Cienc. Tecnol. Agropecuaria, *22*(3): e1919 ISSN: 0122-8706 ISSNe: 2500-5308
DOI: https://doi.org/10.21930/rcta.vol22_num3_art:1919

Production systems management

Review article

Agricultural sustainability indicators associated with soil properties, processes, and management

Oscar Iván Monsalve Camacho[1*], **Carlos Ricardo Bojacá Aldana**[2], **Martha Cecilia Henao Toro**[1]

[1]Universidad Nacional de Colombia. Bogotá, Colombia.

[2]Universidad de Bogotá Jorge Tadeo Lozano. Bogotá, Colombia.

*Corresponding author: Universidad Nacional de Colombia. Facultad de Ciencias Agrarias. Carrera 30 N.º 45 -03, edificio 500, Bogotá, Colombia. oimonsalvec@unal.edu.co

Subject editor: Gustavo Adolfo Rodríguez Yzquierdo (Corporación Colombiana de Investigación Agropecuaria [AGROSAVIA])

Received: April 14, 2020

Accepted: April 23, 2021

Published: October 18, 2021

How to cite this article: Monsalve Camacho, O. I., Bojacá Aldana, C. R., & Henao Toro, M. C. (2021). Agricultural sustainability indicators associated with soil properties, processes, and management. *Ciencia y Tecnología Agropecuaria*, *22*(3), e1919. https://doi.org/10.21930/rcta.vol22_num3_art:1919

Abstract

Sustainability assessments are the most appropriate mechanism to determine if a crop production method, alternative, or tendency is environmentally, economically, and socially viable. These assessments are carried out using indicator-based tools; some are associated with soil properties, composition, processes, and management practices. This review provides an overview of the effect of soil management practices on agricultural system sustainability and describes the soil indicators used in agricultural sustainability assessments. We analyzed 28 indicators divided into soil-inherent indicators (16) and process indicators related to soil-water (3), soil-atmosphere (5), and soil-plant (4) systems. We suggest measuring at least one indicator per soil indicator group associated with soil properties and processes, including indicators considering future climate change scenarios, and adapting current tools to evaluate the sustainability of various production alternatives.

Keywords: farming systems, soil chemicophysical properties, soil management, sustainability, sustainable use

Indicadores de sostenibilidad agrícola asociados a propiedades, procesos y manejo del suelo

Resumen

Las evaluaciones de sostenibilidad son el mecanismo más adecuado para determinar si un método, alternativa o tendencia de producción de cultivos es viable desde el punto de vista ambiental, económico y social. Estas evaluaciones se realizan por medio de herramientas basadas en indicadores, algunos asociados con las propiedades, la composición, los procesos y el manejo del suelo. En esta revisión se ofrece una visión global del efecto de las actividades de manejo del suelo sobre la sostenibilidad de los sistemas de producción agrícola y se hace una descripción general de los indicadores de suelo que se han utilizado en evaluaciones de sostenibilidad agrícola. Se han utilizado 28 indicadores, agrupados en indicadores inherentes al suelo (16) e indicadores de procesos relacionados con los sistemas suelo-agua (3), suelo-atmósfera (5) y suelo-planta (4). Se sugiere la medición de al menos un indicador por cada grupo de indicadores asociados a propiedades y procesos del suelo, la inclusión de indicadores que tengan en cuenta escenarios futuros de cambio climático, así como la adaptación de las herramientas actuales para evaluar la sostenibilidad de diversas alternativas de producción.

Palabras clave: manejo del suelo, propiedades físico-químicas del suelo, sistemas agrícolas, sostenibilidad, uso sostenible

Introduction

Sustainability assessment is one of the most relevant approaches to mitigate the impacts of inadequate crop management on the environment, society, and the economy. It involves three pillars or the triple bottom line (Elkington, 1998): economic viability, social equity, and ecological integrity (De Luca et al., 2017). However, agricultural sustainability is not easily measured (Pollesch & Dale, 2015). In addition to being multidimensional, it can be carried out at different geographic scales: global (e.g., Kanter et al., 2018; Repar et al., 2017; Rockström et al., 2017; Soussana, 2014; Tittonell, 2014), national (e.g., Ghisellini et al., 2014; Kucukvar et al., 2014; Rinne et al., 2013; Roy & Chan, 2012), regional (e.g., Gaudino et al., 2014; Gerdessen & Pascucci, 2013; Milder et al., 2014; Triste et al., 2014; Walraevens et al., 2015), and farm or production unit (e.g., Bockstaller et al., 2015; Marchand et al., 2014; Peano et al., 2014; Schader et al., 2016).

A series of methods, methodological approaches, frameworks, or protocols have been developed for agricultural sustainability assessments (De Olde, Oudshoorn, Sørensen, et al., 2016; Marchand et al., 2014; Schader et al., 2014; Schindler et al., 2015), whose objective is to quantitatively compare systems, methods, alternatives, or trends in agricultural production (De Olde, Oudshoorn, Sørensen, et al., 2016; Dizdaroglu & Yigitcanlar, 2014; Paracchini et al., 2015; Peano et al., 2014; Schindler et al., 2015). These tools are typically built from indicators that systematically monitor the system and its modifications, thus identifying processes that may be out of threshold limits (De Olde, Oudshoorn, Sørensen, et al., 2016). Within the environmental dimension of agricultural sustainability, there are usually indicators associated with soil properties, whose choice depends on the nature and purpose of the analysis to be carried out.

Agricultural activities involving soil could have the following impacts: accumulation of toxic substances in harvested products, pollution of water or atmosphere (if the amount of applied fertilizer exceeds the soil's buffer capacity), wind or water erosion, compaction due to machinery traffic and overgrazing, salinization (by irrigation, especially in arid regions or soils with poor drainage), nutrient depletion, structure alteration, and soil biodiversity reduction. These impacts endanger agricultural production and, therefore, food security (Blume et al., 2016). Sustainable use of soil depends on environmental conditions, soil characteristics, and its management. These factors interact under the system principle, where changing one factor alters the others.

This review aims to i) assess the relationship between agricultural sustainability and soil properties, processes, and management and ii) review the indicators used in agricultural sustainability assessments, which derive from physical, chemical, and biological soil properties and associated processes.

Materials and methods

A preliminary review was made in Google Scholar to obtain the desired information, downloading the relevant publications from the journals' websites. The search included all terms —*soil*, *agriculture,* and *sustainability*—, mainly in titles and anywhere in the article. From this search, we selected the publications that reported on the effects of agricultural practices associated with soil management on the three dimensions of sustainability (environmental, economic, and social). A time scale of 20 years until 2019 was established for the literature search. Subsequently, the search focused on the agricultural sustainability indicators associated with soil management. For this, we considered publications that addressed the three dimensions of sustainability of agricultural production systems only. The cited literature in this review includes scientific articles, academic books and book chapters, academic conference proceedings, and public reports from recognized international agricultural research organizations.

This review included 127 references describing or linking agricultural sustainability to soil management. Three classes of publications were identified: i) publications that define agricultural sustainability and showed information regarding its assessment (40), ii) publications that contextualize soil management in agriculture (63), and iii) publications that evaluated agricultural sustainability through indicators under field conditions (37). Note that some publications are grouped into more than one class. The following criteria were used to include the publications in this review:

- Accepted by academic peers
- Oriented to evaluate the performance of agricultural sustainability, i.e., including and harmonizing the environmental, social, and economic dimensions of the system (classes i and iii)
- Assessed sustainability based on indicators (class iii)
- Included indicators for the three dimensions of sustainability (environmental, social, and economic) (class iii)

Soil and agricultural sustainability

In addition to being modified depending on its management, the method of production, and the study region, the soil is subject to erosion, acidification, alkalization, salinization, structure destruction, compaction, loss of biodiversity, nutritional imbalances, decreased damping capacity, and pollution from natural or anthropogenic sources. All the above leads to its degradation (Bone et al., 2010), making agricultural sustainability assessments involving soil even more complex (Keesstra et al., 2016). A sample of this is sustainable development goals (SDGs) 2, 3, 6, 11, 13, 14, and 15, in which soil properties and functions are relevant to food security (SDGs 2 and 6), food safety (SDG 3), pollution of water sources (SDG 14), urban development (SDG 11), and sustainability of terrestrial ecosystem services (SDG 15) (Bouma et al., 2019; Tóth et al., 2018).

Soil management practices with the highest impact on agricultural sustainability

The agricultural activities associated with the soil that directly influence agricultural production system sustainability include fertilization, tillage, and irrigation, which impact the soil, water sources, and the atmosphere.

Fertilization

Fertilization is one of the processes with the highest environmental (Bojacá et al., 2014; Cellura et al., 2012) and economic impact on agricultural production mainly because the loss of soil fertility, which results in reduced productivity, is commonly compensated for by increasing the amount of fertilizer applied (Tilman et al., 2002). The use of nitrogen fertilizers has increased about seven times, while crop yields without N fertilization have been reduced 2.4 times since the 1960s (Hirel et al., 2011; Spiertz, 2010; Tilman et al., 2002). Something similar occurs with phosphorus since its consumption has increased six to seven times since 1960, with about 85 % of this element used for fertilizer production (Cordell et al., 2009). P fertilizers are manufactured from phosphate rock, a non-renewable resource that may be depleted in 50 to 100 years (Therond et al., 2017). Unlike phosphorus, potassium fertilizer reserves are high, although it has been reported that large areas of agricultural soils around the world (e.g., Australia and China) have deficiencies (Römheld & Kirkby, 2010). More than 90 % of the mined potassium is used to manufacture potash fertilizers (Rawashdeh & Maxwell, 2014; Rawashdeh et al., 2016), whose global consumption has increased from 8.8 million Mg in 1961 to 29.1 million in 2008 (Rawashdeh et al., 2016). Potassium fertilizers are typically applied in smaller amounts than N or P, so less than 50 % of the K uptake by crops is replenished (Zörb et al., 2014).

Tillage

The intensive and long-term practice of tillage has led to significant soil degradation in many parts of the world (Loaiza et al., 2018). During tillage, the mechanical forces cause soil macro-aggregate alteration due to fracturing or compaction (Acar et al., 2018; Blanco-Canqui & Lal, 2004). This practice not only alters the soil structure but also influences organic carbon dynamics (oxidizing organic matter faster than its replacement rate) (Barto et al., 2010; Loaiza et al., 2018; Usman et al., 2018), microbial activity (Lemtiri et al., 2018; Lori et al., 2017; Van Capelle et al., 2012), and greenhouse gas emissions (Stavi & Lal, 2013). Additionally, due to the alteration of soil structure by tillage, it has been established that this cultivation practice is one of the leading causes of erosion in cultivated areas, as it accelerates surface runoff and soil loss (Wang et al., 2018).

Irrigation

Because irrigated areas have tripled in the last 50 years (Food and Agriculture Organization [FAO], 2011), 70 % of water extractions and 80-90 % of the world's fresh water consumption are dedicated to irrigation (Drechsel et al., 2015; Therond et al., 2017). On average, two liters of water per person are enough for daily hydration, but around 3,000 liters are needed to meet their daily food needs (agricultural and agro-industrial production) (Drechsel et al., 2015). In many irrigated regions, water scarcity and salinization problems have increased sharply (Foley et al., 2011; Gomiero et al., 2011). Irrigated agriculture only accounts for 20 % of the total cultivated land area but produces 40 % of the world's food (FAO, 2011).

Effects of soil management practices on agricultural sustainability

Soil degradation

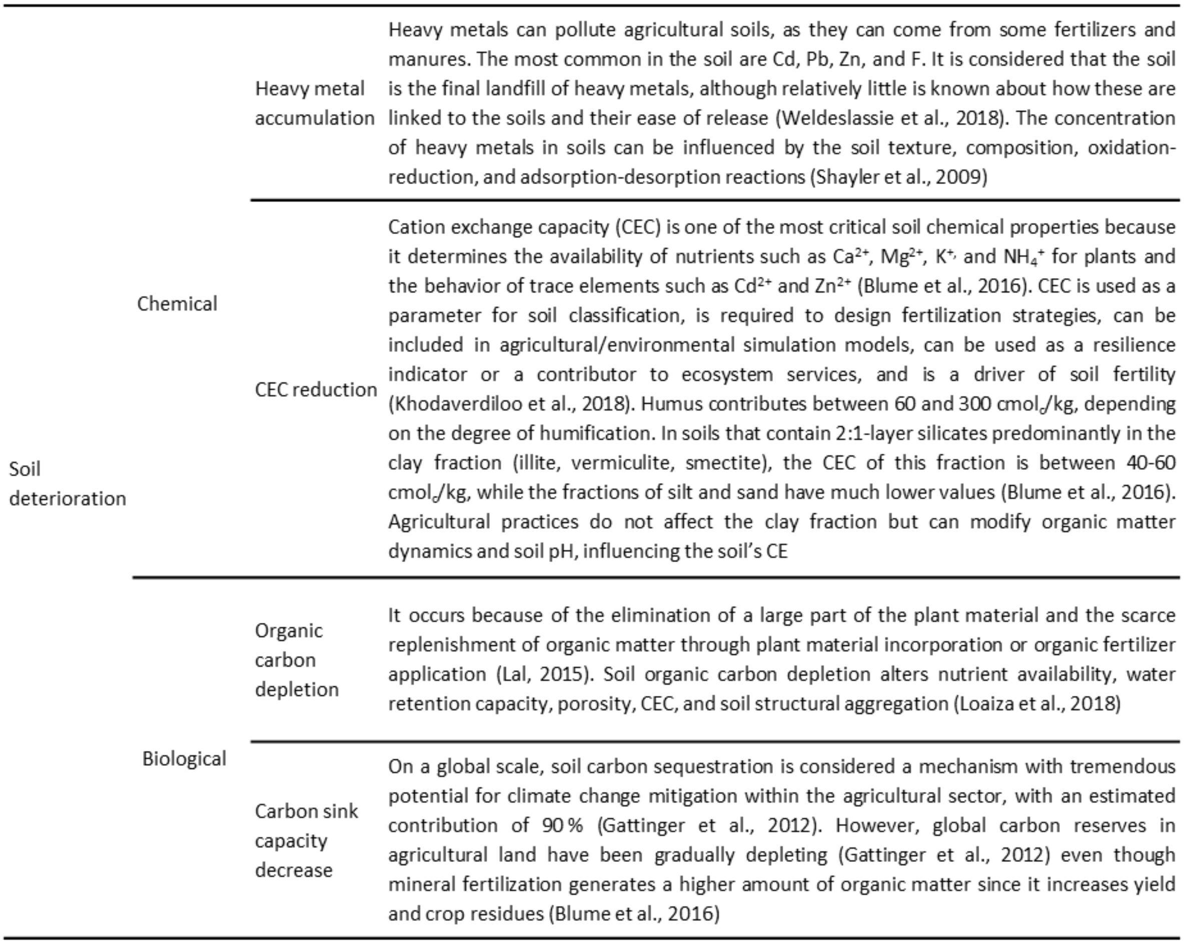
Soil degradation is associated with a decrease in soil quality, which, in agricultural terms, implies the reduction of its production capacity (Lal, 2015; Usman et al., 2018). This degradation is a function of the relief (geomorphology), soil characteristics (physical, chemical, and biological properties), climate (temperature and precipitation), and management practices (intensive or conservation). These factors act as catalysts since soils are highly resistant or vulnerable to degradation depending on their features and interaction. This phenomenon is particularly problematic in arid and sub-arid zones, where evapotranspiration exceeds precipitation (Usman et al., 2018) (table 1).

Table 1. General description of soil degradation processes associated with agricultural activities

Category	Type	Sub-Type	Description
Soil loss	Erosion	Water and wind	Erosion is the leading cause of soil degradation since it induces the removal of its upper layer, where organic matter and nutrients are concentrated (Li et al., 2009). Generally, it leads to irreversible and long-term cumulative damage, reducing the arable layer as well as water and nutrient storage capacity (Blume et al., 2016). Around 40 % of the cultivated areas in the world have experienced some degree of erosion, reduced fertility, or overgrazing in the last decades (Gomiero et al., 2011). It is estimated that intensive tillage, sowing systems (row planting, sowing along the slope, lack of cover), and soil exposure (bare soil) during fallow periods are responsible for the loss of 26 million tons of soil per year, which is 2.6 times higher than the natural loss rate (Verhulst et al., 2010). Considering that soil formation rate is less than that of erosion by at least an order of magnitude (Verheijen et al., 2009), it can be inferred that agricultural activities leading to soil erosion produce the most significant environmental impact and the gradual loss of system sustainability.
Soil deterioration	Physical	Structure modification	Many soil functions are governed, to a large extent, by their structure, being the capacity of transporting fluids (gases —aeration— and liquids —infiltration—) one of the most important. This capacity is typically more sensitive to changes in soil structure than, for example, water retention or porosity because transport functions are affected not only by the pore size (distribution) but also by connectivity, continuity, and sinuosity (Farahani et al., 2018).
	Chemical	A gradual decrease in essential nutrients	It occurs due to the imbalance between nutrient uptake and application. When plants absorb a higher quantity of nutrients than those provided by fertilizers, the nutrient reserves from the soil are extracted, gradually depleting them. This imbalance increases when organic matter is not applied or harvest residues are not reincorporated (Lal, 2015).
		Salinization	Salt accumulation, particularly sodium (Na^+), chlorine (Cl^-), and boron (B), differs from one place to another and represents a danger to agriculture, especially in arid and semi-arid regions (Farahani et al., 2018; Havlin et al., 2014; Lal, 2015). Salinity can originate from mineral weathering, wind salinity, precipitation, and irrigation with saline/sodium water (Farahani et al., 2018; Ivushkin et al., 2018; Weldeslassie et al., 2018). Soil salinization is particularly frequent in areas with high water table levels, inadequate irrigation management, or poor drainage, subject to high evaporation and low leaching (Ivushkin et al., 2018; Lal, 2015; Weldeslassie et al., 2018).
		Acidification and alkalization	Depending on its level, soil acidity causes toxicity by aluminum and manganese, nutrient deficiencies such as calcium, phosphorus, and magnesium, and reduced nitrogen mineralization due to a decrease in microbial activity (Havlin et al., 2014). It also makes boron, zinc, molybdenum, and copper unavailable (Weldeslassie et al., 2018). Alkalinity alters the soil's physical fertility through surface sealing and crust formation and chemical fertility by decreasing iron, manganese, zinc, phosphorus, and copper availability due to high sodium concentrations in the cation exchange complex (Weldeslassie et al., 2018). Acidification is usually caused by excessive acidifying fertilizer application (Lal, 2015), e.g., in the form of ammonium, which results in soil pH decrease after NH_4^+ is nitrified to NO_3^- (Weldeslassie et al., 2018).

Continue on next page

(Continuation of table 1)



Soil deterioration	Chemical	Heavy metal accumulation	Heavy metals can pollute agricultural soils, as they can come from some fertilizers and manures. The most common in the soil are Cd, Pb, Zn, and F. It is considered that the soil is the final landfill of heavy metals, although relatively little is known about how these are linked to the soils and their ease of release (Weldeslassie et al., 2018). The concentration of heavy metals in soils can be influenced by the soil texture, composition, oxidation-reduction, and adsorption-desorption reactions (Shayler et al., 2009)
		CEC reduction	Cation exchange capacity (CEC) is one of the most critical soil chemical properties because it determines the availability of nutrients such as Ca^{2+}, Mg^{2+}, $K^{+,}$ and NH_4^+ for plants and the behavior of trace elements such as Cd^{2+} and Zn^{2+} (Blume et al., 2016). CEC is used as a parameter for soil classification, is required to design fertilization strategies, can be included in agricultural/environmental simulation models, can be used as a resilience indicator or a contributor to ecosystem services, and is a driver of soil fertility (Khodaverdiloo et al., 2018). Humus contributes between 60 and 300 cmol$_c$/kg, depending on the degree of humification. In soils that contain 2:1-layer silicates predominantly in the clay fraction (illite, vermiculite, smectite), the CEC of this fraction is between 40-60 cmol$_c$/kg, while the fractions of silt and sand have much lower values (Blume et al., 2016). Agricultural practices do not affect the clay fraction but can modify organic matter dynamics and soil pH, influencing the soil's CE
	Biological	Organic carbon depletion	It occurs because of the elimination of a large part of the plant material and the scarce replenishment of organic matter through plant material incorporation or organic fertilizer application (Lal, 2015). Soil organic carbon depletion alters nutrient availability, water retention capacity, porosity, CEC, and soil structural aggregation (Loaiza et al., 2018)
		Carbon sink capacity decrease	On a global scale, soil carbon sequestration is considered a mechanism with tremendous potential for climate change mitigation within the agricultural sector, with an estimated contribution of 90 % (Gattinger et al., 2012). However, global carbon reserves in agricultural land have been gradually depleting (Gattinger et al., 2012) even though mineral fertilization generates a higher amount of organic matter since it increases yield and crop residues (Blume et al., 2016)

Source: Adapted from Lal (2015) and Oldeman (1994)

Greenhouse gas (GHG) emissions from soil to atmosphere

Lithosphere contains the largest reserve of carbon and nitrogen (without considering atmospheric N) on the planet, with 10^8 Pg (10^{15} g) and 1.64E10^{11} Tg (10^{12} g), respectively, stored mainly on the surface (1 m deep) (Nieder & Benbi, 2008; Schaufler et al., 2010). Soils naturally emit carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), which are essential GHGs (Oertel et al., 2016). However, agricultural systems intensify biochemical processes in the soil, increasing N_2O (1.7–4.8 Tg N_2O/yr) (Baggs, 2011; Boeckx & Van Cleemput, 2001; Bouwman et al., 1995; Ciais et al., 2013; Intergovernmental Panel on Climate Change [IPCC], 2013), CO_2 (180 Pg CO_2 accumulated during 1750–2011) (Ciais et al., 2013), and CH_4 emissions (up to 6,950 μmol CH_4 m^{-2}/h) (Oertel et al., 2016). Agriculture generates 52 and 84 % of the CH_4 and N_2O global emissions, respectively (Smith et al., 2008), and at the same time, these two gases have 25 and 298 times more global warming potential than CO_2, respectively (IPCC, 2013). It is necessary to consider that CO_2 (30–95 years) has a longer half-life than CH_4 (12 years) but shorter than N_2O (121 years) (IPCC, 2013). The net flow of CO_2 from agricultural soils is small compared to industry emissions

(Smith et al., 2008). However, emissions from industrial manufacture of agricultural inputs using fossil fuels (e.g., plastic and fertilizers) must be added to this flow, which results from soil alteration by tillage and fertilization activities (Arizpe et al., 2011; Smith et al., 2008; West & Marland, 2002). Properties and processes in the soil, such as humidity, pH, nutrient concentration, temperature, exposure, air pressure, wildfires, type of coverage, and change in land use are the main drivers of GHG emissions from the soil to the atmosphere (Oertel et al., 2016).

Nutrient leaching

Under natural conditions, ions are constantly leached from the soil surface into groundwater, varying in intensity according to the magnitude and frequency of rainfall and soil characteristics (Laird et al., 2010). Under agricultural conditions, the leaching of nutrients, such as nitrogen and phosphorus, into aquatic systems is greatly exacerbated (Yao et al., 2012), generating eutrophication because of the excessive production of photosynthetic aquatic microorganisms in marine life and freshwater ecosystems (Karaca et al., 2004). These microorganisms, typically adapted to environments with low nutrient content, rapidly reproduce in the presence of high nutrient concentrations, thus consuming oxygen from the aquatic environment and causing the death of other oxygen-dependent organisms (Dempster et al., 2012).

On average, plants do not take up 50 % of the nitrogen applied through fertilizers (Drechsel et al., 2015; Hoang & Allaudin 2010). This nitrogen is leached into water sources or volatilized into the atmosphere (Galloway et al., 2003), with consequent adverse environmental effects on aquatic ecosystems, climate change, and human health (Bodirsky et al., 2014; Camargo & Alonso, 2006; Giles, 2005; Umar & Iqbal, 2007).

About 25 % of the phosphorus extracted since 1950 has accumulated in landfills or ended up in water sources, increasing eutrophication problems (Cordell et al., 2009). Unlike nitrogen, phosphorus leaching varies substantially in time and space, and, in general, agricultural practices have a more negligible effect on phosphorus leaching than environmental conditions and soil characteristics (Ulén et al., 2018).

Not only soluble nitrogen and phosphorus (anionic form) are liable to leach. When there is an alteration in soil conditions (e.g., the addition of organic matter or mineral fertilizers), metal ions such as iron and manganese, which are usually precipitated and immobilized, can be solubilized due to fluctuations in pH and soil redox potential (Aharonov-Nadborny et al., 2018).

Increase in production costs

The way the soil is handled in agriculture not only impacts the environmental dimension of sustainability but also influences its social and economic dimensions. Agricultural practices associated with soil management, such as fertilization, tillage, and irrigation, require hiring labor, renting or purchasing agricultural machinery/equipment, and acquiring agricultural inputs. Each of these tasks creates wages or jobs and becomes an item in the list of production costs (FAO, 2016).

In general, labor is the item that represents the highest cost in agricultural production. Of the agricultural activities, soil preparation demands much labor, especially in developing countries, where specialized machinery for these tasks is not widespread. Manual labor has a high impact on the social dimension of sustainability since it creates a higher number of jobs than the mechanized option. An increase in social sustainability implies a reduction of economic sustainability and vice versa, which generates a dichotomy in sustainability analysis.

Fertilization places second in production costs since it includes fertilizers and labor costs required to obtain, mix, and apply the fertilizers (FAO, 2016). Additionally, this activity produces the most variability in production costs since it depends on the application method (manual, foliar, or fertigation), dosing (estimation method), timing (weather), and type (compound or simple, soluble or insoluble).

Indicators associated with soil properties, processes, and management

Some of the indicators used in agricultural sustainability assessments are associated with soil properties, processes, composition, and management. Indicators consider aspects inherent to the soil and those associated with soil-water, soil-atmosphere, and soil-plant systems. The indicators included in this review were grouped according to these factors and extracted from international scientific publications referencing agricultural sustainability assessments, i.e., those considering the three sustainability dimensions (environmental, economic, and social).

Soil inherent indicators

This group of indicators refers to the impact that agricultural production systems exert on the soil. The most common indicators in this group are erosion rate and soil organic matter concentration, while properties such as electrical conductivity, cation exchange capacity, exchangeable acidity, clay content, water retention capacity, apparent density, effective depth, and permeability are the least used (table 2).

Although several works reference soil quality (e.g., Rodrigues et al., 2010), we did not find an index or aggregation function to estimate it. This indicator was addressed from the individual determination of soil properties such as soil organic matter (SOM), electrical conductivity (EC), pH, cation exchange capacity (CEC), and Bi (table 2). It should be noted that soil quality is commonly estimated by integrating properties such as texture, effective depth, apparent density, water retention capacity, SOM, nitrogen, phosphorus, exchangeable bases, pH, EC, microbial biomass, potentially mineralizable C and N, and soil respiration (Garrigues et al., 2012; Hayati et al., 2010). Except for SOM, these properties are not commonly considered in agricultural sustainability assessments (table 2).

Table 2. Soil inherent indicators (Ind.) used in agricultural sustainability assessments

Ind.	Unit	Description	Measurement method (a)	References
SOM	%	Soil organic matter content	Organic carbon (OC) was determined by Walkley and Black (1934) and multiplied by the 1.724 factor to obtain soil organic matter	Astier et al. (2011), Baush et al. (2014), Bélanger et al. (2012), Brunett et al. (2005), De Olde, Oudshoorn, Bokkers et al. (2016), Hubeau et al. (2017), Kanter et al. (2018), Meul et al. (2008), Mtengeti et al. (2015), Nambiar et al. (2001), Paracchini et al. (2015), Sadok et al. (2009)
pH	-	Soil acidity, neutrality, and alkalinity	Potentiometric (Okalebo et al., 1993)	Brunett et al. (2005), Kanter et al. (2018), Meul et al. (2008), Nambiar et al. (2001), Rodrigues et al. (2010)
EC	dS/m	Electric conductivity	Conductimetric (Okalebo et al., 1993)	Nambiar et al. (2001)
No - Nm	%	Soil organic or mineral nitrogen content	Kjeldhal modified (Sarkar & Haldar, 2005)	Astier et al. (2011), Meul et al. (2008), Paracchini et al. (2015)
Pd	mg/kg	Soil available phosphorus content	Bray II and Olsen (Sarkar & Haldar, 2005)	Astier et al. (2011), Bélanger et al. (2012), Meul et al. (2008), Rodrigues et al. (2010)
Bi	cmol$_c$/kg	Concentration or sum of interchangeable bases (K, Ca, Mg, and Na)	CEC and interchangeable bases (Ca^{2+}, Mg^{2+}, K^+, and Na^+) through ammonium acetate 1M pH 7 method. To determine CEC, NH_4^+ exchanged with NaCl is displaced, and the assessment is done by titration. Bases are determined in the ammonium acetate extract by atomic absorption spectrophotometry (Sarkar & Haldar, 2005)	Nambiar et al. (2001), Rodrigues et al. (2010)
CEC		Cation exchange capacity		Nambiar et al. (2001)
Al + H	cmol$_c$/kg	Exchangeable acidity	Volumetric. Determination of Al^{3+} and H^+ ions with KCl 1N (Sarkar & Haldar, 2005)	Rodrigues et al. (2010)
Ar	%	Clay content	Hydrometer or Bouyoucos (Sarkar & Haldar, 2005)	Nambiar et al. (2001)
SMR	Bar	Soil moisture retention capacity at different tensions. In this case: 0.1, 0.3, 1, 3, 5, and 15 bars of tension	Pressure plate and pot (Sarkar & Haldar, 2005)	Nambiar et al. (2001)
Bd	g cm^{-3}	Bulk density	Cylinder (Sarkar & Haldar, 2005)	Nambiar et al. (2001)
Ed	cm	Effective depth	Digging with shovel	Nambiar et al. (2001)
In	cm/h	Infiltration	Concentric rings (Sarkar & Haldar, 2005)	Nambiar et al. (2001)

Continue on next page

(Continuation of table 2)

ER	Mg/ha/year	Erosion rate	$\mathrm{ER} = \mathrm{R\ K\ L\ S\ C\ P}$ *Equation 1* Where: *R* = Rain erosion; *K* = Soil erosion; *LS* = Length and degree of slope; *C* = Vegetation factor; *P* = Mechanical practices factor	Astier et al. (2011), Baush et al. (2014), De Olde, Oudshoorn, Bokkers et al. (2016), Gerdessen and Pascucci (2013), Ghisellini et al. (2014), Kanter et al. (2018), Nambiar et al. (2001), Pacini et al. (2003), Praneetvatakul et al. (2001), Rodrigues et al. (2010), Roy and Chan (2012), Sadok et al. (2009), Smith et al. (2017)
Cn	PSI	Compaction	Soil compaction meter (penetrometer)	De Olde, Oudshoorn, Bokkers et al. (2016), Sadok et al. (2009)
TEt	kg 1.4-DB eq	Terrestrial eco-toxicity. Effects of toxic substances found in the environment on terrestrial ecosystems (Audsley et al., 2003)	$\mathrm{TEt} = \sum_{i,n} \mathrm{TTP}_{i,n} \times \mathrm{f}_{i,n} \times \mathrm{m}_i$ *Equation 2* Where *TTP* = Characterization factor for the toxicity of terrestrial ecosystems; $f_{i,n}$ = Fraction of substance *i* transported from the crop to the environmental compartment *n*; m_i = Mass emitted from each pollutant *i* (Audsley et al., 2003)	De Luca et al. (2018), Martínez-Blanco et al. (2014), Neugebauer et al. (2015), Tricase et al. (2018)

Note. (a) Methodologies for measuring indicators are not specified in most publications. Here we show the most common and representative methodology.
Source: Elaborated by the authors

Soil-water relationship indicators

This group of indicators considers soil management's impact on the hydrological cycle. The movement of nitrates (NO3-) from soil to surface and groundwater due to fertilizer application and organic amendments stands out within this group. This indicator is closely related to potential eutrophication (PE), an environmental impact resulting from nitrate and phosphate emissions from soil to water bodies. Aquatic eco-toxicity (AEt) is included in Life Cycle Sustainability Assessments (LCSAs), which are still under development (table 3).

Table 3. Soil-water relationship indicators (Ind.) used in agricultural sustainability assessments

Ind.	Unit	Description	Measurement method	References
NO_3^-	kg NO_3^-/ha	Nitrate emissions to aquatic systems	30 % of the total N is applied after discounting N emissions to the air (Torrellas et al., 2013).	Bockstaller et al. (2009), Lebacq et al. (2013), Pacini et al. (2003), Roy and Chan (2012), Sadok et al. (2009), Van Asselt et al. (2014)
PE	kg PO_4^{3-} eq	Potential eutrophication represents the nitrogen and phosphorus emission to aquatic systems, increasing certain species, such as algae, and reducing oxygen concentration of the aquatic environment —a threat to biodiversity— (Audsley et al., 2003)	$\mathrm{PE} = \sum_{\mathrm{i}} \left(\frac{\frac{\mathrm{v_i}}{\mathrm{M_i}} \mathrm{x} \frac{\mathrm{No_2}}{\mathrm{A_e}}}{\frac{1}{\mathrm{M_{PO_4^{3-}}}} \mathrm{x} \frac{\mathrm{No_2}}{\mathrm{A_p}}} \right) \mathrm{m_i}$ *Equation 3* Where *vi* = Number of moles of *N* or *P* in a molecule of compound *i*; *M* = Molecular mass (kg/mol); NO_2 = Number of O_2 moles consumed during algae degradation; *Ae* = Number of moles of *N* or *P* contained in a molecule of algae; *mi* = Mass of substance *i* (kg) (Guinée et al., 2002)	Lebacq et al. (2013), Martínez-Blanco et al. (2014), Neugebauer et al. (2015), Pergola et al. (2013), Tricase et al. (2018)
EtA	kg 1.4-DB eq	Aquatic eco-toxicity. The effects of toxic substances (pesticides from the air and heavy metals from the ground) on aquatic ecosystems (Audsley et al., 2003)	$\mathrm{EtA} = \sum_{\mathrm{i,n}} \mathrm{TAP_{i,n}} \mathrm{x} \mathrm{f_{i,n}} \mathrm{x} \mathrm{m_i}$ *Equation 4* Where *TAP* = Characterization factor for the toxicity of aquatic ecosystems; $f_{i,n}$ = Fraction of substance *i* that is transported from cultivation to environmental compartment *n*; m_i = Emitted mass of the *i* pollutant (Audsley et al., 2003)	De Luca et al. (2018), Martínez-Blanco et al. (2014), Neugebauer et al. (2015)

Source: Elaborated by the authors

Soil-atmosphere relationship indicators

This group of indicators measures soil management's effects on the atmosphere. Some of them are the emissions of carbon dioxide (CO_2 - global warming potential (GWP)), ammonia (NH_3), nitrous oxide (N_2O), and oxides of nitrogen (NOx) from the soil to the atmosphere, and potential acidification (PA) (table 4). Despite the evident effects of management practices on pollutants, these indicators are commonly estimated through models, conversion factors, or equivalence tables (table 4) due to the methodological difficulties and high assessment costs. In most cases, they are not considered in sustainability assessments.

Table 4. Soil-atmosphere relationship indicators (Ind.) used in agricultural sustainability assessments

Ind.	Unit	Description	Measurement method	References
GWP	kg CO_2 eq	Global warming potential. An increase of the CO_2, N_2O, CH_4, and aerosol concentration in the Earth's atmosphere increases thermal radiation energy absorption and, consequently, temperature (global warming) (Audsley et al., 2003)	$\mathrm{GWP} = \sum_i \left(\frac{\int_0^T a_i c_i(t) dt}{\int_0^T a_{CO_2} c_{CO_2}(t) dt} \right) m_i$ *Equation 5* Where *T* = Time (years); *ai* = Heating produced by the increased concentration of a gas *i* (W m^{-2}/kg); *ci (t)* = Concentration of gas *i* over time (t) (kg m^{-3}); *mi* = Mass of substance *i* (kg). Values corresponding to CO_2 are included in the denominator (Heijungs & Guinée, 2012)	De Luca et al. (2018), Kucukvar et al. (2014), Martínez-Blanco et al. (2014), Neugebauer et al. (2015), Pergola et al. (2013), Ryan et al. (2016), Smith et al. (2017), Tricase et al. (2018), Van Asselt et al. (2014)
NH_3	kg NH_3/ha	Ammonia emissions into the atmosphere due to nitrogen fertilization	Three percent of the total N applied is released in the form of N-NH_3 (Audsley et al., 2003)	Bockstaller et al. (2009), De Olde, Oudshoorn, Bokkers et al. (2016), Sadok et al. (2009), Smith et al. (2017), Tricase et al. (2018)
N_2O	kg N_2O/ha	Di-nitrogen monoxide emissions into the atmosphere due to nitrogen fertilization	One point twenty-five percent of the total N applied is released in the form of N-N_2O (Brentrup et al., 2000; Weidema & Meeusen, 2000)	Rodrigues et al. (2010), Sadok et al. (2009), Tricase et al. (2018)
NOx	kg NOx/ha	Nitrogen oxides emissions into the atmosphere due to nitrogen fertilization	Ten percent of N-N_2O converts into N-NOx (Brentrup et al., 2000; Weidema & Meeusen, 2000)	Rodrigues et al. (2010), Tricase et al. (2018)
PA	kg SO_2 eq	Potential acidification. Emission of sulfur and nitrogen oxides into the atmosphere, where it can combine with another molecule and return to the surface in the form of acid rain (Audsley et al., 2003)	$\mathrm{AP} = \sum_i \left(\frac{\eta_{SO_2} M_{SO_2}}{M_i} \right) m_i$ *Equation 6* Where: ηSO_2 = Number of SO_2 ions (mol/kg) that can potentially be produced by one kg of substance *i*; MSO_2 = Equivalent weight of one mole of SO_2 (kg/mol); *Mi* = Equivalent weight of substance *i*; *mi* = Mass of substance *i* (kg) (Heijungs & Guinée, 2012)	Martínez-Blanco et al. (2014), Van Asselt et al. (2014)

Source: Elaborated by the authors

Soil-plant relationship indicators

The effect of agricultural systems management on the soil-plant relationship is evaluated in two ways: from soil to plant (e.g., element consumption per kilogram produced [Elto-kg]) and from plant to soil (e.g., soil cover [SC]) (table 5). The nitrogen, phosphorus, or potassium balance indicator (NPKBal) stands out in this group and is assessed in many reviewed publications, followed by SC. Despite the information provided on the performance and efficiency of production system management, indicators such as soil-production ratio (S-Pr) and Elto-kg are not considered, even when estimating S-Pr, for example, which can be done without investing resources in laboratory analysis or expensive methodologies.

Table 5. Soil-plant relationship indicators (Ind.) used in agricultural sustainability assessments

Ind.	Unit	Description	Measurement method	References
Elto-kg	g/kg	Element consumption per kg produced. Element quantity (e.g., N, P, or K) consumed per kg of harvested product	$\mathrm{Elto-kg} = \frac{\mathrm{g\ EltoA\ m^{-2}}}{\mathrm{kgP\ m^{-2}}}$ *Equation 7* Where *g EltoA* = Mass of the applied element (g); *kgP* = Mass of harvested product (kg)	Van Asselt et al. (2014)
SC	%	Soil coverage determines the number of days in the year when the soil is covered by vegetation (Gómez-Limón & Riesgo, 2009)	$\mathrm{SC} = \frac{\mathrm{dv}}{365} \times 100$ *Equation 8* Where *dv* = Accumulated days of the year in which the soil is covered by vegetation	De Luca et al. (2018), Gaudino et al. (2014), Gómez-Limón & Riesgo (2009), Gómez-Limón & Sánchez-Fernández (2010), Mascarenhas et al. (2010), Neugebauer et al. (2015)
$\mathrm{NPK_{Bal}}$	kg/ha	Nitrogen, phosphorus, or potassium balance is the difference between the amount of N, P or K applied and the amount accumulated in the crop (plants) per unit area. This difference is the amount of N, P, or K that is released into the environment (air, soil, or water) (Gómez-Limón & Riesgo, 2009)	$\mathrm{NPK_{Bal}} = \mathrm{Nf} - \mathrm{Nc}$ *Equation 9* $\mathrm{Nc} = \left(\sum_{o=1}^{n} o_1 + o_2 + o_n\right) \times \mathrm{Pl}$ *Equation 10* Where *Nf* = Quantity of *N, P* or *K* (kg/ha) applied in the form of fertilizers; *Nc* = Quantity of *N, P* or *K* (kg/ha) accumulated in the crop; *O* = Quantity of *N, P* or *K* (kg) accumulated at the end of the cycle in each organ (1, 2, 3, *n*) of the plant; *Pl* = Number of plants in one hectare	Abbona et al. (2007), Bélanger et al. (2012), De Jager et al. (2001), De Olde, Oudshoorn, Bokkers et al. (2016), Gaudino et al. (2014), Gómez-Limón & Riesgo (2009), Gómez-Limón & Sánchez-Fernandez (2010), (Hayati et al. (2010), Hubeau et al. (2017), Kanter et al. (2018), Lebacq et al. (2013), Paracchini et al. (2015), Roy and Chan (2012), Ryan et al. (2016), Smith et al. (2017), Van Passel & Meul (2012)
S-Pr	$\mathrm{m^2/kg}$	Soil--productivity ratio determines the amount of space required to produce one kilogram of harvested product	$\mathrm{S-Pr} = \frac{1\ \mathrm{m^2}}{\mathrm{kgM}}$ *Equation 11* Where *kgM* = Mass of the harvested product (kg)	Gerdessen and Pascucci (2013), Van Asselt et al. (2014)

Source: Elaborated by the authors

Conclusions

Practices such as fertilization, tillage, and irrigation directly impact soil, water bodies, and the atmosphere, so variations in the production system will modify the state of the agroecosystem. This fact has been known for decades, raising questions such as how to assess these variations' impact on the production system or what to do if the impact is adverse. Regarding the first question, sustainability assessment is the most effective mechanism to determine if a crop production method, alternative, or system is environmentally, economically, and socially viable. Some of the indicators used in these assessments are associated with soil properties, processes, composition, and management. Due to its complexity, it is not easy to define which indicators best represent the agricultural production system, giving rise to a list of selection criteria whose application would help define which indicators may be the most suitable.

Agricultural sustainability assessment compares existing production systems, for instance, organic versus conventional or irrigated versus rainfed production systems. It is not common to analyze the sustainability of new alternatives for agricultural production, such as those developed from scientific experimentation, which would help answer the second question (what to do if the impact is adverse).

Sustainability assessments should evaluate at least one indicator per system (soil, soil-water, soil-atmosphere, and soil-plant) to cover all the soil interactions with the environment. In this way, a broader picture of the agricultural production system's impact on the ecosystem can be obtained.

Very few studies refer to land use and crop productivity indicators, even though this relationship reflects the overall system efficiency. Remember that one of the premises of sustainable intensification is to produce more and higher quality crops in smaller areas, which has repercussions not only on soil cover but also on the efficient management of water, inputs, human resources, food security, and the ecosystem in general.

Acknowledgments

The authors want to thank the Ceiba Foundation and the Universidad Nacional de Colombia.

Disclaimers

All authors made significant contributions to the manuscript; they state no conflicts of interest in this study.

References

Abbona, E. A., Sarandón, S. J., Marasas, M. E., & Astier, M. (2007). Ecological sustainability evaluation of traditional management in different vineyard systems in Berisso, Argentina. *Agriculture, Ecosystems and Environment*, *119*(3-4), 335-445. https://doi.org/10.1016/j.agee.2006.08.001

Acar, M., Celik, I., & Günal, H. (2018). Effects of long-term tillage systems on aggregate-associated organic carbon in the eastern Mediterranean region of Turkey. *Eurasian Journal of Soil Science*, *7*(1), 51-58. http://doi.org/10.18393/ejss.335329

Aharonov-Nadborny, R., Tsechansky, L., Raviv, M., & Graber, E. R. (2018). Mechanisms governing the leaching of soil metals as a result of disposal of olive mill wastewater on agricultural soils. *Science of the Total Environment*, *630*, 1115-1123. https://doi.org/10.1016/j.scitotenv.2018.02.270

Arizpe, N., Giampietro, M., & Ramos-Martin, J. (2011). Food security and fossil energy dependence: An international comparison of the use of fossil energy in agriculture (1991-2003). *Critical Reviews in Plant Sciences*, *30*(1-2), 45-63. https://doi.org/10.1080/07352689.2011.554352

Astier, M., Speelman, E. N., López-Ridaura, S., Masera, O. R., & Gonzalez-Esquivel, C. E. (2011). Sustainability indicators, alternative strategies and trade-offs in peasant agroecosystems: Analysing 15 case studies from Latin America. *International Journal of Agricultural Sustainability*, *9*(3), 409-422. https://doi.org/10.1080/14735903.2011.583481

Audsley, E., Alber, S., Clift, R., Cowell, S., Crettaz, P., Gaillard, G., Hausheer, J., Jolliett, O., Kleijn, R., Mortensen, B., Pearce, D., Roger, E., Teulon, H., Weidema, B., & Van Zeijts, H. (2003). *Harmonisation of environmental life cycle assessment for agriculture: final report, Concerted Action AIR3-CT94-2028*. European Commission DG VI -Centre de documentation. https://www.worldcat.org/title/harmonisation-of-environmental-life-cycle-assessment-for-agriculture-final-report-concerted-action-air3-ct94-2028/oclc/500038315

Baggs, E. M. (2011). Soil microbial sources of nitrous oxide: Recent advances in knowledge, emerging challenges and future direction. *Current Opinion in Environmental Sustainability*, *3*(5), 321-327. https://doi.org/10.1016/j.cosust.2011.08.011

Barto, E. K., Alt, F., Oelmann, Y., Wilcke, W., & Rillig, M. C. (2010). Contributions of biotic and abiotic factors to soil aggregation across a land use gradient. *Soil Biology and Biochemistry*, *42*(12), 2316-2324. https://doi.org/10.1016/j.soilbio.2010.09.008

Baush, J. C., Bojórquez, L. T., & Eakin, H. (2014). Agro-environmental sustainability assessment using multicriteria decision analysis and system analysis. *Sustainable Science*, *9*(3), 303-319. https://doi.org/10.1007/s11625-014-0243-y

Bélanger, V., Vanasse, A., Parent, D., Allard, G., & Pellerin, D. (2012). Development of agri-environmental indicators to assess dairy farm sustainability in Quebec, Eastern Canada. *Ecological Indicators*, *23*, 421-430. https://doi.org/10.1016/j.ecolind.2012.04.027

Blanco-Canqui, H., & Lal, R. (2004). Mechanisms of carbon sequestration in soil aggregates. CRC. *Critical Reviews in Plant Sciences*, *23*, 481-504. https://doi.org/10.1080/07352680490886842

Bockstaller, C., Feschet, P., & Angevin, F. (2015). Issues in evaluating sustainability of farming systems with indicators. *Oilseeds & Fats Crops and Lipids*, *22*(1), 102. https://doi.org/10.1051/ocl/2014052

Bockstaller, C., Guichard, L., Keichinger, O., Girardin, P., Galan, M. B., & Gaillard, G. (2009). Comparison of methods to assess the sustainability of agricultural systems. A review. *Agronomy for Sustainable Development*, *29*(1), 223-235. https://doi.org/10.1051/agro:2008058

Bodirsky, B. L., Popp, A., Lotze-Campen, H., Dietrich, J. P., Rolinski, S., Weindl, I., Schmitz, C., Müller, C., Bonsch, M., Humpenöder, F., Biewald, A., & Stevanovic, M. (2014). Reactive nitrogen requirements to feed the world in 2050 and potential to mitigate nitrogen pollution. *Nature Communications*, *5*(1), Article 3858. https://doi.org/10.1038/ncomms4858

Boeckx, P., & Van Cleemput, O. (2001). Estimates of N2O and CH4 fluxes from agricultural lands in various regions in Europe. *Nutrients Cycling in Agroecosystems, 60*, 35-47. https://link.springer.com/article/10.1023/A:1012604032377

Bojacá, C. R., Wyckhuys, K. A. G., & Schrevens, E. (2014). Life cycle assessment of Colombian greenhouse tomato production based on farmer-level survey data. *Journal of Cleaner Production*, *69*, 26-33. https://doi.org/10.1016/j.jclepro.2014.01.078

Bone, J., Head, M., Barraclough, D., Archer, M., Scheib, C., Flight, D., & Voulvoulis, N. (2010). Soil quality assessment under emerging regulatory requirements. *Environmental International, 36*(6), 609-622. https://doi.org/10.1016/j.envint.2010.04.010

Bouma, J., Montanarella, L., & Evanylo, G. (2019). The challenge for the soil science community to contribute to the implementation of the UN Sustainable Development Goals. *Soil Use Management*, *35*(4), 538-546. https://doi.org/10.1111/sum.12518

Bouwman, A. F., Van Der Hoek, K. W., & Olivier, J. G. J. (1995). Uncertainties in the global source distribution of nitrous oxide. *Journal of Geophysical Research*, *100*(D2), 2785-2800. https://doi.org/10.1029/94JD02946

Brentrup, F., Kusters, J., Lammel, J., & Kuhlmann, H. (2000). Methods to estimate on-field nitrogen emissions from crop production as an input to LCA studies in the agricultural sector. *International Journal of Life Cycle Assessment*, *5*(6), 349-357. https://doi.org/10.1006/bbrc.2000.4000

Brunett Pérez, L., González Esquivel, C., & García Hernández, L. A. (2005). Evaluación de la sustentabilidad de dos agroecosistemas campesinos de producción de maíz y leche, utilizando indicadores. *Livestock Research for Rural Development*, *17*(7), Article 78. http://www.lrrd.org/lrrd17/7/pere17078.htm

Camargo, J. A., & Alonso, Á. (2006). Ecological and toxicological effects of inorganic nitrogen pollution in aquatic ecosystems: A global assessment. *Environment International*, *32*(6), 831-849. https://doi.org/10.1016/j.envint.2006.05.002

Cellura, M., Longo, S., & Mistretta, M. (2012). Life Cycle Assessment (LCA) of protected crops: An Italian case study. *Journal of Cleaner Production*, *28*, 56-62. https://doi.org/10.1016/j.jclepro.2011.10.021

Ciais, P., Sabine, C., Bala, G., Bopp, L., Brovkin, V., Canadell, J., Chhabra, A., DeFries, R., Galloway, J., Heimann, M., Jones, C., Quéré, C. L., Myneni, R. B., Piao, S., & Thornton, P. (2013). Carbon and other biogeochemical cycles. In Intergovernmental Panel on Climate Change (IPCC), *Climate change 2013: the physical science basis. Contribution of working group I to the fifth assessment report of the Intergovernmental Panel on Climate Change* (pp. 465-570). Cambridge University Press. http://www.climatechange2013.org/images/report/WG1AR5_Chapter06_FINAL.pdf

Cordell, D., Drangert, J. O., & White, S. (2009). The story of phosphorus: Global food security and food for thought. *Global Environmental Change*, *19*(2), 292-305. https://doi.org/10.1016/j.gloenvcha.2008.10.009

De Jager, A., Onduru, D., van Wijk, M. S., Vlaming, J., & Gachini, G. N. (2001). Assessing sustainability of low-external-input farm management systems with the nutrient monitoring approach: a case study in Kenya. *Agricultural Systems*, *69*(1-2), 99-118. https://doi.org/10.1016/S0308-521X(01)00020-8

De Luca, A. I., Falcone, G., Stillitano, T., Iofrida, N., Strano, A., & Gulisano, G. (2018). Evaluation of sustainable innovations in olive growing systems: A life cycle sustainability assessment case study in southern Italy. *Journal of Cleaner Production*, *171*, 1187-1202. https://doi.org/10.1016/j.jclepro.2017.10.119

De Luca, A. I., Iofrida, N., Leskinen, P., Stillitano, T., Falcone, G., Strano, A., & Gulisano, G. (2017). Life cycle tools combined with multi-criteria and participatory methods for agricultural sustainability: Insights from a systematic and critical review. *Science of the Total Environment*, *595*, 352-370. https://doi.org/10.1016/j.scitotenv.2017.03.284

De Olde, E. M., Oudshoorn, F., Bokkers, E., Stubsgaard, A., Sørensen, C., & De Boer, I. (2016). Assessing the sustainability performance of organic farms in Denmark. *Sustainability*, *8*(9), 957. https://doi.org/10.3390/su8090957

De Olde, E. M., Oudshoorn, F., Sørensen, C., Bokkers, E., & De Boer, I. (2016). Assessing sustainability at farm-level: Lessons learned from a comparison of tools in practice. *Ecological Indicators*, *66*, 391-404. https://doi.org/10.1016/j.ecolind.2016.01.047

Dempster, D. N., Jones, D. L., & Murphy, D. V. (2012). Clay and biochar amendments decreased inorganic but not dissolved organic nitrogen leaching in soil. *Soil Research*, *50*(3), 216-221. https://doi.org/10.1071/SR11316

Dizdaroglu, D., & Yigitcanlar, T. (2014). A parcel-scale assessment tool to measure sustainability through urban ecosystem components: The MUSIX model. *Ecological Indicators*, *41*, 115-130. https://doi.org/10.1016/j.ecolind.2014.01.037

Drechsel, P., Heffer, P., Magen, H., Mikkelsen, R., Singh, H., & Wichelns, D. (2015). Managing water and nutrients to ensure global food security, while sustaining ecosystem services. In P. Drechsel, P. Heffer, H. Magen, R. Mikkelsen, & D. Wichelns (Eds.), *Managing Water and Fertilizer for Sustainable Agricultural Intensification* (1st ed., pp. 1-7). International Fertilizer Industry Association (IFA); International Water Management Institute (IWMI); International Plant Nutrition Institute (IPNI); International Potash Institute (IPI). https://hdl.handle.net/10568/65338

Elkington, J. (1998). Partnerships from cannibals with forks: The triple bottom line of 21st-century business. *Environmental Quality Management*, *8*(1), 37-51. https://doi.org/10.1002/tqem.3310080106

Farahani, E., Emami, H., & Keller, T. (2018). Impact of monovalent cations on soil structure. Part II. Results of two Swiss soils. *International Agrophysics*, *32*(1), 69-80. https://doi.org/10.1515/intag-2016-0092

Foley, J. A., Ramankutty, N., Brauman, K. A., Cassidy, E. S., Gerber, J. S., Johnston, M., Mueller, N. D., O'Connel, C., Ray, D. K., West, P. C., Balzer, C., Bennett, E. M., Carpenter, S. R., Hill, J., Monfreda, C., Polasky, S., Rockström, J., Sheehan, J., Siebert, … Zaks, D. P. M. (2011). Solutions for a cultivated planet. *Nature*, *478*, 337-342. http://doi.org/10.1038/nature10452

Food and Agriculture Organization [FAO]. (2011). *The State of the World's Land and Water Resources for Food and Agriculture. Managing Systems at Risk* (1st ed.). Routledge. http://doi.org/10.4324/9780203142837

Food and Agriculture Organization [FAO]. (2016). *Handbook on agricultural cost of production statistics. Guidelines for data collection, compilation and dissemination* [Publication prepared in the framework of the Global Strategy to improve Agricultural and Rural Statistics]. FAO. http://www.fao.org/3/ca6411en/ca6411en.pdf

Galloway, J. N., Aer, J. D., Erisman, J. W., Seitzinger, S. P., Howarth, R. W., Cowling, E. B., & Cosby, B. J. (2003). The Nitrogen Cascade. *Bioscience*, *53*, 341. https://doi.org/10.1641/0006-3568(2003)053[0341:TNC]2.0.CO;2

Garrigues, E., Corson, M. S., Angers, D. A., Van Der Werf, H. M. G., & Walter, C. (2012). Soil quality in Life Cycle Assessment: Towards development of an indicator. *Ecological Indicators*, *18*, 434-442. https://doi.org/10.1016/j.ecolind.2011.12.014

Gattinger, A., Muller, A., Haeni, M., Skinner, C., Fliessbach, A., Buchmann, N., Mader, P., Stolze, M., Smith, P., Scialabba, N. E. -H., & Niggli, U. (2012). Enhanced top soil carbon stocks under organic farming. *Proceedings of the National Academy of Sciences*, *109*(44), 18226-18231. https://doi.org/10.1073/pnas.1209429109

Gaudino, S., Goia, I., Borreani, G., Tabacco, E., & Sacco, D. (2014). Cropping system intensification grading using an agro-environmental indicator set in northern Italy. *Ecological Indicators*, *40*, 76-89. https://doi.org/10.1016/j.ecolind.2014.01.004

Gerdessen, J. C., & Pascucci, S. (2013). Data envelopment analysis of sustainability indicators of European agricultural systems at regional level. *Agricultural Systems*, *118*, 78-90. https://doi.org/10.1016/j.agsy.2013.03.004

Ghisellini, P., Zucaro, A., Viglia, S., & Ulgiati, S. (2014). Monitoring and evaluating the sustainability of Italian agricultural system. An emergy decomposition analysis. *Ecological Modelling*, *271*, 132-148. https://doi.org/10.1016/j.ecolmodel.2013.02.014

Giles, J. (2005). Nitrogen study fertilizes fears of pollution. *Nature*, *433*(7028), Article 791. https://doi.org/10.1038/433791a

Gómez-Limón, J. A., & Riesgo, L. (2009). Alternative approaches to the construction of a composite indicator of agricultural sustainability: An application to irrigated agriculture in the Duero basin in Spain. *Journal of Environmental Management*, *90*(11), 3345-3362. https://doi.org/10.1016/j.jenvman.2009.05.023

Gómez-Limón, J. A., & Sánchez-Fernández G. (2010). Empirical evaluation of agricultural sustainability using composite indicators. *Ecological Economics*, *69*(5), 1062-1075. https://doi.org/10.1016/j.ecolecon.2009.11.027

Gomiero, T., Pimentel, D., & Paoletti, M. G. (2011). Is There a Need for a More Sustainable Agriculture? CRC. *Critical Reviews in Plant Sciences*, *30*(1-2), 6-23. https://doi.org/10.1080/07352689.2011.553515

Guinée, J. B., Gorree, M., Heijungs, R., Huppes, G., Kleijn, R., De Koning, A., Wegener Sleeswijk, A., Suh, S., Udo de Haes, H. A., De Bruijn, J. A., Van Duin, R., & Huijbregts, M. A. J. (Eds.). (2002). *Handbook on life cycle assessment. Operational guide to the ISO Standards*. Springer. https://www.springer.com/gp/book/9781402002281

Havlin, J. L., Beaton, J. D., Tisdale, S. L., & Nelson, W. L. (2014). *Soil Fertility and Fertilizers: An introduction to nutrient management* (8th ed.). Pearson. https://www.pearson.com/us/higher-education/product/Havlin-Soil-Fertility-and-Fertilizers-An-Introduction-to-Nutrient-Management-7th-Edition/9780130278241.html

Hayati, D., Ranjbar, Z., & Karami, E. (2010). Measuring Agricultural Sustainability. In E. Lichtfouse (Ed.), *Biodiversity, Biofuels, Agroforestry and Conservation Agriculture* (Sustainable Agriculture Reviews, 5, pp. 73-100). Springer. https://doi.org/10.1007/978-90-481-9513-8_2

Heijungs, R., & Guinée, J. B. (2012). An overview of the life cycle assessment method - Past, Present and Future. In M. A. Curran (Ed.), *Life cycle assessment handbook. A guide for environmentally sustainable products* (pp. 15-42). Willey. https://doi.org/10.1021/es101316v

Hirel, B., Tétu, T., Lea, P. J., & Dubois, F. (2011). Improving nitrogen use efficiency in crops for sustainable agriculture. *Sustainability*, *3*(9), 1452-1485. https://doi.org/10.3390/su3091452

Hoang, V. N., & Alauddin, M. (2010). Assessing the eco-environmental performance of agricultural production in OECD countries: The use of nitrogen flows and balance. *Nutrient Cycling in Agroecosystems*, *87*(3), 353-368. https://doi.org/10.1007/s10705-010-9343-y

Hubeau, M., Marchand, F., Coteur, I., Mondelaers, K., Debruyne, L., & Van Huylenbroeck, G. (2017). A new agri-food systems sustainability approach to identify shared transformation pathways towards sustainability. *Ecological Economics*, *131*, 52-63. https://doi.org/10.1016/j.ecolecon.2016.08.019

Intergovernmental Panel on Climate Change [IPCC]. (2013). *Climate change 2013: The physical science basis. Contribution of working group I to the fifth assessment report of the Intergovernmental Panel on Climate Change*. Cambridge University Press. https://www.ipcc.ch/report/ar5/wg1/

Ivushkin, K., Bartholomeus, H., Bregt, A. K., Pulatov, A., Bui, E. N., & Wilford, J. (2018). Soil salinity assessment through satellite thermography for different irrigated and rainfed crops. *International Journal of Applied Earth Observation and Geoinformation*, *68*, 230-237. https://doi.org/10.1016/j.jag.2018.02.004

Kanter, D. R., Musumba, M., Wood, S. L. R., Palm, C., Antle, J., Balvanera, P., Dale, V. H., Havlik, P., Kline, K. L., Scholes, R. J., Thornton, P., Tittonell, P., & Andelman, S. (2018). Evaluating agricultural trade-offs in the age of sustainable development. *Agricultural Systems*, *163*, 73-88. https://doi.org/10.1016/j.agsy.2016.09.010

Karaca, S., Gürses, A., Ejder, M., & Açikyildiz, M. (2004). Kinetic modeling of liquid-phase adsorption of phosphate on dolomite. *Journal of Colloid and Interface Science*, *277*(2), 257-263. https://doi.org/10.1016/j.jcis.2004.04.042

Keesstra, S. D., Bouma, J., Wallinga, J., Tittonell, P., Smith, P., Cerdà, A., Montanarella, L., Quinton, J. N., Pachepsky, Y., Van Der Putten, W. H., Bardgett, R. D., Moolenaar, S., Mol, G., Jansen, B., & Fresco, L. O. (2016). The significance of soils and soil science towards realization of the United Nations sustainable development goals. *Soil*, *2*(2), 111-128. https://doi.org/10.5194/soil-2-111-2016

Khodaverdiloo, H., Momtaz, H., & Liao, K. (2018). Performance of soil cation exchange capacity pedotransfer function as affected by the inputs and database size. *Clean - Soil, Air, Water*, *46*(3). https://doi.org/10.1002/clen.201700670

Kucukvar, M., Egilmez, G., & Tatari, O. (2014). Sustainability assessment of U.S. final consumption and investments: triple-bottom-line input-output analysis. *Journal of Cleaner Production*, *81*, 234-243. https://doi.org/10.1016/j.jclepro.2014.06.033

Laird, D., Fleming, P., Wang, B., Horton, R., & Karlen, D. (2010). Biochar impact on nutrient leaching from a Midwestern agricultural soil. *Geoderma*, *158*(3-4), 436-442. https://doi.org/10.1016/j.geoderma.2010.05.012

Lal, R. (2015). Restoring soil quality to mitigate soil degradation. *Sustainability*, *7*(5), 5875-5895. https://doi.org/10.3390/su7055875

Lebacq, T., Baret, P. V., & Stilmant, D. (2013). Sustainability indicators for livestock farming. A review. *Agronomy for Sustainable Development*, *33*(2), 311-327. https://doi.org/10.1007/s13593-012-0121-x

Lemtiri, A., Colinet, G., Alabi, T., Bodson, B., Olivier, C., Brostaux, Y., Pierreux, J., Haubruge, E., Cluzeau, D., & Francis, F. (2018). Short-term effects of tillage practices and crop residue exportation on soil organic matter and earthworm communities in silt loam arable soil. In M. Á. Muñoz & R. Zornoza (Eds.), *Soil Management and Climate Change: Effects on Organic Carbon, Nitrogen Dynamics, and Greenhouse Gas Emissions* (pp. 53-71). Elsevier. https://doi.org/10.1016/B978-0-12-812128-3.00005-7

Li, L., Du, S., Wu, L., & Liu, G. (2009). An overview of soil loss tolerance. *Catena*, *78*(2), 93-99. https://doi.org/10.1016/j.catena.2009.03.007

Loaiza, P. V, Pujol, P. E. I., Wittwer, R., van der Heijden, M., & Six, J. (2018). Improvement of soil structure through organic crop management, conservation tillage and grass-clover ley. *Soil Tillage Research*, *180*, 1-9. https://doi.org/10.1016/j.still.2018.02.007

Lori, M., Symnaczik, S., Mäder, P., De Deyn, G., & Gattinger, A. (2017). Organic farming enhances soil microbial abundance and activity—A meta-analysis and meta-Regression. *PLoS One*, *12*(7), 1-25. https://doi.org/10.1371/journal.pone.0180442

Marchand, F., Debruyne, L., Triste, L., Gerrard, C., Padel, S., & Lauwers, L. (2014). Key characteristics for tool choice in indicator-based sustainability assessment at farm level. *Ecology and Society*, *19*(3), 46-56. https://doi.org/10.5751/ES-06876-190346

Martínez-Blanco, J., Lehmann, A., Muñoz, P., Antón, A., Traverso, M., Rieradevall, J., & Finkbeiner, M. (2014). Application challenges for the social Life Cycle Assessment of fertilizers within life cycle sustainability assessment. *Journal of Cleaner Production*, *69*, 34-48. https://doi.org/10.1016/j.jclepro.2014.01.044

Mascarenhas, A., Coelho, P., Subtil, E., & Ramos, T. B. (2010). The role of common local indicators in regional sustainability assessment. *Ecological Indicators*, *10*(3), 646-656. https://doi.org/10.1016/j.ecolind.2009.11.003

Meul, M., Passel, S., Nevens, F., Dessein, J., Rogge, E., Mulier, A., & Hauwermeiren, A. (2008). MOTIFS: a monitoring tool for integrated farm sustainability. *Agronomy for Sustainable Development*, *28*(2), 321-332. https://doi.org/10.1051/agro:2008001

Milder, J. C., Arbuthnot, M., Blackman, A., Brooks, S. E., Giovannucci, D., Gross, L., Kennedy, E. T., Komives, K., Lambin, E. F., Lee, A., Meyer, D., Newton, P., Phalan, B., Schroth, G., Semroc, B., Van Rikxoort, H., & Zrust, M. (2014). An agenda for assessing and improving conservation impacts of sustainability standards in tropical agriculture. *Conservation Biology*, *29*(2), 309-320. https://doi.org/10.1111/cobi.12411

Mtengeti, E. J., Brentrup, F., Mtengeti, E., Olav, E. L., & Chambuya, R. (2015). Sustainable intensification of maize and rice in smallholder farming systems under climate change in Tanzania. In D.L. Mwaseba, D. Kraybill, D.O. Hansen, & L. Olav (Eds.), *Sustainable Intensification to Advance Food Security and Enhance Climate Resilience in Africa* (1st ed., pp. 441-465). Springer. https://link.springer.com/chapter/10.1007/978-3-319-09360-4_24

Nambiar, K. K. M., Gupta, A. P., Fu, Q., & Li, S. (2001). Biophysical, chemical and socio-economic indicators for assessing agricultural sustainability in the Chinese coastal zone. *Agriculture, Ecosystems and Environment*, *87*(2), 209-214. https://doi.org/10.1016/S0167-8809(01)00279-1

Neugebauer, S., Martinez-Blanco, J., & Finkbeiner, M. (2015). Enhancing the practical implementation of life cycle sustainability assessment - proposal of a Tiered approach. *Journal of Cleaner Production*, *102*, 165-176. https://doi.org/10.1016/j.jclepro.2015.04.053

Nieder, R., & Benbi, D. K. (2008). *Carbon and Nitrogen in the Terrestrial Environment*. Springer. https://doi.org/10.1007/978-1-4020-8433-1

Oertel, C., Matschullat, J., Zurba, K., Zimmermann, F., & Erasmi, S. (2016). Greenhouse gas emissions from soils–A review. *Geochemistry*, *76*(3), 327-352. https://doi.org/10.1016/j.chemer.2016.04.002

Okalebo, J. R., Gathua, K. W., & Woomer, P. L. (1993). *Laboratory methods of soil and plant analysis: a working manual.* Tropical Soil Biology and Fertility Programme. https://www.worldcat.org/title/laboratory-methods-of-soil-and-plant-analysis-a-working-manual/oclc/51374874

Oldeman, L. (1994). The global extent of soil degradation. *Soil Resilience and Sustainable Land Use*, 19-36. https://doi.org/10.1016/j.apsoil.2013.10.002

Pacini, C., Wossink, A., Giesen, G., Vazzana, C., & Huirne, R. (2003). Evaluation of sustainability of organic, integrated and conventional farm systems: a farm and field scale analysis. *Agriculture, Ecosystems and Environment*, *95*(1), 273-288. https://doi.org/10.1016/S0167-8809(02)00091-9

Paracchini, M. L., Bulgheroni, C., Borreani, G., Tabacco, E., Banterle, A., Bertoni, D., Rossi, G., Parolo, G., Origgi, R., & De Paola, C. (2015). A diagnostic system to assess sustainability at a farm level: The SOSTARE model. *Agricultural Systems*, *133*, 35-53. https://doi.org/10.1016/j.agsy.2014.10.004

Peano, C., Migliorini, P., & Sottile, F. (2014). A methodology for the sustainability assessment of agri-food systems: An application to the slow food presidia project. *Ecology and Society*, *19*(4), 24. https://doi.org/10.5751/ES-06972-190424

Pergola, M., D'Amico, M., Celano, G., Palese, A. M., Scuderi, A., Di Vita, G., Pappalardo, G., & Inglese, P. (2013). Sustainability evaluation of Sicily's lemon and orange production: An energy, economic and environmental analysis. *Journal of Environmental Management*, *128*, 674-682. https://doi.org/10.1016/j.jenvman.2013.06.007

Pollesch, N., & Dale, V. H. (2015). Applications of aggregation theory to sustainability assessment. *Ecological Economics*, *114*, 117-127. https://doi.org/10.1016/j.ecolecon.2015.03.011

Praneetvatakul, S., Janekarnkij, P., Potchanasin, C., & Prayoonwong, K. (2001). Assessing the sustainability of agriculture: A case of Mae Chaem Catchment, northern Thailand. *Environment International*, *27*, 103-109. https://doi.org/10.1016/S0160-4120(01)00068-X

Rawashdeh, R. A., & Maxwell, P. (2014). Analysing the world potash industry. *Resources Policy*, *41*, 143-151. https://doi.org/10.1016/j.resourpol.2014.05.004

Rawashdeh, R. A., Xavier-Oliveira, E., & Maxwell, P. (2016). The potash market and its future prospects. *Resources Policy*, *47*, 154-163. https://doi.org/10.1016/j.resourpol.2016.01.011

Repar, N., Jan, P., Dux, D., Nemecek, T., & Doluschitz, R. (2017). Implementing farm-level environmental sustainability in environmental performance indicators: A combined global-local approach. *Journal of Cleaner Production*, *140*(Part 2), 692-704. https://doi.org/10.1016/j.jclepro.2016.07.022

Rinne, J., Lyytimäki, J., & Kautto, P. (2013). From sustainability to well-being: Lessons learned from the use of sustainable development indicators at national and EU level. *Ecological Indicators*, *35*, 35-42. https://doi.org/10.1016/j.ecolind.2012.09.023

Rockström, J., Williams, J., Daily, G., Noble, A., Matthews, N., Gordon, L., Wetterstrand, H., DeClerck, F., Shah, M., Steduto, P., de Fraiture, C., Hatibu, N., Unver, O., Bird, J., Sibanda, L., & Smith, J. (2017). Sustainable intensification of agriculture for human prosperity and global sustainability. *Ambio*, *46*(1), 4-17. https://doi.org/10.1007/s13280-016-0793-6

Rodrigues, G. S., Rodrigues, I. A., Buschinelli, C. C. de A., & de Barros, I. (2010). Integrated farm sustainability assessment for the environmental management of rural activities. *Environmental Impact Assessment Review*, *30*(4), 229-239. https://doi.org/10.1016/j.eiar.2009.10.002

Römheld, V., & Kirkby, E. A. (2010). Research on potassium in agriculture: Needs and prospects. *Plant and Soil*, *335*(1-2), 155-180. https://doi.org/10.1007/s11104-010-0520-1

Roy, R., & Chan, N. W. (2012). An assessment of agricultural sustainability indicators in Bangladesh: Review and synthesis. *Environmentalist*, *32*(1), 99-110. https://doi.org/10.1007/s10669-011-9364-3

Ryan, M., Hennessy, T., Buckley, C., Dillon, E. J., Donnellan, T., Hanrahan, K., & Moran, B. (2016). Developing farm-level sustainability indicators for Ireland using the Teagasc National Farm Survey. *Irish Journal of Agricultural and Food Research*, *55*(2), 112-125. https://doi.org/10.1515/ijafr-2016-0011

Sadok, W., Angevin, F., Bergez, J. E., Bockstaller, C., Colomb, B., Guichard, L., Reau, R., Messéan, A., & Doré, T. (2009). MASC, a qualitative multi-attribute decision model for ex ante assessment of the sustainability of cropping systems. *Agronomy for Sustainable Development*, *29*(3), 447-461. https://doi.org/10.1051/agro/2009006

Sarkar, D., & Haldar, A. (2005). Physical and chemical methods in soil analysis. Fundamental concepts of analytical chemistry and instrumental techniques. *New Age International Publishers*. https://www.worldcat.org/title/physical-and-chemical-methods-in-soil-analysis-fundamental-concepts-of-analytical-chemistry-and-instrumental-techniques/oclc/369173262

Schader, C., Baumgart, L., Landert, J., Muller, A., Ssebunya, B., Blockeel, J., Weisshaidinger, R., Petrasek, R., Mészáros, D., Padel, S., Gerrard, C., Smith, L., Lindenthal, T., Niggli, U., & Stolze, M. (2016). Using the Sustainability Monitoring and Assessment Routine (SMART) for the systematic analysis of trade-offs and synergies between sustainability dimensions and themes at farm level. *Sustainability*, *8*(3), 1-20. https://doi.org/10.3390/su8030274

Schader, C., Grenz, J., Meier, M. S., & Stolze, M. (2014). Scope and precision of sustainability assessment approaches to food systems. *Ecology and Society*, *19*(3), 42-57. https://doi.org/10.5751/ES-06866-190342

Schaufler, G., Kitzler, B., Schindlbacher, A., Skiba, U., Sutton, M. A., & Zechmeister-Boltenstern, S. (2010). Greenhouse gas emissions from European soils under different land use: Effects of soil moisture and temperature. *European Journal of Soil Science*, *61*(5), 683-696. https://doi.org/10.1111/j.1365-2389.2010.01277.x

Blume, H. P., Brümmer, G. W., Horn, R., Kandeler, E., Kögel-Knabner, I., Kretzschmar, R., Schad, P., Stahr, K., Wilke, B. -M. (2016). *Scheffer/Schachtschabel Soil Science* (1st ed.). Springer. http://doi.org/10.1007/978-3-642-30942-7

Schindler, J., Graef, F., & König, H. J. (2015). Methods to assess farming sustainability in developing countries. A review. *Agronomy for Sustainable Development*, *35*(3), 1-15. https://doi.org/10.1007/s13593-015-0305-2

Shayler, H., McBride, M., & Harrison, E. (2009). *Sources and impacts of contaminants in soils* [Fact sheet]. Cornell Waste Management Institute. https://hdl.handle.net/1813/14282

Smith, A., Snapp, S., Chikowo, R., Thorne, P., Bekunda, M., & Glover, J. (2017). Measuring sustainable intensification in smallholder agroecosystems: A review. *Global Food Security*, *12*, 127-138, http://doi.org/10.1016/j.gfs.2016.11.002

Smith, P., Martino, D., Cai, Z., Gwary, D., Janzen, H., Kumar, P., McCarl, B., Ogle, S., O'Mara, F., Rice, C., Scholes, B., Sirotenko, O., Howden, M., McAllister, T., Pan, G., Romanenkov, V., Schneider, U., Towprayoon, S., Wattenbach, M., & Smith, J. (2008). Greenhouse gas mitigation in agriculture. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *363*, 789-813. https://doi.org/10.1098/rstb.2007.2184

Soussana, J. F. (2014). Research priorities for sustainable agri-food systems and life cycle assessment. *Journal of Cleaner Production*, *73*, 19-23. https://doi.org/10.1016/j.jclepro.2014.02.061

Spiertz, J. H. J. (2010). Nitrogen, sustainable agriculture and food security. A review. *Agronomy for Sustainable Development*, *30*, 43-55. https://doi.org/10.1051/agro:2008064

Stavi, I., & Lal, R. (2013). Agriculture and greenhouse gases, a common tragedy. A review. *Agronomy for Sustainable Development*, *33*(2), 275-289. https://doi.org/10.1007/s13593-012-0110-0

Therond, O., Duru, M., Roger-Estrade, J., & Richard, G. (2017). A new analytical framework of farming system and agriculture model diversities. A review. *Agronomy for Sustainable Development*, *37*(3), 21. https://doi.org/10.1007/s13593-017-0429-7

Tilman, D., Cassman, K. G., Matson, P. A., Naylor, R., & Polasky, S. (2002). Agricultural sustainability and intensive production practices. *Nature*, *418*(6898), 671-677. https://doi.org/10.1038/nature01014

Tittonell, P. (2014). Ecological intensification of agriculture-sustainable by nature. *Current Opinion in Environmental Sustainability*, *8*, 53-61. https://doi.org/10.1016/j.cosust.2014.08.006

Torrellas, M., Antón, A., & Montero, J. I. (2013). An environmental calculator for greenhouse production systems. *Journal of Environmental Management*, *118*, 186-195, https://doi.org/10.1016/j.jenvman.2013.01.011

Tóth, G., Hermann, T., da Silva, M. R., & Montanarella, L. (2018). Monitoring soil for sustainable development and land degradation neutrality. *Environmental Monitoring and Assessment*, *190*(2), Article 57. https://doi.org/10.1007/s10661-017-6415-3

Tricase, C., Lamonaca, E., Ingrao, C., Bacenetti, J., & Lo Giudice, A. (2018). A comparative life cycle assessment between organic and conventional barley cultivation for sustainable agriculture pathways. *Journal of Cleaner Production*, *172*, 3747-3759. https://doi.org/10.1016/j.jclepro.2017.07.008

Triste, L., Marchand, F., Debruyne, L., Meul, M., & Lauwers, L. (2014). Reflection on the development process of a sustainability assessment tool: learning from a Flemish case. *Ecology and Society*, *19*(3), 47-57. https://doi.org/10.5751/ES-06789-190347

Ulén, B., Larsbo, M., Koestel, J., Hellner, Q., Blomberg, M., & Geranmayeh, P. (2018). Assessing strategies to mitigate phosphorus leaching from drained clay soils. *Ambio*, *47*(S1), 114-123. https://doi.org/10.1007/s13280-017-0991-x

Umar A. S., & Iqbal, M. (2007). Nitrate accumulation in plants, factors affecting the process and human health implications. A review. *Agronomy for Sustainable Development*, *27*(1), 45-57, http://doi.org/10.1051/agro:2006021

Usman, M., Ibrahim, F., & Oyetola, S. O. (2018). Sustainable agriculture in relation to problems of soil degradation and how to amend such soils for optimum crop production in Nigeria. *International Journal for Research in Agricultural and Food Science*, *4*, 1-17. http://gnpublication.com/index.php/afs/article/view/471

Van Asselt, E. D., Van Bussel, L. G. J., Van der Voet, H., Van der Heijden, G. W. A. M., Tromp, S. O., Rijgersberg, H., Van Evert, F., & Van Wagenberg, C. P. A. (2014). A protocol for evaluating the sustainability of agri-food production systems–A case study on potato production in peri-urban agriculture in The Netherlands. *Ecological Indicators*, *43*, 315-321. https://doi.org/10.1016/j.ecolind.2014.02.027

Van Capelle, C., Schrader, S., & Brunotte, J. (2012). Tillage-induced changes in the functional diversity of soil biota – A review with a focus on German data. *European Journal of Soil Biology*, *50*, 165-181. https://doi.org/10.1016/j.ejsobi.2012.02.005

Van Passel, S., & Meul, M. (2012). Multilevel and multi-user sustainability assessment of farming systems. *Environmental Impact Assessment Review*, *32*(1), 170-180. https://doi.org/10.1016/j.eiar.2011.08.005

Verheijen, F. G. A., Jones, R. J. A., Rickson, R. J., & Smith, C. J. (2009). Tolerable versus actual soil erosion rates in Europe. *Earth-Science Reviews*, *94*(1-4), 23-38. https://doi.org/10.1016/j.earscirev.2009.02.003

Verhulst, N., François, I., & Govaerts, B. (2010). Conservation agriculture, improving soil quality for sustainable production systems? In L. Rattan, & B.A. Stewart (Eds.), *Advances in Soil Science: Food Security and Soil Quality* (pp.137-208). Taylor & Francis Group. http://repository.cimmyt.org/xmlui/bitstream/handle/10883/4732/97756.pdf?sequence=1

Walkley, A., & Black, I. A. (1934). An examination of the degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. *Soil Science*, *37*(1), 29-38. https://doi.org/10.1097/00010694-193401000-00003

Walraevens, K., Tewolde, T. G., Amare, K., Hussein, A., Berhane, G., Baert, R., Ronsse, S., Kebede, S., Van Hulle, L., Deckers, J., Martens, K., & Van Camp, M. (2015). Water balance components for sustainability assessment of groundwater-dependent agriculture: example of the Mendae plain (Tigray, Ethiopia). *Land Degradation and Development*, *26*(7), 725-736. https://doi.org/10.1002/ldr.2377

Wang, Y., Fan, J., Cao, L., Zheng, X., Ren, P., & Zhao, S. (2018). The influence of tillage practices on soil detachment in the red soil region of China. *Catena*, *165*, 272-278. https://doi.org/10.1016/j.catena.2018.02.011

Weidema, B. P., & Meeusen, M. J. G. (Eds.). (2000). *Agricultural data for life Cycle Assessments* (Vol. 1). Agricultural Economics Research Institute (LEI). https://www.researchgate.net/publication/268044707_IV_Agricultural_data_for_Life_Cycle_Assessments

Weldeslassie, T., Naz, H., Singh, S., & Oves, M. (2018). Chemical contaminants for soil, air, and aquatic ecosystem. In M. Oves, M.Z. Khan, & I.M.I. Ismail (Eds.), *Modern age environmental problems and their remediation* (1st ed.). Springer. http://doi.org/10.1007/978-3-319-64501-8

West, T. O., & Marland, G. (2002). A synthesis of carbon sequestration, carbon emissions, and net carbon flux in agriculture: Comparing tillage practices in the United States. *Agriculture, Ecosystems & Environment*, *91*(1-3), 217-232. https://doi.org/10.1016/S0167-8809(01)00233-X

Yao, Y., Gao, B., Zhang, M., Inyang, M., & Zimmerman, A. R. (2012). Effect of biochar amendment on sorption and leaching of nitrate, ammonium, and phosphate in a sandy soil. *Chemosphere*, *89*(11), 1467-1471. https://doi.org/10.1016/j.chemosphere.2012.06.002

Zörb, C., Senbayram, M., & Peiter, E. (2014). Potassium in agriculture - Status and perspectives. *Journal of Plant Physiology*, *171*(9), 656-669. https://doi.org/10.1016/j.jplph.2013.08.008