Chapter

Harnessing Soil Potential: Innovation in Strategic Tillage and Management - New Perspectives

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Abstract

The sustainability of the environment and the productivity of agriculture are both critically dependent on soil. Maximizing agricultural yields while reducing agriculture's negative environmental effects is becoming more and more important as the world's population continues to expand. Innovating tillage and management techniques to harness the potential of the soil is a topic that is explored in this chapter. The first section of the chapter describes the difficulties that contemporary agriculture faces, such as soil erosion, nutrient depletion, and water shortages. The part new technology has played in managing soil. Making educated management decisions is made easier by using precision agricultural technology like soil sensors, remote sensing, and geographic information systems (GIS). These technologies provide useful insights into soil variability. It emphasizes how crucial it is to implement sustainable soil management techniques in order to guarantee long-term agricultural output and ecological harmony. The chapter's conclusion emphasizes the need of maximizing soil potential through creative methods of tactical tillage and management. Agricultural systems may raise crop yield, lessen their environmental effect, and become more resilient to climate change by using sustainable soil practises, assuring a more sustainable and food-secure future.

Keywords: sustainability, innovative tillage, nutrient depletion, remote sensing, soil potential

1. Introduction

Degraded soil and less ecosystem services, which in turn promotes unsustainable agricultural development [1]. This is true even though intensive agriculture is crucial for meeting the world's growing food demand [2]. One of the most important anthropogenic activities that have had a substantial impact on soil health is the intensive use of farms and tillage practices. A key issue affecting the sustainability and productivity of the soil is the degradation of the soil's health brought on by multiple-cropping systems and tillage. Tillage intensive cropping practices have deteriorated soil chemical, physical, and biological characteristics and decreased soil organic carbon (SOC) levels [3]. Soil ecosystems to function and perform sustainably, it is essential to safeguard and improve soil function and health [4, 5]. It is possible to establish whether diverse soil management strategies have the necessary effectiveness for soil functions and productivity if multiple soils attributes and processes are merged into a single estimate value of soil health [6, 7]. The effect of the tillage system on soil characteristics must be taken into account in order to maintain soil fertility and assess the sustainability of agricultural systems [8–10]. By using a system of soil minimal tillage, the amount of larger vegetal leftovers (minimum 30%) that are left at the soil surface and in the upper 10–20 cm layers of the soil, in various phases of decomposition, shows an increasing tendency. Through the use of minimal systems, humus determination after 4 years shows an increasing trend, with an increase of up to about 0.41%. Conservative agriculture impacted on organic carbon accumulates in soil at a rate between 0.27 and 1.10 tha^{-1} $year^{-1}$ [11–15] which ultimately improve the soil health. Strategic tillage is a practice in agriculture that involves the targeted and purposeful manipulation of soil through mechanical means to achieve specific objectives. It encompasses various techniques used for soil preparation before planting and for managing soil conditions after planting. Tillage tools are employed to bring about desired effects such as pulverization, cutting, or movement of the soil. The primary goals of strategic tillage are to enhance soil structure, control weeds, manage crop residues, improve water intake and storage, facilitate root development, and promote optimal growing conditions for crops [16].

2. Fundamentals of strategic tillage

Strategic tillage involves different types of tillage operations, including primary tillage and secondary tillage. Primary tillage is performed to break and loosen the soil for a significant depth, typically ranging from 15 to 90 cm (6–36 inches). It includes various equipment such as moldboard plows, disk plows, rotary plows, chisel plows, and subsoil plows [17]. These tools are used based on the soil type, the desired depth of tillage, and the specific objectives of the tillage operation.

2.1 Key principles and objectives

The key principles and objectives of strategic tillage can be summarized as follows:

(i) *Soil structure modification*: strategic tillage aims to improve soil structure by creating desirable conditions for optimal plant growth. This helps in creating an environment conducive to root development and moisture retention [18]. Strategic tillage, according to research, can drastically affect soil structure and porosity, resulting in better water transport and root growth [19, 20]. It can contribute to the long-term sustainability and productivity of agricultural systems [21]. Research studies have indicated that strategic tillage can improve soil biological activity, increase nutrient availability, and enhance soil organic carbon content [22]. (ii) *Weed control*: tillage plays a crucial role in weed management by disrupting weed growth, burying weed seeds, and uprooting established weeds [16]. Studies have demonstrated the effectiveness of strategic tillage in suppressing weed populations and reducing weed biomass [23, 24]. Tillage plays a crucial role in controlling weeds. Strategic tillage practices, such as timely tillage operations and burying weed seeds, can help reduce weed populations and minimize the need for herbicides [25]. (iii) *Crop residue management*: strategic tillage helps incorporate agricultural byproducts in the ground, facilitating their decomposition and nutrient release [26]. Strategic tillage facilitates the incorporation of crop residues and soil modifications such as lime and manure, into the soil. This helps distribute nutrients more evenly, improves nutrient availability to plants, and reduces nutrient losses through runoff [27]. Strategic farming, according to research, can improve the breakdown of crop residues, leading to improved nutrient cycling and soil organic matter content [28]. (iv) *Water intake and storage*: strategic tillage optimizes the uptake, storage, and transfer of water in the soil profile by enhancing soil structure. It promotes better water infiltration, reduces runoff, and increases water-holding capacity, thus mitigating the risks of drought stress and improving crop water-use efficiency [29]. (v) *Root zone deepening*: strategic tillage can help break through compacted layers, such as hardpans, and enhance root penetration into the subsoil. This enables crops to access deeper water reserves and nutrients, leading to improved yields and plant health [30]. (vi) *Integrated weed and pest management*: strategic tillage can be integrated into broader weed and pest management strategies. By disrupting weed life cycles and providing favorable conditions for natural predators, tillage can contribute to reducing the reliance on herbicides and pesticides [31]. Studies have highlighted the potential of strategic tillage in integrated weed management approaches, leading to reduced herbicide use and improved weed control [32].

3. Recent innovations in tillage equipment

3.1 Modern tillage equipment

Modern tillage equipment has seen several advancements in recent years, aiming to improve efficiency, soil health, and sustainability in agricultural practices. Some notable innovations include:

(i) *Strip-till rigs*: strip-tillage is gaining popularity as a conservation-minded practice. Strip-till rigs are designed to till narrow strips, typically 6–12 inches wide, between rows. This approach reduces soil erosion, speeds up soil warming, conserves energy and fuel, and maintains higher levels of soil organic matter [33]. (ii) *Vertical-tillage implements*: with vertical tillage, crop residue is broken down and the top 2–3 inches of soil are loosen. It improves soil contact with residue, enhances infiltration, reduces runoff, and creates more uniform field conditions. The advantages of traditional disks, vertical tillage, and soil-finishing products have been combined into a single device by equipment manufacturers [34]. (iii) *Rotary finishers*: rotary finishers are innovative tools used for soil conditioning. They incorporate rotary harrows or rolling baskets to further refine the soil surface after primary tillage operations. These implements help improve seedbed preparation, promote soil structure, and enhance moisture retention [35]. (iv) *Soil conditioners*: soil conditioners are specialized machines used to enhance soil quality. They can incorporate organic matter into the soil, break up compacted layers, and improve soil structure. Soil conditioners help promote root growth, increase nutrient availability, and optimize water infiltration [36].

3.2 Precision tillage tools and implements

Precision tillage focuses on precise control of tillage operations to optimize seedbed conditions, minimize soil disturbance, and preserve soil structure. Some recent innovations in precision tillage tools and implements include: (a) *TruSet technology*: advanced precision control systems like TruSet technology allow farmers to adjust shank depth in small increments (e.g., 0.10 inch) from the tractor cab. These systems offer precise depth control and can optimize tillage operations based on soil conditions and crop requirements [37]. (b) *Reduced-till implements*: reduced-till implements, such as chisel plows and disk rippers, have gained popularity due to their ability to perform efficient tillage while minimizing soil disturbance. These implements allow farmers to maintain residue cover, reduce erosion, and conserve soil moisture [38].

3.3 Conservation tillage machinery

Conservation tillage focuses on minimizing soil disturbance and maintaining residue cover to protect soil health and reduce erosion. Recent innovations in conservation tillage machinery include:

(i) *No-till seeders/drills*: no-till seeders or drills are designed to plant seeds directly into untilled soil, leaving crop residue undisturbed. These machines have precise seed placement mechanisms that help ensure optimal seed-to-soil contact while preserving soil structure and minimizing erosion risks [39]. (ii) *Cover crop inter-seeding equipment*: inter-Seeding cover crops between cash crop rows is an effective conservation practice. Specialized equipment has been developed to accurately seed cover crops in standing cash crops without causing significant disturbance. This approach enhances soil health, reduces weed pressure, and improves nutrient cycling [40].

3.4 No-till and reduced-till systems

No-till and reduced-till systems have gained traction as sustainable alternatives to intensive tillage. Recent developments in these systems include: *No-till planters*: no-till planters are equipped with features that enable precise seed placement into untilled soil. They typically incorporate residue managers, row cleaners, and depth control mechanisms to facilitate successful planting while preserving soil structure and moisture [41]. *Conservation-ready tractors*: manufacturers have introduced tractors equipped with specialized features for conservation tillage, such as advanced guidance systems, reduced compaction tire technology, and variable-rate planting capabilities. These tractors offer improved efficiency and precision in implementing no-till and reduced-till practices [42].

4. Soil health improvement techniques

Utilizing cover crops is one method for enhancing soil health and environmental quality [43]. When the primary cash crops are not growing, certain crops, referred to as cover crops, are planted instead. These cover crops were chosen because of their range of beneficial effects on the soil.

Benefits of cover cropping for soil health improvement: 1. *Erosion control*: cover crops help to minimize soil erosion by providing ground cover and protecting the soil surface from wind and water erosion [44]. The risk of soil loss is decreased by the roots of cover crops holding the soil particles together. 2. *Nutrient management*: by scavenging and absorbing surplus nutrients from the soil, cover crops can stop these nutrients from evaporating into groundwater or being lost through runoff. Following the termination of the cover crops and their incorporation into the soil, the released nutrients become available for the succeeding cash crops [45]. 3. *Adding organic matter*: cover crops decompose and increase the amount of organic matter in the soil. Organic matter enhances the soil's structure, ability to retain water and nutrients, microbial activity, and overall health [46]. 4. *Controlling weed growth*: cover crops can inhibit the growth of weeds by competing with them for sunlight, nutrients, and space. Herbicides and manual weed management are not necessary because of the dense cover crop canopy's ability to shade out emerging weeds and these crops also have allopathic effects [47]. 5. *Biological diversity*: cover crops enhance soil microbiome [48]. Beneficial insects, earthworms, and other soil organisms can find a home and food source in cover crops. These species support healthy soil ecosystems, pest management, and nutrient cycling [49]. 6. *Controlling soil moisture*: some cover crops, like legumes, have deep roots that can improve the soil's structure and drainage. By lowering evaporation from the soil surface, they also assist in conserving soil moisture [50]. Considerations for cover crop implementation should include the regional climate, the kind of soil, and any special goals for soil development [51]. Different cover crop varieties and species can be adapted to meet certain requirements for soil health and work with crop rotation systems [52].

5. Soil amendment and fertilization practices

By promoting soil fertility, nutrient availability, and general soil structure, soil amendment and fertilization practices are essential for enhancing soil health. The following are some essential components of fertilization and soil amendment techniques and how they help to promote soil health: *organic matter addition*: rich sources of organic matter include crop wastes, compost, and manure, improved soil structure, moisture retention, and nutrient-holding capacity [53]. Additionally, feeding beneficial soil organisms, organic matter encourages microbial diversity and activity. *Refueling with nutrients*: fertilizers are used to replenish vital nutrients that the soil may be lacking. In addition to secondary macronutrients like calcium, magnesium, and sulfur, as well as micronutrients like iron, zinc, and manganese, among others, the primary macronutrients for plant growth are nitrogen (N), phosphorus (P), and potassium (K) [54]. Crops are guaranteed to acquire enough nutrients for the best development and production when fertilization is properly balanced. *Nutrient cycling and recycling*: cycling and recycling of nutrients in the soil ecosystem are made possible by organic fertilizers and soil amendments. As nutrients are released through the breakdown of organic materials, plants may now absorb them [55]. By transforming and moving nutrients through biological, chemical, and physical processes, nutrient cycling helps to increase nutrient usage efficiency while minimizing nutrient losses. *pH adjustment*: soil amendments can assist with pH adjustment, which impacts the availability of nutrients. In alkaline soils, elemental sulfur or acidic organic materials can be used to reduce soil pH, whereas lime is frequently used to raise soil pH in acidic soils [56]. The availability and uptake of nutrients by plants are maximized when soil pH is kept at the right level [57]. *Microbial activity promotion*: organic fertilizers and soil additives give beneficial soil microorganisms a home and a food source. These microorganisms, which include bacteria, fungi, and earthworms, support the Composting of organic materials, nutrient cycling, and the prevention of disease. Improved soil structure, nutrient availability, and general soil health are all benefits of healthy microbial communities [58]. *Sustainable nutrient management*: this seeks to lessen nutrient losses that could harm ecosystems and water quality, such as leaching or runoff. Improved fertilizer input rates, timing, and locations can be achieved by split applications, precision farming, and soil testing, all of which reduce adverse environmental consequences and increase soil health. It is crucial to remember that fertilization and soil amendment techniques should be adjusted to the particular requirements and characteristics of the soil and the crops being grown. Effective and long-term maintenance of soil fertility requires soil testing, nutrient management strategies, and adherence to recommended application rates. Additionally, adopting practices like organic farming, crop rotation, and cover crops can enhance soil health and long-term sustainability by working in conjunction with soil amendment and fertilization techniques.

6. Precision agriculture and soil mapping

Precision farming, often referred to as agricultural precision or smart farming, is a cutting-edge method of managing agriculture that makes use of technology to enhance production, efficiency, and sustainability in farming practices [59]. It entails utilizing a variety of technologies to gather and analyze data in order to give farmers all the knowledge they need to manage their crops and livestock. Several crucial technologies for accurate agriculture include:

1. Global positioning system (GPS) technology: GPS enables precise mapping and tracking of agricultural machinery and field operations [60]. This aids farmers in maximizing planting, irrigation, and harvesting, ensuring that each process is carried out precisely and with the least amount of overlap possible.

2. Geographic information system (GIS): GIS creates precise maps of farmers' fields by fusing information from GPS with additional geographic information. They can use this information to recognize variations in soil types, moisture levels, and other characteristics, allowing for management techniques that are site-specific.

3. Real-time information on crop health, water stress, and insect infestations can be obtained via remote sensing devices [61], like satellites and drones. Producers can use this knowledge to spot problems early and execute targeted treatments.

4. Soil sensors are used in the field to detect vital characteristics such as soil moisture, nutrient levels, pH, and others. With the aid of this information, farmers can accurately apply fertilizer and irrigation, minimizing waste and maximizing crop development.

5. Weather monitoring: farmers can make educated decisions about planting, harvesting, and other significant operations by using weather stations on the farm or having an understanding of local meteorological data [62].

6. With the help of a technology known as variable rate technology (VRT), farmers can adjust the rates at which inputs like insecticides are used and fertilizers are applied based on the particular requirements of various fields [63]. This limits abuse while reducing environmental effects and increasing production.

7. Automated machinery: autonomous or semi-autonomous machinery can carry out operations with great precision, such as planting, spraying, and harvesting, which lowers labor expenses.

8. Internet of Things (IoT) devices, including sensors and actuators, are utilized to remotely control and automate a range of farming operations while giving real-time data [64] to their scalable and environmentally friendly capabilities [65]. These tools deliver insightful infoPrecision farming, often referred to as agricultural precision or smart farming, is a cutting-edge method of managing agriculture that makes use of technology to enhance production, efficiency, and sustainability in farming practices [59]. It entails utilizing a variety of technologies to gather and analyze data in order to give farmers all the knowledge they need to manage their crops and livestock.

7. Soil erosion processes

Water erosion, wind erosion, tillage erosion, and soil loss during crop harvesting are the typical classifications of soil erosion (sometimes known as "harvest erosion"). The primary driver distinguishes the various erosion kinds, as indicated by the nomenclature. Water (such as precipitation and snowmelt) is the primary cause of water erosion, and its various forms include sheet erosion, rill erosion, and gully erosion [66]. Wind, the main driver of wind erosion, causes many types of soil transport, including creeping, saltation, and suspension, depending on the particle size [67]. The type of tillage tool being used (such as a mouldboard plow or chisel plow) affects how much dirt is moved throughout the plowing process [68]. Soil loss occurs during crop harvesting when crops are harvested and the harvested product comes into touch with the soil directly, as in the case of sugar beet and potatoes [69]. Although all types of soil erosion are significant environmental processes, the number of peer-reviewed papers is drastically out of proportion as shown in **Figure 1**. While water erosion

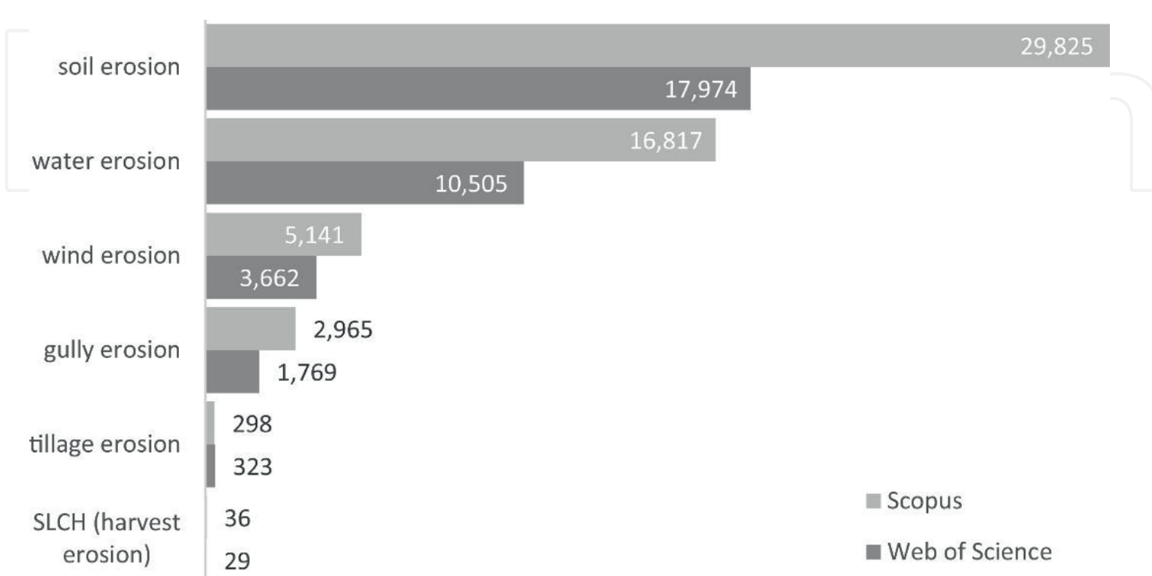
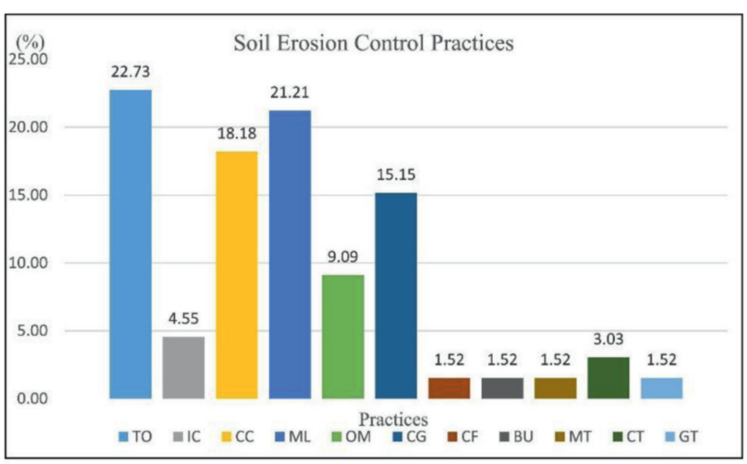


Figure 1.
Number of peer-reviewed publications on the subject of soil erosion (Web of Science and Scopus search, 17 February 2021) [70].

predominates in publications (10,505–16,817 research), agricultural harvesting-related soil loss is almost completely ignored (29–36 studies). This may be explained by the fact that, according to [71], water erosion accounts for 35.9 Petagrams of carbon (Pg) of soil loss annually, making it the most significant soil erosion process in the world.

One of the biggest problems in many countries today is soil erosion, which is a global concern. According to [72], the process called soil erosion through which soil is destroyed as a result of a combination of natural (such as water, wind, and snow) and man-made (such as intense and extensive agriculture) forces. In terms of the aquatic and terrestrial environments, the effects of soil erosion on agricultural output, source water quality, and ecosystem health are detrimental [73]. The primary causes of soil erosion include geography, ground cover, climate erosivity, and soil erodibility. Agriculture output is based on soil. Soil erosion in the agricultural area has put the sustainability of agricultural activities in jeopardy. Accelerated soil erosion harms both the environment and the economy [74]. Both on-site and off-site productivity may have been impacted by soil erosion. The loss in output from soil erosion that occurs both on-site and off-site is attributed to three interrelated consequences: a drop in soil quality, long-term productivity effects, and short-term productivity effects [75]. Two effects of soil erosion that render the area concerned unsuitable for agriculture and affect the productivity of agricultural land are denudation of topsoil and a loss in soil fertility. Asia is home to the majority of the world's tropical and subtropical fruit production, which accounts for 90% of the world's rice production [76]. Asia is also well-known for its vast plantations of key cash crops including tea, palm oil, coconut, sugarcane, and rubber. Sadly, agriculture activities have a negative impact on the environment, namely soil erosion, despite giving Asia a healthy supply of riches. Asia has possibly had the most severe soil erosion of any continent.



Agronomics practices		Agrostological practices	Mechanical practices	
TO=Tillage operation IC= Intercropping CC= Cover crop	ML=Mulching OM= Organic matter	CG= Cultivation of grass	CF= Contour farming BU= Bund MT=Micro basin tillage	CT= Contour terracing GT=Geo-textile

Figure 2.
Research on soil erosion control practices in Asia's agricultural land [83].

Numerous studies on soil erosion management techniques are carried out every year across Asia. Studies mostly concentrate on the impact of various management practices, such as tillage operation [77], mulching [78], cover crop [79], and intercropping [80] on runoff generation and erosion process. Studies on control methods have also been found to be extremely encouraging outside of Asia. Additionally, those studies use a variety of techniques, including straw mulch [81] and catch crop [82]. Researchers in the linked subject have consistently produced studies on how to address soil erosion issues and produced a number of sometimes-conflicting findings. These can be the result of sampling variation, study faults, or discrepancies in the studies. As a result, it is unclear if the most accurate outcomes should be employed or used in the real world. So, in order to locate previously conducted research, a systematic review is required.

According to **Figure 2**, over the previous 6 years, tillage operations (22.73%) have been tested the most frequently, followed by mulching (21.21%), cover crops (18.18%), grass culture (15.15%), and other management techniques.

8. Economic and environmental implications

1. *Cost-benefit analysis of strategic tillage*: cost-benefit analysis (CBA) is a systematic approach used to assess the pros and cons of a specific project or activity. In the context of strategic tillage, it involves evaluating the expenses associated with implementing strategic tillage practices and comparing them to the benefits it offers. Strategic tillage refers to targeted and controlled tillage techniques that aim to achieve predetermined goals while minimizing negative environmental impacts [84]. The costs of strategic tillage include equipment and machinery expenses, labor costs, training and education expenses, fuel and maintenance costs, and potential environmental impacts. On the other hand, the benefits include improved soil structure, better weed control, reduced soil erosion, enhanced water conservation, increased crop yields, and cost savings compared to traditional tillage methods [85]. 2. *Environmental impact assessment of strategic tillage*: the primary objectives of the assessment are to understand the effects of strategic tillage on various environmental aspects, identify potential hazards, and propose solutions to mitigate negative impacts. The assessment aims to determine the likelihood of soil erosion caused by tillage activities and assess the effectiveness of strategic tillage in reducing erosion [86]. The potential for sediment discharge, leading to water pollution and sludge buildup in water bodies, is also analyzed. The effects of strategic tillage on soil health are investigated, including modifications to soil structure, organic matter content, nutrient levels, and microbial activity. Long-term or heavy tillage techniques can lower soil quality and its ability to support healthy plant growth [87]. The impact of strategic tillage on plant, insect, and soil biodiversity is examined. Reduced tillage practices generally promote biodiversity by providing habitat and minimizing habitat degradation caused by conventional tillage. The assessment looks into the potential release of nutrients and pesticides from tilled fields, which can lead to water pollution. A comparison is made between the effects of strategic tillage and traditional tillage on water quality [88]. The analysis focuses on how strategic tillage affects water use efficiency and irrigation needs. Reduced tillage techniques may help retain soil moisture, thus improving water use efficiency. The assessment includes an analysis of greenhouse gas emissions associated with strategic tillage, such as carbon dioxide (CO_2) and nitrous oxide (N_2O) [89]. Reduced tillage techniques have the potential to sequester carbon in the soil, reducing

emissions. The impact of strategic tillage techniques on weed and pest populations is analyzed. Reduced tillage practices that disturb the soil less may alter pest dynamics. The assessment examines how strategic tillage affects crop yields and overall agricultural productivity, with the goal of supporting or enhancing crop output through sustainable tillage practices [86]. Potential effects on wildlife habitat, environmental esthetics, and changes in land use patterns resulting from strategic tillage are also analyzed in the assessment.

9. Future directions and emerging trends

Modern farming techniques that attempt to increase output while reducing environmental impacts include strategic tillage and sustainable agriculture. The need for creative and sustainable ways is becoming more and more obvious as the agriculture sector deals with issues like climate change, soil degradation, and population expansion [90]. Strategic tillage and sustainable agriculture are being shaped by a number of rising trends, pushing the sector toward more effective and environmentally friendly methods [91]. *Precision farming*: precision farming maximizes the use of resources like water, fertilizer, and pesticides by utilizing cutting-edge technologies like GPS, remote sensing, and data analytics [92]. Farmers can customize their tillage operations to meet the particular requirements of each fields by using site-specific management techniques, which results in higher yields and fewer negative environmental effects [93]. *Conservation tillage*: in conservation tillage, crop wastes are left on the field after harvest with minimal soil disturbance. Long-term sustainability is improved by this approach because it improves soil health, lessens erosion, and sequesters carbon in the soil [94]. This group includes no-till and reduced-till techniques, which are gaining acceptance due to their capacity to preserve soil moisture and enhance general soil structure. *Climate-resilient farming*: farming practices are becoming more climate-resilient as a result of how climate change is affecting weather patterns and escalating the frequency of extreme events [95]. This entails varying crop types, utilizing drought-tolerant cultivars, and putting in place irrigation techniques that use little water. *Agroforestry and agroecology*: agroforestry involves integrating trees with agricultural crops to create sustainable and biodiverse systems [96]. These systems not only provide multiple income streams but also enhance soil fertility, biodiversity, and carbon sequestration. Agroecology, on the other hand, promotes a systems-thinking approach, focusing on enhancing the ecological interactions within the farm ecosystem [97]. *Data-driven decision making*: big data and sophisticated analytics are revolutionizing the agricultural industry. Through real-time data gathering and analysis, tillage practice optimization, and resource efficiency, farmers can now make better decisions [98].

10. Conclusion

Harnessing soil potential through innovation in strategic tillage and management practices is crucial for ensuring sustainable agricultural productivity and environmental health. Throughout this chapter, we have explored various aspects of soil management and how they contribute to optimizing crop yields while minimizing negative environmental impacts. Modern agriculture faces a number of difficulties, including soil deterioration, nutrient depletion, and water shortages, which emphasize the pressing, need to use sustainable soil management techniques. Conventional tillage techniques have shown to be successful in the short term, but they can have negative long-term effects such soil erosion and loss of soil fertility. We can maintain soil structure, hold onto organic matter, and boost soil health by using alternative tillage techniques including conservation tillage, reduced tillage, and no-till farming. However, farmer education and extension services are necessary for the effective adoption of new soil management practices. In order to ensure widespread acceptance and long-term success, it will be essential to equip farmers with the information and abilities to embrace sustainable practices. In addition, encouraging government policies and incentives are required to promote the use of sustainable agriculture methods. Governments may play a key role in promoting sustainable soil management by offering financial incentives, technical assistance, and legislative frameworks. In conclusion, the key to attaining sustainable agriculture is to maximize the potential of the soil via innovation in strategic tillage and management practices. We can make future generations more food secure and resilient by maintaining soil health, maximizing resource utilization, and reducing environmental consequences. Protecting the wellbeing of both people and the environment will depend on adopting sustainable soil management techniques.

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References

[1] Bagnall DK, Shanahan JF, Flanders A, Morgan CL, Honeycutt CW. Soil health considerations for global food security. Agronomy Journal. 2021;**113**(6):4581-4589

[2] Tilman D, Balzer C, Hill J, Befort BL. Global food demand and the sustainable intensification of agriculture. Proceedings of the National Academy of Sciences. 2011;**108**(50):20260-20264

[3] Wander MM, Cihacek LJ, Coyne M, Drijber RA, Grossman JM, Gutknecht JL, et al. Developments in agricultural soil quality and health: Reflections by the research committee on soil organic matter management. Frontiers in Environmental Science. 2019;**7**:109

[4] Lima A, Brussaard L, Totola M, Hoogmoed W, De Goede R. A functional evaluation of three indicator sets for assessing soil quality. Applied Soil Ecology. 2013;**64**:194-200

[5] Masto RE, Chhonkar PK, Singh D, Patra AK. Soil quality response to long-term nutrient and crop management on a semi-arid Inceptisol. Agriculture, Ecosystems & Environment. 2007;**118**(1-4):130-142

[6] Armenise E, Redmile-Gordon M, Stellacci A, Ciccarese A, Rubino P. Developing a soil quality index to compare soil fitness for agricultural use under different managements in the Mediterranean environment. Soil and Tillage Research. 2013;**130**:91-98

[7] Yuan P, Wang J, Li C, Xiao Q, Liu Q, Sun Z, et al. Soil quality indicators of integrated rice-crayfish farming in the Jianghan Plain, China using a minimum data set. Soil and Tillage Research. 2020;**204**:104732

[8] Almagro M, Garcia-Franco N, Martínez-Mena M. The potential of reducing tillage frequency and incorporating plant residues as a strategy for climate change mitigation in semiarid Mediterranean agroecosystems. Agriculture, Ecosystems & Environment. 2017;**246**:210-220

[9] Biddoccu M, Ferraris S, Pitacco A, Cavallo E. Temporal variability of soil management effects on soil hydrological properties, runoff and erosion at the field scale in a hillslope vineyard, North-West Italy. Soil and Tillage Research. 2017;**165**:46-58

[10] Martínez-Mena M, Perez M, Almagro M, García-Franco N, Díaz-Pereira E. Long-term effects of sustainable management practices on soil properties and crop yields in rainfed Mediterranean almond agroecosystems. European Journal of Agronomy. 2021;**123**:126207

[11] Aguilera E, Lassaletta L, Gattinger A, Gimeno BS. Managing soil carbon for climate change mitigation and adaptation in Mediterranean cropping systems: A meta-analysis. Agriculture, Ecosystems & Environment. 2013;**168**:25-36

[12] Francaviglia R, Almagro M, Vicente-Vicente JL. Conservation agriculture and soil organic carbon: Principles, processes, practices and policy options. Soil Systems. 2023;**7**(1):17

[13] Moraru PI, Rusu T. No-tillage and minimum tillage systems with reduced energy consumption and soil conservation in the hilly areas of Romania. Journal of Food, Agriculture & Environment. 2013;**11**(2):1227-1231

[14] Pardo G, Del Prado A, Martínez-Mena M, Bustamante M,

Martín JR, Álvaro-Fuentes J, et al. Orchard and horticulture systems in Spanish Mediterranean coastal areas: Is there a real possibility to contribute to C sequestration? Agriculture, Ecosystems & Environment. 2017;**238**:153-167

[15] Sheehy J, Regina K, Alakukku L, Six J. Impact of no-till and reduced tillage on aggregation and aggregate-associated carbon in Northern European agroecosystems. Soil and Tillage Research. 2015;**150**:107-113

[16] Jayaraman S, Dalal RC. No-till farming: Prospects, challenges – productivity, soil health, and ecosystem services. CSIRO Publishing; 2022;**60**(6):435-441

[17] Lobb DA, Huffman E, Reicosky DC. Importance of information on tillage practices in the modelling of environmental processes and in the use of environmental indicators. Journal of Environmental Management. 2007;**82**(3):377-387

[18] Ball B, Bingham I, Rees R, Watson C, Litterick A. The role of crop rotations in determining soil structure and crop growth conditions. Canadian Journal of Soil Science. 2005;**85**(5):557-577

[19] Keller T, Colombi T, Ruiz S, Schymanski SJ, Weisskopf P, Koestel J, et al. Soil structure recovery following compaction: Short-term evolution of soil physical properties in a loamy soil. Soil Science Society of America Journal. 2021;**85**(4):1002-1020

[20] Qi H, Paz-Kagan T, Karnieli A, Jin X, Li S. Evaluating calibration methods for predicting soil available nutrients using hyperspectral VNIR data. Soil and Tillage Research. 2018;**175**:267-275

[21] Krauss M, Berner A, Perrochet F, Frei R, Niggli U, Mäder P. Enhanced soil quality with reduced tillage and solid manures in organic farming–A synthesis of 15 years. Scientific Reports. 2020;**10**(1):4403

[22] Acir N, Günal H, Celik I, Barut ZB, Budak M, Kılıç Ş. Effects of long-term conventional and conservational tillage systems on biochemical soil health indicators in the Mediterranean region. Archives of Agronomy and Soil Science. 2022;**68**(6):795-808

[23] Cherry K, Mila A. Temporal progress and control of tomato spotted wilt virus in flue-cured tobacco. Crop Protection. 2011;**30**(5):539-546

[24] Nord EA, Ryan MR, Curran WS, Mortensen DA, Mirsky SB. Effects of management type and timing on weed suppression in soybean no-till planted into rolled-crimped cereal rye. Weed Science. 2012;**60**(4):624-633

[25] Singh D, Ranjan P, Solanki K, Sandeep S. Effect of tillage and weed management practices on dry matter, yield and nutrient uptake by plant and depletion by Weedin Lentil Crop (*Lens culinaris* M.). International Journal of Environment and Climate Change. 2023;**13**(9):288-298

[26] Sarkar S, Skalicky M, Hossain A, Brestic M, Saha S, Garai S, et al. Management of crop residues for improving input use efficiency and agricultural sustainability. Sustainability. 2020;**12**(23):9808

[27] Kaur R, Kaur S, Deol JS, Sharma R, Kaur T, Brar AS, et al. Soil properties and weed dynamics in wheat as affected by rice residue management in the rice–wheat cropping system in south Asia: A review. Plants. 2021;**10**(5):953

[28] Zhang Y, Xie D, Ni J, Zeng X. Optimizing phosphate fertilizer application to reduce nutrient loss in a

mustard (*Brassica juncea* var. *tumida*)-maize (*Zea mays* L.) rotation system in three gorges reservoir area. Soil and Tillage Research. 2019;**190**:78-85

[29] Basset C, Abou Najm M, Ghezzehei T, Hao X, Daccache A. How does soil structure affect water infiltration? A meta-data systematic review. Soil and Tillage Research. 2023;**226**:105577

[30] Akbarnia A, Farhani F, Heidary B. Economic comparison of tillage and planting operations in three tillage systems. Agricultural Engineering International: CIGR Journal. 2013;**15**(4):180-184

[31] Mia MS, Azam G, Nouraei S, Borger C. Strategic tillage in Australian conservation agricultural systems to address soil constraints: How does it impact weed management? Weed Research. 2023;**63**(1):12-26

[32] Oreja FH, Batlla D, de la Fuente EB. *Digitaria sanguinalis* seed dormancy release and seedling emergence are affected by crop canopy and stubble. Weed Research. 2020;**60**(2):111-120

[33] Schomberg HH, McDaniel RG, Mallard E, Endale DM, Fisher DS, Cabrera ML. Conservation tillage and cover crop influences on cotton production on a southeastern US coastal plain soil. Agronomy Journal. 2006;**98**(5):1247-1256

[34] Zeng Z, Thoms D, Chen Y, Ma X. Comparison of soil and corn residue cutting performance of different discs used for vertical tillage. Scientific Reports. 2021;**11**(1):2537

[35] Gupta PR, Chandan YN, Banginwar AR, Gawande GR, Inglekar PS, Shrirao PN. An overview on design analysis and development of agricultural rotavator blade. International Journal of Advance Scientific Research and Engineering Trends. 2021;**6**(4):35-36

[36] Rizwan M, Rubina Gilani S, Iqbal Durani A, Naseem S. Materials diversity of hydrogel: Synthesis, polymerization process and soil conditioning properties in agricultural field. Journal of Advanced Research. 2021;**33**:15-40

[37] Chunlei W, Hongwen L, Jin H, Qingjie W, Caiyun L, Liping C. State-of-the-art and Prospect of automatic navigation and measurement techniques application in conservation tillage. Smart Agriculture. 2020;**2**(4):41

[38] McLaughlin N, Drury C, Reynolds W, Yang X, Li Y, Welacky T, et al. Energy inputs for conservation and conventional primary tillage implements in a clay loam soil. Transactions of the ASABE. 2008;**51**(4):1153-1163

[39] Tessier S, Hyde G, Papendick R, Saxton K. No-till seeders effects on seed zone properties and wheat emergence. Transactions of the ASAE. 1991;**34**(3):733-0739

[40] Noland RL, Wells MS, Sheaffer CC, Baker JM, Martinson KL, Coulter JA. Establishment and function of cover crops interseeded into corn. Crop Science. 2018;**58**(2):863-873

[41] Lin J, Liu A, Li B, Li B, Zhao D, Lu C. 2BG-2 type corn ridge planting no-till planter. Nongye Jixie Xuebao = transactions of the Chinese Society for Agricultural Machinery. 2011;**42**(6):43-62

[42] Somasundaram J, Sinha N, Dalal RC, Lal R, Mohanty M, Naorem A, et al. No-till farming and conservation agriculture in South Asia–issues, challenges, prospects and benefits. Critical Reviews in Plant Sciences. 2020;**39**(3):236-279

[43] Adetunji AT, Ncube B, Mulidzi R, FB L. Management impact and benefit of cover crops on soil quality: A review, Soil and Tillage Research. 2020;**204**:104717

[44] Gómez JA, Campos M, Guzmán G, Castillo-Llanque F, Vanwalleghem T, Lora Á, et al. Soil erosion control, plant diversity, and arthropod communities under heterogeneous cover crops in an olive orchard. Environmental Science and Pollution Research. 2018;**25**:977-989

[45] Delgado JA, Mosquera VHB, Alwang JR, Villacis-Aveiga A, Ayala YEC, Neer D, et al. Potential use of cover crops for soil and water conservation, nutrient management, and climate change adaptation across the tropics. Advances in Agronomy. 2021;**165**:175-247

[46] López-Vicente M, Calvo-Seas E, Álvarez S, Cerdà AJ. Effectiveness of cover crops to reduce loss of soil organic matter in a rainfed vineyard. Land. 2020;**9**(7):230

[47] Seifert CA, Azzari G, Lobell DB. Satellite detection of cover crops and their effects on crop yield in the Midwestern United States., Environmental Research Letters. 2018;**13**(6):064033

[48] Kim N, Zabaloy MC, Guan K, Villamil MBJ. Do cover crops benefit soil microbiome? A meta-analysis of current research. Soil Biology and Biochemistry. 2020;**142**:107701

[49] de Pedro L, Perera-Fernández LG, López-Gallego E, Pérez-Marcos M, Sanchez JA. The effect of cover crops on the biodiversity and abundance of ground-dwelling arthropods in a Mediterranean pear orchard. Agronomy. 2020;**10**(4):580

[50] Meyer N, Bergez J-E, Constantin J, Belleville P, Justes E. Cover crops reduce drainage but not always soil water content due to interactions between rainfall distribution and management. Agricultural Water Management. 2020;**231**:105998

[51] Kaye JP, Quemada M. Using cover crops to mitigate and adapt to climate change. A review. Agronomy for Sustainable Development. 2017;**37**:1-17

[52] Chapagain T, Lee EA, Raizada MNJ. The potential of multi-species mixtures to diversify cover crop benefits. Sustainability. 2020;**12**(5):2058

[53] Wu H, Lai C, Zeng G, Liang J, Chen J, Xu J, et al. The interactions of composting and biochar and their implications for soil amendment and pollution remediation: A review. Critical Reviews in Biotechnology. 2017;**37**(6):754-764

[54] Alley MM, Vanlauwe B. The Role of Fertilizers in Integrated Plant Nutrient Management. United Kingdom: International Fertilizer Industry Association; 2009

[55] Tully K, Ryals R. Nutrient cycling in agroecosystems: Balancing food and environmental objectives. Agroecology and Sustainable Food Systems. 2017;**41**(7):761-798

[56] Agegnehu G, Amede T, Erkossa T, Yirga C, Henry C, Tyler R, et al. Extent and management of acid soils for sustainable crop production system in the tropical agroecosystems: A review. Acta Agriculturae Scandinavica, Section B — Soil & Plant Science. 2021;**71**(9):852-869

[57] Neina DJ. The role of soil pH in plant nutrition and soil remediation. Applied and Environmental Soil Science. 2019;**2019**:1-9

[58] Frouz JJ. Effects of soil macro-and mesofauna on litter decomposition

and soil organic matter stabilization. Geoderma. 2018;**332**:161-172

[59] Vecchio Y, De Rosa M, Adinolfi F, Bartoli L, Masi M. Adoption of precision farming tools: A context-related analysis. Land Use Policy. 2020;**94**:104481

[60] Radoglou-Grammatikis P, Sarigiannidis P, Lagkas T, Moscholios IJ. A compilation of UAV applications for precision agriculture. Computer Networks. 2020;**172**:107148

[61] Rwanga SS, Ndambuki JM. Accuracy assessment of land use/ land cover classification using remote sensing and GIS. International Journal of Geosciences. 2017;**8**(04):611

[62] Singh T, Asim M. Weather monitoring system using IoT. In: Innovations in Cyber Physical Systems: Select Proceedings of ICICPS 2020. Germany: Springer; 2021

[63] Späti K, Huber R, Finger RJEE. Benefits of increasing information accuracy in variable rate technologies. Ecological Economics. 2021;**185**:107047

[64] Dolci R, editor. IoT solutions for precision farming and food manufacturing: Artificial intelligence applications in digital food. In: 2017 IEEE 41st Annual Computer Software and Applications Conference (COMPSAC). Canada: IEEE; 2017

[65] Phupattanasilp P, Tong S-R. Augmented reality in the integrative internet of things (AR-IoT): Application for precision farming. Sustainability. 2019;**11**(9):2658

[66] AJT G, Fullen MA, Jorge MCO, JFR B, Shokr MS. Slope processes, mass movement and soil erosion: A review. Pedosphere. 2017;**27**(1):27-41

[67] Merrison J. Sand transport, erosion and granular electrification. Aeolian Research. 2012;**4**:1-16

[68] Van Oost K, Govers G, De Alba S, Quine T. Tillage erosion: A review of controlling factors and implications for soil quality. Progress in Physical Geography. 2006;**30**(4):443-466

[69] Ruysschaert G, Poesen J, Verstraeten G, Govers G. Soil loss due to crop harvesting: Significance and determining factors. Progress in Physical Geography. 2004;**28**(4):467-501

[70] Kuhwald M, Busche F, Saggau P, Duttmann R. Is soil loss due to crop harvesting the most disregarded soil erosion process? A review of harvest erosion. Soil and Tillage Research. 2022;**215**:105213

[71] Borrelli P, Robinson DA, Fleischer LR, Lugato E, Ballabio C, Alewell C, et al. An assessment of the global impact of 21st century land use change on soil erosion. Nature Communications. 2017;**8**(1):2013

[72] Zachar D. Soil erosion. United Kingdom: Elsevier; 2011

[73] Fayas CM, Abeysingha NS, Nirmanee KGS, Samaratunga D, Mallawatantri A. Soil loss estimation using rusle model to prioritize erosion control in KELANI river basin in Sri Lanka. International Soil and Water Conservation Research. 2019;**7**(2):130-137

[74] Lal R. Soil erosion impact on agronomic productivity and environment quality. Critical Reviews in Plant Sciences. 1998;**17**(4):319-464

[75] Lal R. Soil degradation by erosion. Land Degradation & Development. 2001;**12**(6):519-539

[76] Bandumula N. Rice production in Asia: Key to global food security. Proceedings of the National Academy of Sciences, India Section B: Biological Sciences. 2018;**88**:1323-1328

[77] Wang L, Yuan X, Liu C, Li Z, Chen F, Li S, et al. Soil C and N dynamics and hydrological processes in a maize-wheat rotation field subjected to different tillage and straw management practices. Agriculture, Ecosystems & Environment. 2019;**285**:106616

[78] Pan D, Zhao X, Gao X, Song Y, Dyck M, Wu P, et al. Application rate influences the soil and water conservation effectiveness of mulching with chipped branches. Soil Science Society of America Journal. 2018;**82**(2):447-454

[79] Dai C, Liu Y, Wang T, Li Z, Zhou Y. Exploring optimal measures to reduce soil erosion and nutrient losses in southern China. Agricultural Water Management. 2018;**210**:41-48

[80] Sharma N, Singh RJ, Mandal D, Kumar A, Alam N, Keesstra S. Increasing farmer's income and reducing soil erosion using intercropping in rainfed maize-wheat rotation of Himalaya, India. Agriculture, Ecosystems & Environment. 2017;**247**:43-53

[81] Keesstra S, Rodrigo-Comino J, Novara A, Giménez-Morera A, Pulido M, Di Prima S, et al. Straw mulch as a sustainable solution to decrease runoff and erosion in glyphosate-treated clementine plantations in eastern Spain. An assessment using rainfall simulation experiments. Catena. 2019;**174**:95-103

[82] Cerdà A, Rodrigo-Comino J, Giménez-Morera A, Keesstra SD. Hydrological and erosional impact and farmer's perception on catch crops and weeds in citrus organic farming in Canyoles river watershed, Eastern Spain. Agriculture, Ecosystems & Environment. 2018;**258**:49-58

[83] Ahmad NSBN, Mustafa FB, Didams G. A systematic review of soil erosion control practices on the agricultural land in Asia. International Soil and Water Conservation Research. 2020;**8**(2):103-115

[84] Azumah SB, Adzawla W, Osman A, Anani PY. Cost-benefit analysis of on-farm climate change adaptation strategies in Ghana. Ghana Journal of Geography. 2020;**12**(1):29-46

[85] Shongwe P. Cost Benefit Analysis of Climate Change Adaption Strategies on Crop Production Systems: A Case of Mpolonjeni Area Development Programme (ADP) in Swaziland. 2013

[86] Wang X, Qi JY, Liu BY, Kan ZR, Zhao X, Xiao XP, et al. Strategic tillage effects on soil properties and agricultural productivity in the paddies of southern China. Land Degradation & Development. 2020;**31**(10):1277-1286

[87] Brentrup F, Küsters J, Lammel J, Barraclough P, Kuhlmann H. Environmental impact assessment of agricultural production systems using the life cycle assessment (LCA) methodology II. The application to N fertilizer use in winter wheat production systems. European Journal of Agronomy. 2004;**20**(3):265-279

[88] Dang Y, Seymour NP, Walker S, Bell M, Freebairn D. Strategic tillage in no-till farming systems in Australia's northern grains-growing regions: I. Drivers and implementation. Soil and Tillage Research. 2015;**152**:104-114

[89] Melland A, Antille D, Dang Y. Effects of strategic tillage on short-term erosion, nutrient loss in runoff and

greenhouse gas emissions. Soil Research. 2016;**55**(3):201-214

[90] Guimarães RM, Lamandé M, Munkholm LJ, Ball BC, Keller T. Opportunities and future directions for visual soil evaluation methods in soil structure research. Soil and Tillage Research. 2017;**173**:104-113

[91] Dang YP, Dalal RC, Menzies NW. No-Till Farming Systems for Sustainable Agriculture: Challenges and Opportunities. Sweden: Springer; 2020

[92] Blasch J, van der Kroon B, van Beukering P, Munster R, Fabiani S, Nino P, et al. Farmer preferences for adopting precision farming technologies: A case study from Italy. European Review of Agricultural Economics. 2022;**49**(1):33-81

[93] Raj EFI, Appadurai M, Athiappan K. Precision farming in modern agriculture. In: Smart Agriculture Automation Using Advanced Technologies: Data Analytics and Machine Learning, Cloud Architecture, Automation and IoT. Switzerland: Springer; 2022. pp. 61-87

[94] Hussain S, Hussain S, Guo R, Sarwar M, Ren X, Krstic D, et al. Carbon sequestration to avoid soil degradation: A review on the role of conservation tillage. Plants. 2021;**10**(10):2001

[95] Amoak D, Luginaah I, McBean G. Climate change, food security, and health: Harnessing agroecology to build climate-resilient communities. Sustainability. 2022;**14**(21):13954

[96] Buratti-Donham J, Venn R, Schmutz U, Migliorini P. Transforming food systems towards agroecology – A critical analysis of agroforestry and mixed farming policy in 19 European countries. Agroecology and Sustainable Food Systems. 2023;**47**(7):1-29

[97] Peredo Parada S, Barrera C, Burbi S, Rocha D. Agroforestry in the Andean Araucanía: An experience of agroecological transition with women from Cherquén in Southern Chile. Sustainability. 2020;**12**(24):10401

[98] Kamble SS, Gunasekaran A, Gawankar SA. Achieving sustainable performance in a data-driven agriculture supply chain: A review for research and applications. International Journal of Production Economics. 2020;**219**:179-194