compared to not using this practice or using a conventional one. Figure 3a shows that most of the links related to these attributes occur with a system-related practice.

In addition to soil management practices, we found that the scientific literature related to the Atlantic Forest Biome reported increases in water quality, quantity and infiltration when buffer strips and grass cover were present. Our results showed that all eight combinations between these two practices and these attributes were positive. In this biome, securing water is highly related to securing energy production, as there are many hydropower reservoirs. In this sense, figures 3b and 3c show that most of the water quantity and quality interactions occur with these practices related to the vegetation's capacity to control erosion.

DISCUSSION

This study described the connections between rural conservation practices and the F-W-E Nexus. It is notable that soil management practices, mostly driven by the effect of these practices on soil quality and erosion control, are the most studied rural practices influencing the attributes related to the Nexus within the Atlantic Forest Biome. This result is completely linked with our proposition that rural management practices that directly affect soils can positively impact food, water, and energy security systems. Moreover, we found that most of the studies reported an improvement (positive impact) of rural conservation practices on the F-W-E Nexus compared to sites without any conservation practice or under conventional practices.

Our findings demonstrated the ability of conservation agriculture (CA) to improve some soil parameters that go beyond soil productivity and express its multifunctional capacity and ability to influence water and energy dynamics. For instance, no-tillage and crop rotation were the rural management practices that had more studies demonstrating their improvement on soil quality and soil erosion control attributes. Hence, it is possible to establish the impact of these practices on F-W-E security, since the reduction of water infiltration in eroded soils, and the consequent continuous and rapidly occurring sediment accumulation, is one of the processes that affect the water reservoir's lifetime, essential to ensure the proper functioning of these supply systems (Schellenberg et al., 2017).

Indeed, we found that soil quality was the most studied attribute related to rural conservation practices within the Atlantic Forest Biome. According to Bünemann et al. (2018), there are two main ideas regarding soil quality: one that focuses on the inherent soil properties and another that emphasizes the effects of human management on the soil. Within this second approach, the goal is not limited to agricultural productivity and trade-offs between food, water, and energy production need to be explicitly recognized. As a consequence, soil scientists start to play a more relevant role in relation to societal stakeholders. For instance, Palm et al. (2014) stated that there is a well-defined linkage between CA and the improvement of topsoil organic matter. The authors pointed out that this is a relevant aspect since there is a correlation between soil properties that reduce erosion and runoff while increasing wat and soil organic matter improvement.

Erosion is a sensitive aspect in the Brazilian agriculture sector. There are some estimates that the rate of water erosion is between 600 and 800 million t yr^{-1}, without a comprehensive understanding of how different agricultural activities contribute to this high amount (Merten and Minella, 2013). Some authors call attention to the reduction this causes to the productive capacity of soils, to aquatic ecosystems, and to sediment deposition in hydropower dams (Allin et al., 2002; Campagnoli, 2005). Soil erosion is also considered a threat to food production; according to FAO (2008), several practices and technologies can generate and spread, as well as buffer, production risks. As shown in this study, all groups of rural conservation practices can direct and positively influence erosion control and help change the business-as-usual projections of the Brazilian agriculture sector. Moreover, our findings also highlighted the potential threat to energy security when land stewards are not adopting conservation practices. It is an important hint for stakeholders involved in hydroelectric power generation to consider the planned actions of agricultural land use upstream to their reservoir recharge areas.

Our findings demonstrated the wide range of potential impact of the system-related practices group on F-W-E attributes, since this group had studies that reported influence on all attributes. This group presented the same number of correlations to food production and soil quality attributes. Indeed, Muchane et al. (2020) argued that agroforestry can impact the reduction of soil erosion rates, possibly up to 50 %, when compared to monocultures. This reduction can be achieved because agroforestry practices promote higher infiltration rates, lower runoff, a higher proportion of soil macroaggregates, and greater soil structure stability.

Additionally, among the studies within our research, the "system-related practices group" was the only one that reported influence on "Energy efficiency" and "Energy from biofuels" attributes. Indeed, Kamali et al. (2017), comparing conventional and organic systems for soybean production, found that energy use was lower for organic systems. Moreover, Nakajima et al. (2015), who applied the "energy evaluation approach" to compare conventional and organic horticultural systems, concluded that organic and other systems based on agroecology have better thermodynamic behavior than the conventional agro-chemical farms. However, Ceccon (2008) found that intercropping with *Eucalyptus urophylla* affected the bean (during rainy and dry season) and rice productivity negatively in the first two years, but with higher forest biomass production. The author stated that agroforestry systems combined with Eucalyptus plantations, when indicated in small-farm partnership programs, have a good chance of increasing biomass production.

Therefore, considering the F-W-E Nexus, we ponder that the ecological benefits of the system-related practices are very well described in the literature, and there are no doubts about their positive effects. However, considering the complexity of food systems, it is important to use integrated system models suited to local specificities and the production scale in question. Integrated systems suitable for small farms may not be suitable for medium/large-scale producers and vice-versa.

In the biological and water-related management practices group, grass cover was the management practice with the highest number of records and covering mostly soil quality and water infiltration F-W-E attributes. Thus, we highlight the importance of considering these practices, especially regarding water security aspects, since they can maintain the water in the system more efficiently. Although they were not the subject of this study, areas with more limiting natural conditions, such as semi-arid climate and sandy soils, can have more need for this kind of conservation practices, since water is a factor that can constrain agricultural production.

All the combinations of engineering practices were related to soil erosion control F-W-E attributes. Where severe processes of soil erosion taking place, the adoption of only a few CA practices, such as no-tillage management, is not sufficient to provide erosion control, especially in hilly landscapes (Londero et al., 2018), such as most of the Atlantic Forest biome. The authors found that the combination of no-tillage and terraces reduced the surface runoff and sediment yield more than only no-tillage without terraces. So, considering the scenario of advanced soil erosion processes and hilly landscapes, it is indicated to combine rural management practices with engineering practices to ensure the F-W-E Nexus.

Despite the amount of data that demonstrated the effects of rural conservation practices on soil parameters and the relevance of the agriculture sector in Brazil, it was still a challenge to establish the impact of these practices on the F-W-E Nexus. This is a key aspect regarding land use planning, and it is relevant especially in highly populated areas such as the Atlantic Forest biome. In addition, the potential of rural conservation practices to impact the environmental and socioeconomic targets set by society is a widely accepted topic in the scientific debate. However, it still remains out of the decision-making and political agenda. We believe that the results presented here can provide subsidies to improve Brazilian policies, scientific debates, and strategies in the agricultural, energy, and water supply sectors, since they link recognized management practices to the stability of F-W-E Nexus.

CONCLUSIONS

Our results demonstrated the interconnectedness of the F-W-E nexus security and how the rural practices impact this nexus. The attributes proposed “opened the box” of each F-W-E pilar and allowed us to state that soil quality and soil erosion control are the attributes that have the strongest role when evaluating the impact of agricultural practices on F-W-E security.

Soil management practices were the most studied conservation practices group in the Atlantic Forest Biome and presented a high rate of positive impact on F-W-E nexus, demonstrating their potential to be included in the process of decision making related to landscape agriculture planning in this biome. Still about this group, no-tillage and crop rotation were the rural management practices that strongly improved the soil quality and soil erosion control attribute, enabling us to establish the impact of these rural management practices on F-W-E security.

The “system-related practices” group, which we defined as the set of practices that increase ecological interactions and decrease the need for inputs from outside the system, was the only group able to influence all attributes, including those related to energy security.

Besides the step forward in understanding the impact of agricultural practices on the F-W-E nexus demonstrated by this study and its potential to be used by decision-makers regarding agricultural landscape planning, we also highlight the potential of studies based on data already published in the literature that can synthesize the findings from different authors about a specific thematic.

We recommend the observance of some directives such as a survey on reliable databases and in peer-reviewed papers to consider publications that present similarities - environmental, social, economic - related to the research question and an accurate review with experts on the subject of the list of records.

ACKNOWLEDGMENTS

This research is funded by the National Council for Scientific and Technological Development (CNPq) - 441313/2017-5. JCA was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) - Finance Code 001. We would like to thank Luiza Leal, Matheus Malta, Laura Vetter and Daniela Cunha for their contribution to this research. In addition, we would like to extend our thanks to the reviewers for their constructive comments.

AUTHOR CONTRIBUTIONS

Conceptualization: Ana Paula Dias Turetta (lead).

Data curation: Ana Paula Dias Turetta (supporting), Gabriela Teixeira Duarte (lead) and Julia Camara Assis (equal).

Formal analysis: Ana Paula Dias Turetta (supporting), Gabriela Teixeira Duarte (lead), Julia Camara Assis (equal) and Rafaela Aparecida da Silva (equal).

Funding acquisition: Ana Paula Dias Turetta (lead).

Investigation: Gabriela Teixeira Duarte (lead).

Methodology: Ana Paula Dias Turetta (equal) and Gabriela Teixeira Duarte (equal).

Project administration: Ana Paula Dias Turetta (lead).

Resources: Ana Paula Dias Turetta (lead).

Supervision: Ana Paula Dias Turetta (lead).

Writing – original draft: Ana Paula Dias Turetta (supporting), Gabriela Teixeira Duarte (lead), Julia Camara Assis (equal) and Rafaela Aparecida da Silva (equal).

Writing – review & editing: Ana Paula Dias Turetta (supporting) and Gabriela Teixeira Duarte (lead).

REFERENCES

Allin SR, O'Reily CM, Cohen AS, Dettman DL, Palacios-Fest MR, Mackee BA. Effects of land use changes on aquatic biodiversity: a view from the paleo record of Lake Tanganyica, East Africa. Geology. 2002;30:1143-6. https://doi.org/10.1130/0091-7613(2002)030<1143:EOLUCO>2.0.CO;2

AQUASTAT Food and Agriculture Organization of the United Nations - FAO. AQUASTAT - FAO's global information system on water and agriculture. Rome: FAO; 2019 [cited 2019 Feb 26]. Available from: http://www.fao.org/nr/water/aquastat/main/index.stm.

Bommarco R, Kleijn D, Potts SG. Ecological intensification: harnessing ecosystem services for food security. Trends Ecol Evol. 2013;28:230-8. https://doi.org/10.1016/j.tree.2012.10.012

Brazilian M, Rogner H, Howells M, Hermann S, Arent D, Gielen D, Steduto P, Mueller A, Komor P, Rol RSJ, Yumkella KK. Considering the energy, water and food nexus: Towards an integrated modelling approach. Energ Policy. 2011;39:7896-906. https://doi.org/10.1016/j.enpol.2011.09.039

Bünemann EK, Bongiorno G, Bai Z, Creamer RE, De Deyn G, de Goede R, Fleskens L, Geissen V, Kuyper TW, Mäder P, Pulleman M, Sukkel W, van Groenigen JW, Brussaard L. Soil quality – A critical review. Soil Biol Biochem. 2018;120:105-25. https://doi.org/10.1016/j.soilbio.2018.01.030

Campagnoli F. The Brazilian lands: rates of potential production of sediments. Sediments Budgets Symposium. VII IAHS Scientific Assembly; 2005.

Ceccon E. Production of bioenergy on small farms: a two-year agroforestry experiment using *Eucalyptus urophylla* intercropped with rice and beans in Minas Gerais, Brazil. New Forest. 2008;35:285-98. https://doi.org/10.1007/s11056-007-9077-0

Chaddad F. The economics and organization of Brazilian agriculture: Recent evolution and productivity gains. Cambridge: Academic Press; 2015.

Federal Ministry for Economic Cooperation and Development (BMZ). Strategy for interlinkages between water, energy and agriculture (Nexus perspective): Synergies and conflicting goals. Alemanha: BMZ; 2018 [cited 2020 May 18]. Available from: http://www.bmz.de/de/zentrales_downloadarchiv/web-apps/wasser/Strategiepapier430_01_2018.pdf.

Food and Agriculture Organization of the United Nations - FAO. Climate change and food security: a framework document. Rome: FAO; 2008 [cited 2019 Feb 26]. Available from: http://www.fao.org/forestry/15538-079b31d45081fe9c3dbc6ff34de4807e4.pdf.

Food and Agriculture Organization of the United Nations - FAO. “Energy-smart” food for people and climate. Issue paper. Rome: FAO; 2011a [cited 2019 Feb 26]. Available on http://www.fao.org/3/i2454e/i2454e00.pdf.

Food and Agriculture Organization of the United Nations - FAO. Green manure/cover crops and crop rotation in conservation agriculture on small farms. Integrated Crop Management. Vol. 12. Rome: FAO; 2011b [cited 2019 Dec 15]. Available from: http://www.fao.org/ fileadmin/user_upload/agp/icm12.pdf

Flammini A, Puri M, Pluschke L, Dubois O. Walking the nexus talk: assessing the water-energy-food nexus in the context of sustainable energy for all initiatives. Climate, energy and tenure division (NRC) Rome: Food and Agriculture Organization of the United Nations - FAO; 2014 [cited 2017 Aug 17]. Available from: http://www.fao.org/energy/water-food-energy-nexus/en/

Godfray HCJ, Beddington JR, Crute IR, Haddad L, Lawrence D, Muir JF, Pretty J, Robinson S, Thomas SM, Toulmin C. Food security: the challenge of feeding 9 billion people. Science. 2010;327:812-8. https://doi.org/10.1126/science.1185383

Hatfield JL, Sauer TJ, Cruse RM. Soil: the forgotten piece of the water, food, energy nexus. Adv Agron. 2017;143:1-46. https://doi.org/10.1016/bs.agron.2017.02.001

Hellegers PJ, Zilberman D, Steduto P, McCornick P. Interactions among water, energy, food and environment: evolving perspectives and policy issues. Water Policy. 2008;10(S1):1-10. https://doi.org/10.2166/wp.2008.048

Helming K, Daedlow K, Paul C, Techen A-K, Bartke S, Bartkowski B, Kaiser D, Wollschläger U, Vogel H-J. Managing soil functions for a sustainable bioeconomy - Assessment framework and state of the art. Land Degrad Dev. 2018;29:3112-26. https://doi.org/10.1002/ldr.3066

Hoff H. Understanding the Nexus. In: Background Paper for the Bonn2011 Conference: The Water, Energy and Food Security Nexus; 2011; Stockholm. Stockholm: Environment Institute; 2011 [cited 2021 Aug 2]. Available from https://www.sei.org/publications/understanding-the-nexus/

Joly CA, Metzger JP, Tabarelli M. Experiences from the Brazilian Atlantic Forest: ecological findings and conservation initiatives. New Phytol. 2014;204:459-73. https://doi.org/10.1111/nph.12989

Kamali FP, Meuwissen MPM, Boer IJM, Middelaar CE, Moreira A, Lansink AGJMO. Evaluation of the environmental, economic, and social performance of soybean farming systems in southern Brazil. J Cleaner Production. 2017;142:385-94. https://doi.org/10.1016/j.jclepro.2016.03.135

Lal R, Mohtar RH, Assi AT, Ray R, Baybil H, Jahn M. Soil as a basic nexus tool: Soils at the center of the food–energy–water nexus. Curr Sust Renew Energ Rep. 2017;4:117-29. https://doi.org/10.1007/s40518-017-0082-4

Londero AL, Minella JPG, Deuschle D, Schneider FJA, Boeni M, Merten GH. Impact of broad-based terraces on water and sediment losses in no-till (paired zero-order) catchments in southern Brazil. J Soils Sediments. 2018;18:1159-75. https://doi.org/10.1007/s11368-017-1894-y

Liu J, Hull V, Godfray HCJ, Tilman D, Gleick P, Hoff H, Li S. Nexus approaches to global sustainable development. Nature Sustainability. 2018;1:466. https://doi.org/10.1038/s41893-018-0135-8

Merten GH, Minella JPG. The expansion of Brazilian agriculture: soil erosion scenarios. Int Soil Water Conser Res. 2013;1:37-48. https://doi.org/10.1016/S2095-6339(15)30029-0

Muchane MN, Sileshi GW, Gripenberg S, Jonsson M, Pumariño L, Barrios E. Agroforestry boosts soil health in the humid and sub-humid tropics: A meta- analysis. Agr Ecosyst Environ. 2020;295:106899. https://doi.org/10.1016/j.agee.2020.106899

Nakajima ES, Ortega E. Exploring the sustainable horticulture productions systems using the emergy assessment to restore the regional sustainability. J Cleaner Production. 2015;96:531-8. https://doi.org/10.1016/j.jclepro.2014.07.030

Palm C, Blanco-Canquib H, De Clerck F, Gaterea L. Graced P. Conservation agriculture and ecosystem services: An overview. Agr Ecosyst Environ. 2014;187:87-105. https://doi.org/10.1016/j.agee.2013.10.010

Rasul G. Food, water, and energy security in South Asia: a nexus perspective from the Hindu Kush Himalayan region. Environ Sci Policy. 2014;39:35-48. https://doi.org/10.1016/j.envsci.2014.01.010

Rezende CL, Uezu A, Scarano FR, Araujo DSD. Atlantic Forest spontaneous regeneration at landscape scale. Biodivers Conserv. 2015;24:2255-72. https://doi.org/10.1007/s10531-015-0980-y

Schellenberg G, Donnelly RC, Holder C, Briand MH, Ahsan R. Sedimentation, dam safety and hydropower: issues, impacts and solutions. Hydro Review. 2017:1-24. Available from: http://www.hydroworld.com/content/dam/hydroworld/online-articles/2017/04/Sedimentation%20Dam%20Safety%20and%20Hydropower-%20Issues%20Impacts%20and%20Solutions.pdf.

SOS Mata Atlântica. Casa da maioria dos brasileiros. São Paulo: Fundação SOS Pro-Mata Atlântica; 2020 [cited 2020 Jan 22]. Available from: https://www.sosma.org.br/causas/mata-atlantica/.

Tilman D, Clark M. Global diets link environmental sustainability and human health. Nature. 2015;515:518-22. https://doi.org/10.1038/nature13959

Turetta APD, Tonucci R, Mattos LM, Amaro G, Balieiro FC, Prado RB, Souza HA, Oliveira AP. An approach to assess the potential of agroecosystems in providing environmental services. Pesq Agropec Bras. 2016;51:1051-60. https://doi.org/10.1590/S0100-204X2016000900004

Valin H, Sands RD, van der Mensbrugghe D, Nelson GC, Ahammand H, Blanc E, Bodirsky B, Fulimori S, Hasegawa T, Havlik P, Heyhoe E, Kyle P, Manson-D'Croz D, Paltsev S, Rolinski S, Tabeau A, van Meijl H, von Lampe M, Willenbockel D. The future of food demand: understanding differences in global economic models. Agr Econ. 2013;45:51-67. https://doi.org/10.1111/agec.12089

World Bank. The World Bank Annual Report 2010: Year in Review. World Bank Annual Report. Washington, DC: World Bank; 2010 [cited 2018 May 15]. Available from: https://openknowledge.worldbank.org/handle/10986/5906

Xiong M, Sun R, Chen L. Effects of soil conservation techniques on water erosion control: A global analysis. Sci Total Environ. 2018;15:753-60. https://doi.org/10.1016/j.scitotenv.2018.07.124