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Review

Cover Crops for Sustainable Cropping Systems: A Review

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Abstract: Cover cropping is a promising and sustainable agronomic practice to ameliorate soil health and crop performances in agro-ecosystems. Indeed, cover crops (CCs) may regulate several ecosystem services such as nutrient cycling, soil fertility, moderation of extreme meteorological events, pollination, and climate and water regulation; in addition, CCs are also used as forage crops and have considerable effects on plant and soil biodiversity. However, to achieve the desired effects on agro-ecosystems, cover cropping should be carefully adopted by considering the specie choice, period of cultivation, and termination method based on site, farm, or purpose-specific. The main objective of this manuscript is to analyze the effects of modern agriculture on soil and environmental health and how cover crops can support sustainable cropping systems and global food security. In addition, it focuses on how the incorporation of cover crops into conventional cropping systems can help in the diversification of crops and assist in mitigating the environmental effects of cropping systems. Finally, this review thoroughly investigates the potential effects of CCs on environmental sustainability, which can be an important source of information for sustainable crop production and food security.

Keywords: agro-ecosystems; soil cover; subsidiary crops; crop yield; carbon sequestration; nutrient cycle; greenhouse gas emissions

Citation: Quintarelli, V.; Radicetti, E.; Allevato, E.; Stazi, S.R.; Haider, G.; Abideen, Z.; Bibi, S.; Jamal, A.; Mancinelli, R. Cover Crops for Sustainable Cropping Systems: A Review. *Agriculture* **2022**, *12*, 2076. https://doi.org/10.3390/agriculture12122076

Academic Editor: Manuel Ângelo Rosa Rodrigues

Received: 1 November 2022
Accepted: 30 November 2022
Published: 3 December 2022

1. Introduction

Global agri-food systems are facing challenges in realizing food chains for feeding the growing population, which is expected to be 10 billion people by 2050 [1]. At the same time, agricultural systems need to be managed by a sustainable approach to reducing external inputs, such as fossil fuels, and non-judicious use of mineral fertilizers and pesticides. In addition, environmental concerns such as greenhouse gas emissions (GHGs), nutrient leaching, especially nitrogen, and its associated environmental pollution should be addressed by means of sustainable practices [2].

The United States Department of Agriculture (USDA) defines conventional farming systems as "agricultural practices which include the use of synthetic chemical fertilizers, pesticides, herbicides, and other continual inputs, genetically modified organisms, concentrated animal feeding operations, heavy irrigation, intensive tillage, or concentrated monoculture production" [3]. In fact, these approaches to managing agricultural lands are considered unsustainable in terms of solving environmental issues such as climate change, environmental pollution, soil erosion, and loss of natural resources [4]. Although modern agricultural practices are managed through highly specialized machinery in industrialized farming to apply carefully agricultural inputs, this behavior is leading to unsustainable cropping systems that generates, in time, a progressive loss of soil fertility and weakening of agro-ecosystems [5]. This kind of "conventionally" managed agriculture is characterized by excessive use of inputs, with negative effects on air, soil, and water and causing pollution and biodiversity loss [6]. Recently, Scopel et al. [7] explained that monoculture has led to a negative impact on the agro-ecosystems and increased the loss of soil organic matter (SOM), as well as increasing soil erosion, nitrate leaching, and agrochemicals utilization required for pest control. In addition, the Intergovernmental Panel on Climate Change (Ginevra) observed that the greenhouse gasses (GHGs) emissions from modern agricultural practices contribute to climate change accounting for about 24% of net emissions of anthropogenic activities [8]. Therefore, to preserve limited resources and agro-environmental stability, it is necessary to develop sustainable agronomic practices that could sustain crop production and environmental issues.

Agroecological practices contribute to agri-environmental sustainability because they are based on different ecological and biological processes that combine high-quality crops without damaging the environment, stimulating natural soil regeneration, enhancing biodiversity, and mitigating climate change [9]. The development of sustainable agricultural practices, therefore, has become necessary to combine the need to produce enough quantities of food for consumers with the conscious use of natural resources [10]. The importance of sustainable agricultural production is increasingly recognized also in European policies with the EU Green Deal and Common Agricultural Policy [11].

Cover crops are defined as a "close-growing crop that provides soil protection, seeding protection, and soil improvement between periods of normal crop production" [12]. The cultivation of cover crops is performed during the bare fallow period, between the cultivation of two consecutive main cash crops by using the residual soil nutrients, and their growth is interrupted either before the next main crop is sown or after sowing the next crop, in any case before competition between cover crop and main crop starts (Figure 1). Cover crops can increase soil cover during the bare period, and their biomass support photosynthetic process, root exudation, and microbial biomass, increasing biodiversity at the agro-ecosystem level; in addition, cover crop biomass also contributes to the input of litter to the soil leading to an increase of C and N contents to the soil that could become available for the next crops [13,14]. In fact, in contrast to the bare soil, the cultivation of cover crops improves soil physical properties (e.g., soil structural stability, water retention capacity, infiltration rate). It promotes C sequestration and N retention [15]. In addition, root exudates of cover crop plants can contribute to an integrated strategy to manage biotic crop constraints, like weeds, insects, and diseases [16]. Cover crops can contribute indirectly to overall soil and water quality by absorbing excess nutrients before they leach from the soil profile, especially with grass species, or by adding nitrogen (N) to the soil in the case of legume cover crops [17], resulting in a reduced N requirement of the next cash crop (Figure 1). For instance, the decomposing residues of brassica cover crops, through the release of glucosinolates, aid in the control of parasitic nematodes (Figure 2). In addition, during the same phase, they can cause chemical and physical changes in the soil and facilitate root penetration of the next crop and act as a buffer for the soil [18]. Several studies confirm that the use of legume cover crops in crop rotations, such as clover and alfalfa, and graminaceous cover crops, such as ryegrass, oat, and barley, enhance the yields of the following cash crop [19–21] (Figure 2). In addition, even with the exclusive use of grass species, the soil nutrient profile can be improved compared to monoculture [22]. All these benefits identify the cover crops as a sustainable practice able to support a series of agro-ecological services, even if proper cover crop management is needed to significantly increase soil C stocks and climate change mitigation, especially in semi-arid Mediterranean environments, through the reduction of GHGs emissions [23,24]. In fact, the biomass produced by CC cultivation represent an input of organic matter that has an ameliorative effect on microbial activity in the soil, which is the main driver of soil greenhouse gas fluxes [25]. Moreover, recent research has evaluated the potential beneficial effects of cover crops on nitrate leaching [26,27], weed control [28], cash crop yield [29], and pollinator insects [30,31].

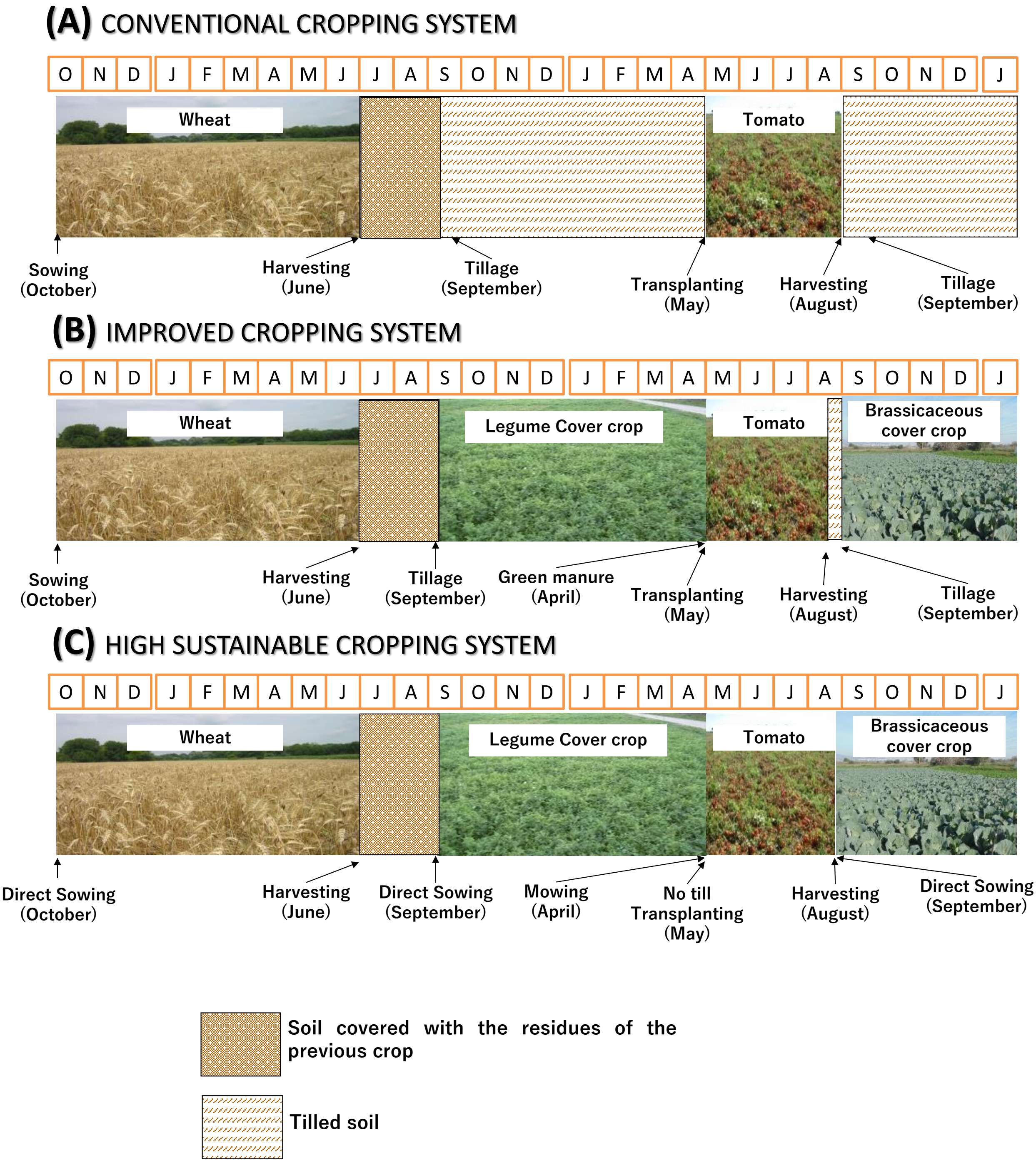

Figure 1. Comparison between conventional (**A**), improved (**B**), and high sustainable cropping systems (**C**) to support the adoption of cover cropping strategy for improving the sustainability of agro-ecosystems.

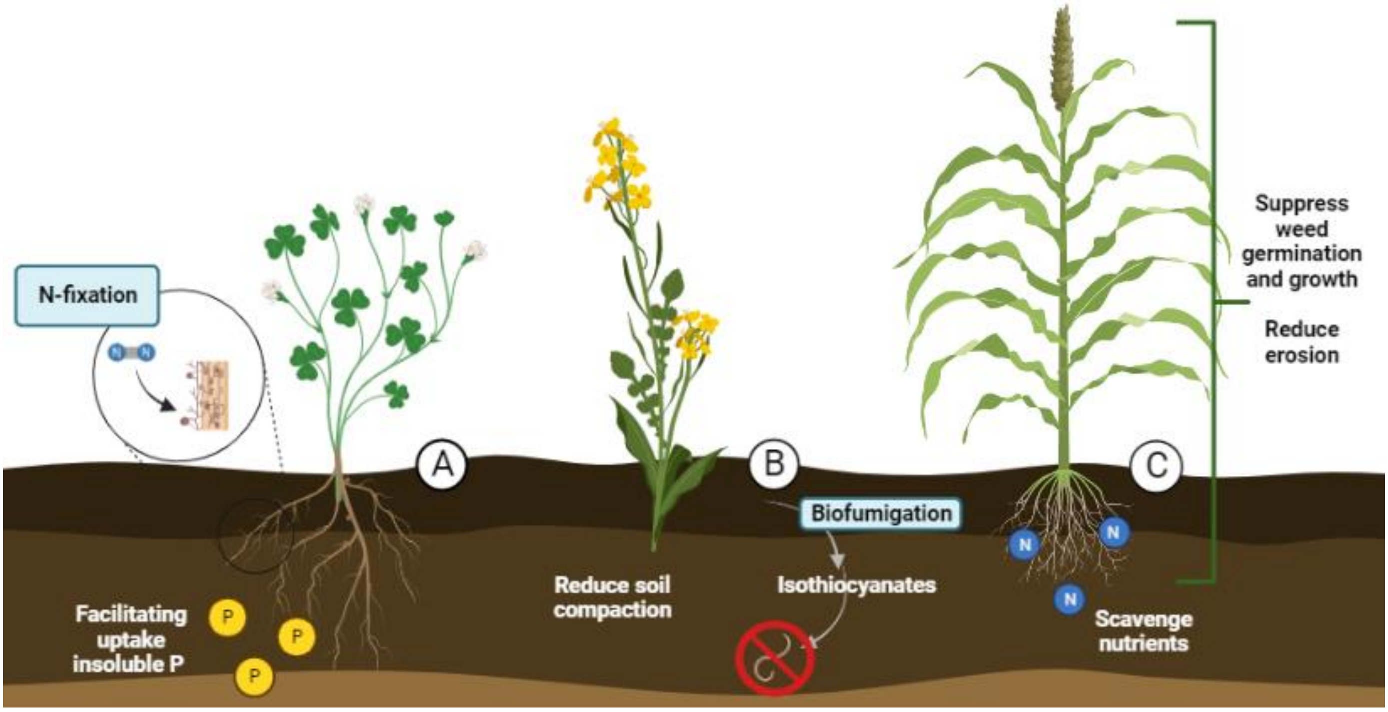

Figure 2. Schematic diagram explaining the role of different type of cover crops in the agroecosystems and their main ecological services. A = Leguminous species, B = Brassicaceous species, C = Gramineous species.

The adoption of CCs in innovative agricultural systems opens alternative solutions toward sustainable approaches to cultivation (Figure 1). The cultivation of cover crops associated with no-tillage management is increasingly accepted by researchers and farmers that identify it as conservation agriculture (CA) practice [32,33] (Figure 1). Under conservation agriculture, cover crop cultivation allows an increase in a diverse range of beneficial soil flora and fauna that contribute to nutrient cycling and affect plant nutrition [34]. The increase in plant diversity affects the composition and abundance of soil microorganisms which can have ameliorative effects on the uptake and cycling of limited nutrients [35]. Generating residues and adding diversity to the CA system could be achieved by cover crops (CCs). Indeed, one of the fundamental principles of conservation agriculture is to keep the soil covered by employing crop residues that are left on the soil surface; however, when the period between the harvesting of the previous main crop and the establishment of the next one is too long, crop residues cannot be sufficient to cover the soil generating a gap where the soil is exposed to weather conditions. Cover crops represent a key aspect of conservation agriculture needed to avoid this gap and improve the stability of the CA system, not only in the improvement of soil properties but also for their capacity to promote increased biodiversity in the agro-ecosystem.

Although cover crops are associated with sustainable cropping systems and support crop production and the environment, their effective adoption presents some challenges that should be addressed to avoid misleading farmers in carrying out efficient agroecosystems. Hence, the main aim of this review is, therefore, to produce a critical overview of the use of cover cropping to assess the change in environmental aspects and cropping systems due to cover crop adoption. The specific objectives are: (i) to review the available literature on soil and environmental health associated with cover crops, (ii) to summarize the role of cover crops in improving soil conditions for sustainable agriculture, and (iii) to report the effect of cover crops on greenhouse gas emissions and climate change mitigation.

2. Effect of Cover Crops on Soil Health

There are numerous crop options that can be used as vegetative covers, like grains, legumes, root crops and oil crops, all of which show different benefits to support soil health (Figure 2). Among the benefits related to the adoption of CCs in agricultural lands there are the increased soil organic carbon and available soil nutrients, reduced soil compaction and increased soil structure and particle aggregation; as well as enhanced microbial activity, abundance, and diversity [36]. In particular, some species of cover crops may enrich the soil with nitrogen (N) due to their ability to fix atmospheric nitrogen (e.g., *Vicia sativa* L.) [37] or their fibrous root system able to scavenge nutrients lost from the previous crop and act as catch crop for reducing the leaching of nutrients (e.g., *Avena sativa* L.) [38]. In addition, rye is effective in reducing N leaching from winter to spring [39]. Grass and crucifer species (e.g., *Secale cereale* L. or *Sinapis alba* L.) can improve soil hydraulic properties through the improvement of soil structure, aggregate stability, and soil porosity [15]. In addition, Brassicaceous CCs are chosen to improve soil penetration resistance due to taproot growth but are also used as a highly effective catch crop [40]. Indeed, the taproot system of brassicas, by creating cavities, can help in reducing soil compaction, and improve water infiltration, ultimately reducing soil erosion. For example, radish (*Raphanus raphanistrum* subsp. *sativus*), a widely used and highly beneficial cover crop, catch soil nutrients, especially nitrogen [41]. All CCs, due to photosynthesis activity, produce high above- and belowground biomass that contributes to enhancing soil organic matter accumulation [36,42] (Figure 3). In addition, CCs are characterized by a rapid establishment rate covering the soil and providing a significant reduction of the soil erosion process [43]. The adoption of rye (*Secale cereale* L.) under no-tillage conditions sustains the yield performance of main crops [44], enhancing soil quality parameters and keeping N_2O emissions under control [24].

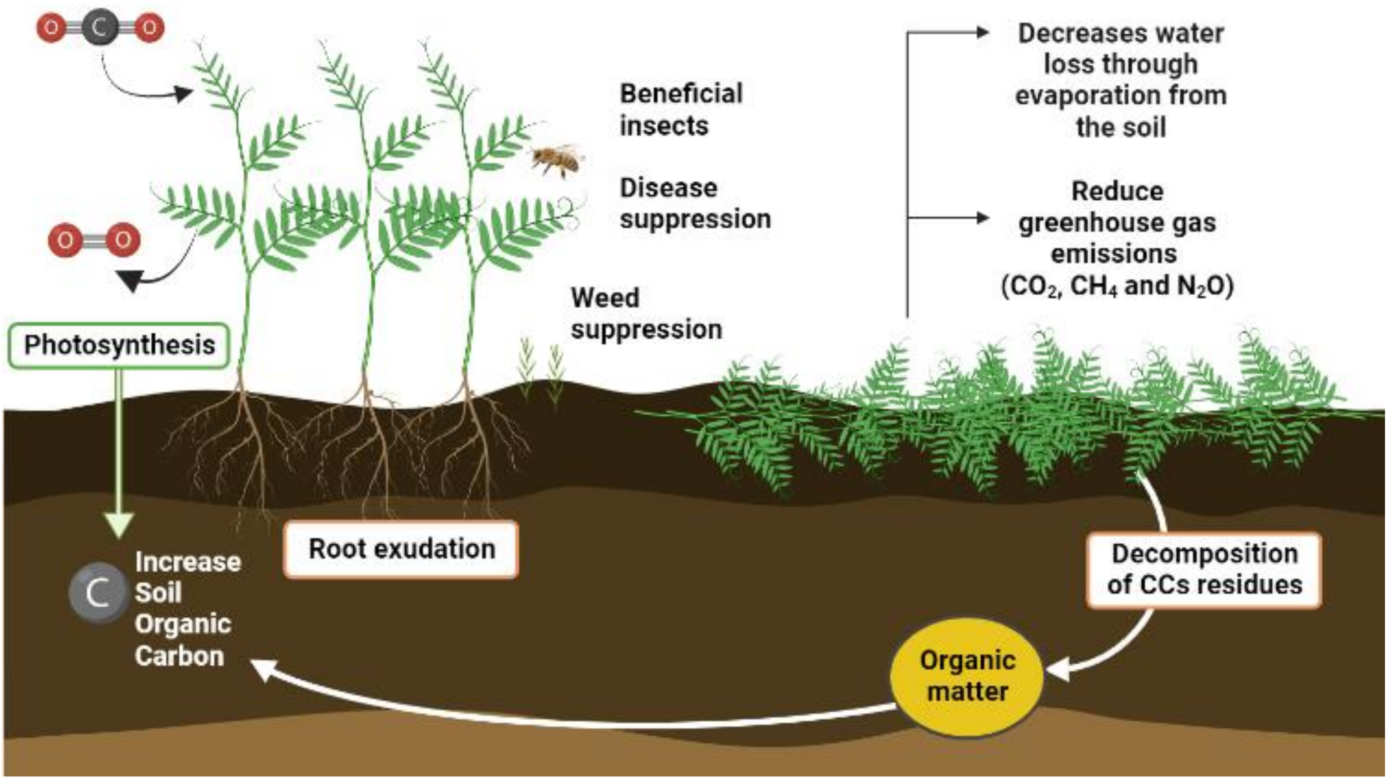

Figure 3. Ecological services associated with cover crops.

Recently, Papp et al. [45] showed that cultivation of cover crops affects soil microorganism environments that are critically important for maintaining soil functions and ecosystem sustainability as they are involved in the cycling of nutrients and the turnover of organic matter (Table 1). It has been reported that cover crops can alter the dynamics of soil bacterial and fungal communities [46], stimulate beneficial microorganisms [47], and suppress soilborne pathogens [48]. It is interesting to note that some cruciferous CCs, such as rape (*Brassica rapa* L.) and canola (*Brassica napus* L.), when terminated, release isothiocyanates (ITCs) through hydrolysis of glucosinolates (GSLs) throughout the decomposition process of their tissues that are effective biofumigants for the control of a range of soil-borne pathogens and pests [49]. In that sense, the use of cruciferous species as cover crops could allow the natural control of potential diseases. Waisen et al. [50] showed that radish (*Raphanus raphanistrum* subsp. *sativus*) or brown mustard (*Brassica juncea* L.) as a biofumigant crop could be effective against plant-parasitic nematodes without compromising on soil health or changing the structure of the nematode community. Furthermore, Aydınlı et al. [51] revealed that using radish (*R. sativus*) and arugula (*Eruca sativa*) as winter cycle plants before plants that are susceptible to the root-knot nematode *Meloidogyne arenaria* would help to reduce gall index, egg masses and consequently damage and also increase crop yields. Last, leguminous CCs are recognized as the most effective when maximizing nitrogen (N) input becomes the priority [52]. Indeed, leguminous CCs can deposit significant amounts of N in the soil during growth and have the ability to acidify the rhizosphere by facilitating the uptake of insoluble phosphorous into the soil [53,54]. Especially, legume cover crops can fix atmospheric N through symbiosis with rhizobia in the root nodules [55]. In addition, the fixed N can be transferred to intercropped non-legumes in mixed cropping systems, or it can follow crops in rotations [56–59]. The biological N-fixing (BNF) systems can reduce the internal inputs of industrial N fertilizers [60–62]. According to Scavo et al. [63], the presence of *Trifolium subterraneum,* for three consecutive years, determined a considerable increase in ammoniacal nitrogen, nitric nitrogen, and the N cycle bacteria (Table 1). Similarly, Campiglia et al. [64] observed similar wheat yield when subterranean clover is used as living mulch in intercropping systems. Furthermore, Guardia et al. [65] revealed that the mitigation effect of the legume (vetch) CC is mainly due to the reduction of synthetic N inputs in the subsequent cash crop as well as a decrease in indirect N_2O emissions from NO_3^- leaching and an increase in C sequestration due to an intensive photosynthetic activity (Figure 3). In addition, the mitigation efficacy of barley is mainly due to C sequestration in agreement with Aguilera et al. [66] and the abatement of NO_3^- leaching, as reported by Ferrari Machado et al. [60]. One of the potential disadvantages of cover crops identified by Abdalla et al. [26] was the yield reduction of about −4% of the following cash crop compared to the bare soil. However, in the selection of the right cover crop species with a range of legumes and non-legumes, several studies showed an average increase of 13% in crop yield [67–69]. Recently, Taab et al. [70] observed a yield reduction of wheat when Persian clover (*T. resupinatum* L.) is sown at a high rate because it competes with the cereal for limited resources. Therefore, management practices concerning cover crops (i.e., choice, cultivation period, termination) needed to be adapted to the specific soil and cash crop, farming system, and regional climatic conditions (Table 1).

The adoption of cover crops in agro-ecosystems provides multiple benefits to the agro-ecosystems (Figure 3) [71]. To maximize the agro-ecological functions, complementing and synergizing the effects, cover crops are usually cultivated in a mixture. Very important, in the constitution of these mixes is to use the functional complementarity of the species [72]. The potential application of crop mixtures (involving cereal, legume, and even crucifer CCs) is an issue of strategic interest when designing low-C cropping systems in Mediterranean areas. Couëdel et al. [73] and Kaye et al. [74] have obtained positive results regarding N_2O emissions and N leaching in comparison with the use of monoculture. For example, mixing radish with rye can mitigate both soil compaction and soil erosion risks due to the bio-drilling potential of radish and abundant aboveground biomass cover produced by rye [75].

In long-term cropping systems such as orchards, cover crops have economic benefits because, in addition to protecting soil against water and wind erosion (Figure 4), they can contribute, through residue deposition, to nutrient recycling, increased soil health and reduced mineral fertilization needs [76,77]. This could be useful on vineyard and olive tree systems that are generally affected by erosion due to the high loss of organic matter and excessive tillage operations [78]. Other tree systems that have the same issues are those consisting of almond [79], apricot [80], and persimmon orchards [81]. Several studies showed that the cultivation of cover crops is an effective solution to minimize soil erosion in these orchards caused by intensive tillage, excessive mineral fertilizer applications and herbicide use [82] and, therefore, preserve soil from the risk of desertification [83–85]. García-Díaz et al. [86] observed that the use of CCs could reduce soil losses by 3.8 to 0.7 Mg ha^{-1} in a vineyard. Novara et al. [87] showed that using CC reduces by 27% annual water runoff and can be used as an agronomic strategy for improving water use efficiency.

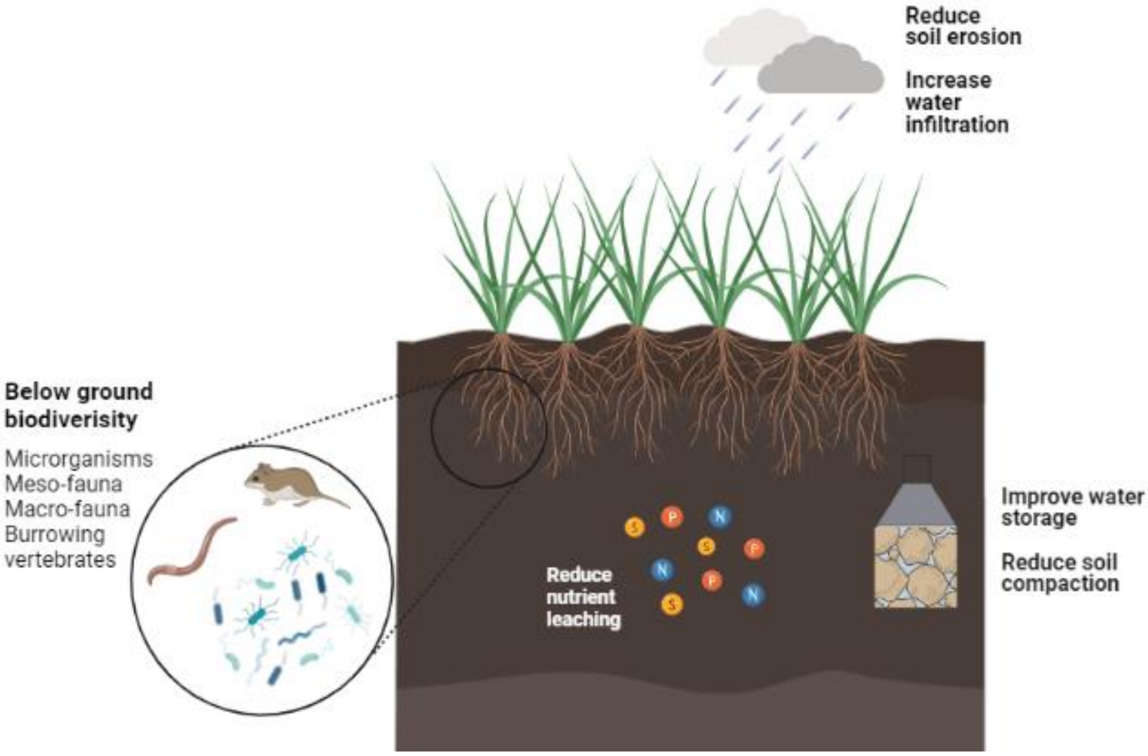

Figure 4. Benefits of cover crops on physical, chemical, and biological components of agro-ecosystems.

Table 1. Agro-ecosystem services related to the use of different species of CCs.

Type	Management Goals	References
Graminaceous	Increase SOM	[36,42]
	Reduce erosion, control weed growth	[43]
	Sustain crops yield performance	[44]
	Effective C sequestration	[66]
	Keeping N_2O emissions under control	[24]
	Reduce NO_3^- leaching	[39,60,77]
	Reduction of weeds and increase in production yield	[88]
Brassicaceous	Reduce subsoil compaction, reduce soil erosion	[40,75]
	Catch soil nutrients, especially nitrogen	[41]
	Effective against pest	[50]
	Reduce significantly gall index, increase crop yields	[51]
Legume	Promote nitrogen (N) input	[52]
	Promote uptake of insoluble phosphorous	[53,54]
	Increase ammoniacal nitrogen, nitric nitrogen, increase N cycle bacteria	[63]
	Nitrogen fixation, effective C sequestration	[65]
	Improve soil quality	[89]
	Reduce water and wind erosion, contribute to nutrient recycling, and reduce fertilization application	[76,78–81,83–87]

3. Effects of Cover Crops on Different Cropping Systems

It is widely recognized that the adoption of monoculture and conventional farming practices causes changes in the biodiversity of agro-ecosystems leading to the reduction of soil fertility due to high inputs of chemical fertilizers and increasing resistance in weeds and phytopathogens associated with overuse of pesticides [90]. This farming approach of modern industrialized agriculture leads farmers to assume that a simple and linear system is more productive and profitable than sustainable agronomic practices into farm planning [91]. It is certainly true that the introduction of cover crops into cropping systems means a series of modifications in the technical and productive organization [92]. However, as shown by Bowles et al. [93], long term crop diversification produces the 'rotation effect', which in most cases leads to an increase in agro-ecosystem productivity compared to a monoculture system and leads to a reduced inputs uses [94]. Jacobs et al. [32] have shown that the cultivation of winter CCs reduces cash crop production costs in both conventional and conservation systems (Table 2). Therefore, when introducing cover crops into the farm cropping systems, it is very important to choose the appropriate species of cover crop and its suitable termination method must be chosen according to the intended aims [95–97]. In general, legumes and brassicas tend to have a more in-depth effect due to their taproot system, while grasses have more superficial effects due to their fasciculate root system [98]. Effects of cover crops on the various soil organisms are extremely complex and diversified, most frequently including an increase in the biological activity of soils, which promotes nematode diversity and thus control the allelopathic effect of certain species and varieties of brassicaceous and graminaceous plants on certain pathogens and nematodes [99,100]. An important benefit of adopting cover crops is the reduction of chemical inputs for weed control (Figure 3). Indeed, the cultivation of CCs have an important role in low input agro-ecosystems, because reduce the ecological niche available for weed establishment and growth, as observed by Campiglia et al. [101]. Grass CCs have an important role in weeds control are mainly represented by rye, sorghum, wheat, barley, and oats. Leguminous plants include alfalfa, vetches, peas, and clovers while Brassicaceae cover crops are generally represented by rape and mustard [63]. In addition, CCs have important functions in reducing the presence of weeds and costs in herbicide applications [101,102]. For example, Demir et al. [89] have observed that the specific use of *Trifolium repens* and *Vicia villosa* as cover crops can improve soil quality and yield in apple orchards. Moreover, the use of *V. villosa* and *Festuca arundinacea* Schreb. in hazelnut orchards enhance the reduction of weeds and increase production yield [88].

After their suppression the CCs residue management are a key factor for weed management in the next following crop (Table 2). Under CA systems, the CCs residues left on the soil surface as organic dead mulches can physically impede weed germination and emergence due to a reduction of seed stimulus (temperature, light and moisture) to germination [103]. In addition, during their decomposition, they can exude and release in the soil allelochemicals that have phytotoxic effects on weeds [104]. This phenomenon is variable depending on the climatic conditions, the cover crop species, the amount and type of mulch, and the weed species composition [105].

At cover crop termination, the aboveground biomass represents an important source of soil organic matter input that could determine increases in soil microbial biomass and their respiration and enzymatic activity [106]. The findings of Thapa et al. [107] using variations in the species composition of cover crops showed that the different biomass sources influenced the relative microbial growth and their respective enzymatic activity [108,109]. The presence of a diversified bacterial community can also directly promote crop yields, as different types of plant growth-promoting rhizobacteria are found in agricultural soils. Garland et al. [110] revealed that increased bacterial diversity improves the nitrogen cycle in the soil leading to more efficient use of the added fertilizers. Thus, improved nitrogen uptake by cover crop residue mineralization leads to higher grain yields. The type and number of benefits provided by organic matter from cover cropping are highly dependent on the species that is chosen. For example, crops characterized by succulent tissues and a low C/N ratio (e.g., *Leguminosae*), undergoing mineralization processes, represent sources of available nutrients, especially nitrogen, in the short term (Figure 5) [109]. On the other hand, the phytomass characterized by a high C/N ratio (e.g., *Graminaceae*) with a high lignin content will persist in the soil for a longer time, improving physical characteristics and increasing element exchange capacity (Figure 5) [87]. However, the use of these species must be carefully evaluated concerning the amount of soil nitrogen available for the main crop, to avoid competition between the associated crops or unavailability of the element for the cash crops that will follow [111]. The use of cover crops through improved soil macroaggregate architecture provides diverse microhabitats for soil micro and macro fauna (Table 2). Indeed, optimal soil microstructural organization provides a suitable environment for nematodes to graze on microorganisms [112]. These trophic niches are characterized by important differences in the availability of numerous resources (e.g., SOC and nutrients), physical pore networks, or predation pressures [113]. These microscopic worms are the largest component of the active soil community and serve multiple functions. Primarily, nematodes act on the regulation of carbon cycling [114], biogeochemical cycling of elements [115,116], and in the evolution of soil microbial population composition [117,118], contributing to soil functionality. Diversifying plant species in the cropping system using rotations and cover crops has been shown to promote benefits in agroecosystem functioning [119,120]. The results of the meta-analysis conducted by Kim et al. [121], showed that the use of CCs increases microbial activity and its activity compared to bare fallow. Similar results were also confirmed by the findings of Daryanto et al. [76]. This, most likely, is due to the input of plant biomass and from cover crop root exudates [47] increasing the amount of available carbon main substrate for microbial activity and nematode populations.

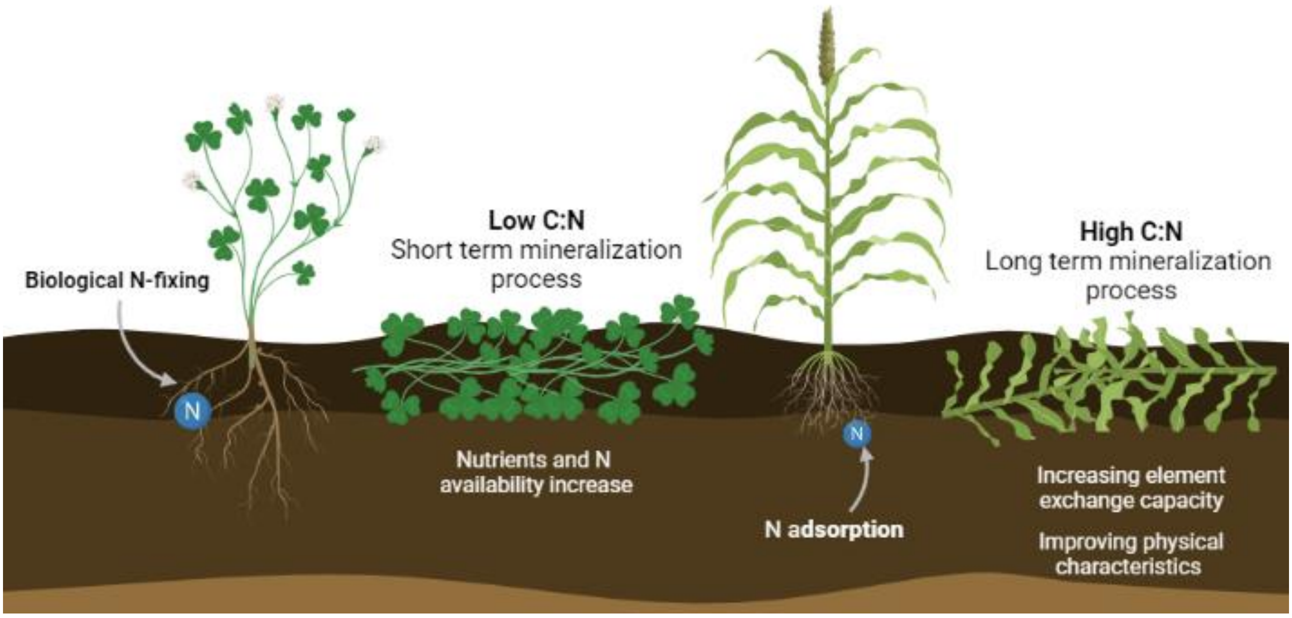

Figure 5. Role of cover crops and their residues on nitrogen cycling in the agroecosystem.

Table 2. Benefits of cropping systems achieved through the use of cover crops.

Cropping Systems Benefits	References
Reduction in inputs	[94]
Reduction of cash crop production costs	[32]
Increase in the biological activity of soils	[99,100]
Reduction of weeds	[103,122]
Reducing infestations for the next cash crop	[123]

Table 2. *Cont.*

Cropping Systems Benefits	References
Release in the soil allelochemicals that have phytotoxic effects on weeds	[104]
Influence soil microbial biomass, soil respiration, enzymatic activity	[106–109]
Support cash crop growth	[124]
Improve tropic niches	[112]
Increasing soil water retention capacity and organic matter content	[125–127]
Increases microbial activity	[47,120,121]

4. Effects of Cover Crops on Greenhouse Gas Emission and Climate Change Mitigation

The term "climate change" refers to anomalous variations of climate conditions that persist over an extended period, usually a few decades or even longer [8]. These phenomena include the increased temperature trends known as global warming, even if they also encompass changes such as sea-level rise and extreme weather events. Climate change has a significant impact on agriculture because it generates several abiotic stresses that reduce plant establishment, growth, and shifts in their blooming [128] and; therefore, it is one of the factors affecting production yields and food security, despite the continued efforts and advances in crop selection and the optimization of agricultural practices [129].

Biomass production is the result of terrestrial plants being able to catch and convert solar radiation through the process of photosynthesis, which, however, can be hindered by undesired climatic variations such as extreme temperature changes and/or low water availability [130]. Due to climate changes that increase flood and drought intensity, cover crop cultivation has recently gained considerable attention due to its benefits in agro-ecosystem services conservation. Indeed, cover crops could represent a valid agricultural management option, which has the potential to increase soil C stocks [131] and contribute to climate change mitigation by sequestering atmospheric CO_2, by increase soil organic carbon (SOC) pools, and offsetting emissions from fossil fuels [132,133]. Recently, it has been estimated that cover crops have the potential to mitigate climate change through C sequestration of up to 0.22 t ha^{-1} year^{-1} of C fixed in their biomass and useful integrated with the agro-ecosystem [40]. Adopting practices of crop diversification, such as cover crops for periods between 4–12 years determine a significant accumulation of organic matter in the soil [134,135]. This is mostly due to the production of biomass from the whole plant is incorporated in the agro-ecosystems, through transformations operated by soil microorganisms, becoming an integrated part of the soil carbon pools [134,136]. In addition, the difference in concentrations and proportions of SOC fractions between available and recalcitrant C pools biomass inputs may have an impact on soil fauna through modifications in their microhabitat and food resources [45,137]. After cover crop termination, the management of the CC residues increases the rate of C input to the soil, thus promoting soil organic matter accumulation that can potentially reduce the use of synthetic fertilizers and, through the production of some secondary metabolites, could reduce pest damage and, therefore, support sustainable agro-chemicals application [37,40,45,138]. However, the intensity and the benefits could differ based on the soil tillage practice adopted for cover crop suppression [38,67,102]. Indeed, the CC biomass could be terminated by incorporating residues into the soil, as green manure under the traditional tillage approach, or left on the soil surface as dead organic mulch under a no-tillage regime [36]. In general, the mineralization of organic residues is faster when CC residues are green-manured compared with CC residue left on the soil surface because there are greater surface contacts of CC residues with the soil microorganisms that in aerobic conditions mineralize more rapidly the organic residues with the release of plant nutrients [139,140]. In addition, higher greenhouse gas emissions are more intensive when CC residues are incorporated into the soil than CC residues left on the surface [141]. Therefore, CCs could also be responsible for

GHGs emissions, especially CO_2, that are commonly associated with CC characteristics such as botanical species, CC phenological stage, residue quality (C: N ratio), and method of CC termination [142]. Several studies have shown that some legume CC species are found to have higher GHGs emissions than other cover crops [142–144]. It was observed that the biomass of CC legume, i.e., vetches or clovers, is characterized by residues with low C: N ratio and therefore decompose faster than grass cover crops, i.e., ryegrass or oat, that are commonly characterized by a high C: N ratio in their residues and, therefore, could cause an increase in nitrous oxide emissions (N_2O) [145–147]. Some findings suggest that the cultivation of mixtures of legume CC and grass CC species could mitigate the excessive biomass mineralization of residues [148]. However, regardless of the CC species, the period of CC termination represents a valuable aspect that affect the C: N ratio of CC residues [149,150]. Indeed, early suppression of cover crops before the flowering stage showed a biomass characterized by a lower C: N ratio than those cover crops that are terminated in the late season, after the flowering stage [151].

Although cover crop residues and their management could be responsible for CO_2 and N_2O emissions from agricultural soils, their impact on GHGs emissions should be evaluated by a holistic approach. Recently, Radicetti et al. [131] showed that the cultivation of cover crops in vegetable cropping systems resulted in a greater C input: C output ratio than conventional cropping systems without the adoption of cover crops, meaning that the carbon accumulated was higher compared with the one that leaves the agroecosystem with crop yield and CO_2 emissions (Table 3). Furthermore, replacing bare fallow with CC provides additional C inputs from plant biomass and rhizodeposition [152], determining a significative impact on soil health and environmental benefits [37,45]. In addition, the findings of Behnke et al. [153] indicate that cover crops can significantly reduce GHG emissions by reducing inorganic soil N, confirming the hypothesis that cover crops reduce N_2O emissions (Table 3). Moreover, if the growing conditions are suitable, some winter CC species can become well established and consequently produce significant biomass in the spring season, reducing air and water pollution without affecting subsequent cash crop yields [153].

Although nitrogen (N) is one of the essential macro-elements in plant nutrition, it is also the main nutrient reintegrated employing fertilization practices each year through the application of synthetic nitrogen. The direct emission from agricultural soils of nitrous oxide (N_2O) is estimated at 1.8 N_2O Tg N year^{-1}; more than half of it is lost from the agro-ecosystems in the form of reactive N forms to the environment due to meteorological variation. This is particularly true in Mediterranean areas, characterized by hot and dry summers followed by torrential autumn precipitations. The amount of N_2O emission due to synthetic fertilizers alone accounted for 0.9 N_2O Tg N year^{-1} [154]. Nitrification is the process of microbial conversion of ammonium ions (NH_4^+) to nitrite and nitrate ions (NO_3^-) under aerobic conditions, and it is also responsible for producing N_2O via denitrification. However, NO_3^- is highly labile and prone to leaching and runoff losses, particularly in well-drained, light-textured soils. Nitrate leaching and contamination of ground and surface water bodies due to generally too severe rain phenomenon led to deterioration of water quality (e.g., eutrophication, algal bloom, loss of biodiversity in rivers and lakes), toxicity for fauna, and also human health problems [98,155–158]. Through the choice of timing of sowing, harvesting, and CC species, farmers can achieve diversified levels of agro-ecosystem benefits when referring to the dynamic nitrogen [159–161]. Furthermore, cover crop management could decrease water erosion and alternate nitrogen cycling microbial groups, and therefore on NO_3^- leaching [162]. The use of cover crops has an improving effect on precipitation storage efficiency (PSE), which has an important role in the sustainability of natural and farm resource use [76]. During the crop cycle, CCs reduce soil water content for the following crop due to the transpiration process [163]. However, if CC residues are left on the soil surface, these can reduce water evaporation [164] and also facilitate soil water retention and infiltration [165], reducing the need for irrigation (Table 3). Specifically, cover crop termination through the incorporation of residues into the soil can have ameliorative effects on soil water storage, succeeding crop yield, and water use efficiency [166].

Another major problem of modern agriculture contributing to the increase in climate change is methane (CH_4) emissions [8]. Specifically, the contribution of agricultural land to CH_4 emissions accounts for ~52% of global methane emissions [167]. Specifically, emissions from rice crops, a staple food for most of the world's population, account for ~48% of global agricultural emissions [168]. The introduction of catch crops can be considered an effective strategy for improving soil carbon storage capacity and hence enhancing the fertility of soil. Concerning rice cultivation and its massive emissions, a long-term experiment was designed to clarify the impact of catch crops on this phenomenon [169], comparing different crops, showed that continuous planting of milk vetch, compared to ryegrass, is a recommended catch crop strategy as it maintains rice yield without increasing CH_4 emissions (Table 3).

Incorporation and decomposition of legumes have a solubilizing effect on N, P, K, and micronutrients (Zn, Mn, Fe, and Cu) in the soil and mitigate the deficiency of different nutrient elements by way of recycling of nutrients [134,170], reducing the leaching and gaseous losses of N and increasing the efficiency of applied plant nutrients [171–177]. In addition to a reduction of synthetic fertilizers, the adoption of cover crops allows for reducing the farming operation contributing to a reduction of fossil fuel consumption. Alonso-Ayuso et al. [178] observed that the use of roller crimping, commonly used for terminating cover crops in conservation agriculture, contributes to reduced energy consumption. In addition, Duzy et al. [179] observed that combining cover crop termination and cash crop sowing reduces fuel consumption by 47% on average, CO_2 emissions by 43–51%, and labor and machinery hours, which can increase production efficiency and reduce the environmental impact. Another effect of climate change is represented by the salinity phenomenon caused by precipitation deficiency. Efficient and sustainable management of agricultural resources can mitigate and overcome the negative effects of drought on cash crop yield [180]. Soil salinity can be recovered through the leaching of salt from the rhizosphere, the modification of agronomic practices at the farm level, and the introduction of salt-tolerant crops [181,182]. Different studies revealed that cover crop residues left on the soil surface in combination with amendments allows the notable reduction of salinity phenomena while maintaining an acceptable level of cash crop productivity [183]. Forkutsa et al. [184] have demonstrated that the use of mulching would notably decrease secondary soil salinization. In this regard, straw mulching is a promising option for farmers to control soil salinity, as it decreases soil water evaporation and regulates soil water and salt movement. Song et al. [185] proved that the better straw method is the combination of surface mulch and straw layer burial. Zhang et al. [186] demonstrated that the presence of a residue layer on the soil, in addition to allowing the reduction of salt concentration, improves crop water utilization compared to bare soil conditions. These results can be considered important in contributing to the resilience of farming systems to climate change.

Table 3. Environmental aspects influenced by the use of cover crops.

Environmental Aspects	References
Increase C and N stocks	[131–136,152,179]
Reduce N_2O emissions,	[153]
influence soil thermal condition	[160]
Increase SOM	[161,187]
Increase soil water storage	[165,166,188–190]
Reduce evaporation	[166]
Improving soil porosity	[191]
Decrease CH_4 emission	[169]
Limit excess soil NO_3^-	[170–174]
Increase the efficiency of applied plant nutrients	[176,177]

Table 3. *Cont.*

Environmental Aspects	References
Reduce energy consumption	[134,178,179]
Mitigate the negative effects of drought	[180,183]
Decrease secondary soil salinization	[184–186]

5. Final Remarks and Future Challenges

There is a lot of scientific evidence that supports the adoption of cover crops as a valid solution for allowing the ecological transition of modern and intensive systems toward sustainable farming systems. Several beneficial effects could be accounted for following the cultivation of cover crops, such as the improvement of soil health, enhancement of nutrient cycling, carbon sequestration and reduction of greenhouse gas emissions, reduction of synthetic fertilizers, and economic returns. Therefore, the introduction of cover crops into agricultural systems can sustain the productive stability of cash crops and increase soil fertility through organic matter accumulation. Furthermore, cover crops may enhance soil structure, water conservation, and aid in pests and weed management.

Most likely, the limited use of cover crops could be due to insufficient evaluation of the short-term economic costs and long-term benefits of introducing cover crops into conventional systems such as conservation, protection, and valuation of natural resources. However, it is also important to note that cover crops could be subjected to practical limitations that require special attention. In fact, not all cropping systems are equally suited to cover cropping, especially when there are long-season cash crop rotations that may not be compatible with a cover crop cultivation period. Although in the long-term period cover crops increase soil, organic matter, soil water infiltration, and soil water capacity, in the short term, cover crop could result in a shortage of available water for the cash crop. Other important limitation includes the cost to establish cover crops and expenditures for new equipment (i.e., roller-crimper). In addition, regardless of the farming system adopted, the termination of cover crops currently represents an unusual and complicated management practice for farmers, which adsorbs time rather than managing cash crops. Therefore, there is a need to expand knowledge on the effects of the use of cover crops through short- and long-term field trials, regarding the implications of using various CCs species in agricultural systems with different climate characteristics to achieve more sustainable global agricultural production, considering that the contribution of cover crops on soil health is crucial in climate change mitigation.

Author Contributions: Conceptualization, V.Q., E.R. and R.M.; methodology, V.Q., E.R., S.R.S. and E.A.; investigation, V.Q. and E.R.; resources, E.R.; data curation, V.Q. and E.R.; writing—original draft preparation, V.Q., E.R., G.H. and A.J.; writing—review and editing, E.R., S.R.S., E.A., G.H., Z.A., S.B., A.J. and R.M.; visualization, E.R., S.R.S., E.A., G.H., Z.A., S.B., A.J. and R.M.; supervision, E.R. All authors have read and agreed to the published version of the manuscript.

Funding: This research is a part of Valentina Quintarelli's Ph.D. thesis entitled "Impact of sustainable agronomic practices for the improvement of agricultural production", funded by the University of Ferrara. The manuscript is funded under the National Recovery and Resilience Plan (NRRP), Mission 04 Component 2 Investment 1.5–NextGenerationEU, Call for tender n. 3277 dated 30 December 2021.

Institutional Review Board Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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