Conservation Tillage in Medicinal Plant Production

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Contributor: Da-Cheng Hao , Cheng-Xun Li , Pei-Gen Xiao , Hong-Tu Xie , Xue-Lian Bao , Lian-Feng Wang

The application of no-tillage (NT) has a long history and can reduce tillage frequency and intensity and protect soil from erosion and deterioration. NT is often combined with organic mulch to significantly reduce soil disturbance. NT and stover mulching have the advantages of saving manpower and resources and improving soil quality, crop yield, and quality. The ecological and economic benefits of NT in long-term medicinal plant cultivation could be prominent. Soil health is associated with various agronomic and environmental benefits, which are deemed essential for the optimal production of medicinal plants. Soil health indicators include physical, chemical, biological, and other ones, all of which can be influenced by NT and relevant manipulations.

no tillage   reduced tillage   stover mulch   medicinal plant

1. Effects on Soil Structure and Physical Properties

Various conservation tillage approaches, such as straw mulching and ST, can protect soil and improve soil structure [1]. In the Loess Plateau of Northwest China, the alternation pattern NT/CT/ST significantly increased the mechanically stable aggregates and water-stable aggregates, with an increased mean weight diameter and geometric mean diameter. In the 0–20 cm soil layer, NT/CT/ST reduced the soil bulk density (SBD) and increased the soil porosity. In a study of long-term maize production modes suitable for loess dryland, the SBD was lower under NT/ST rotational tillage [2]; in the 0–60 cm soil layer, it averaged 1.31 g/cm^3. In a continuous tillage cultivation positioning trial, the mean weight diameter, geometric mean diameter, and >0.25 mm aggregate content of ST straw cover were 27.3%, 17.5%, and 7.6% more than CT straw cover, respectively [3].

In the chickpea field of India, it is essential to find a compatible combination of tillage and crop residue management for achieving sustainable food production by improving soil properties and providing a favorable environment to crop plants [4]. NT with 60 cm residue height (NT60) led to lower SBD and higher soil moisture content than that of NT30, and the SBD under NT30, NT60, RT30, and RT60 was higher than that under CT. In the maize fields of Iraq, compared with RT and DT, CT decreased SBD but increased soil water content [5]. The soil surface under NT/RT with residue retention is usually colder and wetter, and SBD is higher than that under CT, which could affect the growth of plant roots and the absorption of nutrients. While paying attention to reducing the frequency and intensity of tillage, DT and ST have the potential to break the compacted zone in the soil, leading to a better soil structure and crop yield.

The effects of NT/RT on SBD have been inconsistent among studies, as the subjective and objective factors that affect the implementation of NT/RT are very complex. In the trial of Daodi medicinal materials *Radix glycyrrhizae* and *Radix isatidis*, NT straw mulching reduced the SBD and aggregate damage rate [6], increased soil total porosity, and saturated hydraulic conductivity. The intercropping of spring wheat and licorice, and potato and alfalfa can improve soil physical properties. In the trial of wheat-*Isatis indigotica* dual sequence rotation, conservative tillage reduced the SBD, increased total porosity [7], and significantly improved saturated hydraulic conductivity. These results can only be observed in long-term experiments, and some short-term studies of one to two years cannot observe such effects.

The ecological environment is closely related to the growth, development, and quality formation of medicinal herbs. Ginseng has stringent requirements for the natural environment, often growing in damp valleys with abundant forests. Various ecological factors, e.g., light, temperature, altitude, water, and edaphic factors, impact the shape and ginsenosides of ginseng. It was found that soil physical factors, especially SBD, were more important ecological factors affecting the shape of ginseng [8]. When SBD was between 0.85 and 0.95 g/cm^3, the ginseng roots had the best growth and development, with excellent yield and quality. When SBD was above 1.0 g/cm^3, the development of ginseng roots was limited, with a significant increase in short branches, resulting in a noteworthy decrease in ginseng quality and yield. The optimal SBD and other soil conditions could be achieved via NT/RT and understory planting [9]. Temperature is the dominant ecological factor affecting the accumulation of ginsenosides in ginseng [8] and could also be regulated by conservation tillage.

During the potato tuber formation stage in southern Ningxia, China, the straw mulch significantly reduced the average soil effective accumulated temperature by 18.7% [10], in comparison with no mulching plots. In the trial of wheat-*I. indigotica* rotation, NT and straw cover significantly increased the soil temperature during low temperature seasons [7] and effectively reduced the soil temperature during high temperature seasons, which helped crop emergence and root growth.

2. Effects on Soil Erosion

Presently, the total planting area of Chinese medicinal materials (CMMs) in China is about 5.56 million hm^2 [11], with trees and shrubs accounting for about 58% and herbs and vines accounting for about 42%. The planting area of 191 commonly used CMMs is about 3.85 million hm^2, accounting for 69.2% of the total area, with herbaceous plants accounting for a relatively large proportion. As a series of policies that prevent “non-grain” of cultivated land have been promulgated [12], farmland-grown medicinal plants are being replaced by food crops. Many medicinal plants are very much like weeds, which are self-growing, do not need to compete with food crops for farmland, and have strong adaptability to the NT/RT environment [13]. Therefore, in some areas of rolling topography, especially in mountainous and hilly rural areas in the central and western regions of China, abandoned land on slopes can be fully utilized to plant perennial/biennial herbaceous medicinal plants under NT/RT, e.g., *I. indigotica*, *Pseudostellaria heterophylla*, and *Nepeta cataria* (**Figure 1**). When tillage is at right angles to the direction of the slope, it is referred to as contour tillage [14], an acknowledged form of conservation tillage. According to local climate and soil, medicinal plants that are suitable for local growth can be selected for NT/RT cultivation, which not only reduces soil erosion and runoff and loosens the soil but also brings certain economic benefits to farmers.

Figure 1. Examples of NT, RT, organic mulch, and understory planting in eight major production areas of terrestrial TCM plants. I, Northeast China: Aco, *Aconitum coreanum*; Ak, *Aconitum kusnezoffii*; Al, *Atractylodes lancea*; Asm, *Astragalus membranaceus*; Bc, *Bupleurum chinense*; Cp, *Codonopsis pilosula*; Ek, *Epimedium koreanum*; Es, *Eleutherococcus senticosus*; Hr, *Hippophae rhamnoides*; Ii, *Isatis indigotica*; Pag, *Panax ginseng*; Pl, *Paeonia lactiflora*; Sb, *Scutellaria baicalensis*; Sc, *Schisandra chinensis*; Sd, *Saposhnikovia divaricata*; Sim, *Silybum marianum*; Te, *Tagetes erecta* [15][16][17][18]. II, North China: Am, *Atractylodes macrocephala*; Ana, *Anemarrhena asphodeloides*; Cf, *Cymbidium faberi*; Cm, *Chrysanthemum morifolium*; Fs, *Forsythia suspensa*; Gb, *Ginkgo biloba*; Ii; Pg, *Platycodon grandiflorus*; Pot, *Polygala tenuifolia*; Ps, *Polygonatum sibiricum*; Sm, *Salvia miltiorrhiza* [19][20][21][22][23][24]. III, East China: Al; Ar, *Anoectochilus roxburghii*; Bs, *Bletilla striata*; Cm; Cy, *Corydalis yanhusuo*; Dh, *Dendrobium huoshanense*; Dn, *Dendrobium officinale*; Ge, *Gastrodia elata*; Lj, *Lonicera japonica*; Oj, *Ophiopogon japonicus*; Pc, *Polygonatum cyrtonema*. Pp, *Paris polyphylla*; Pq, *Panax quinquefolium*; Th, *Tetrastigma hemsleyanum* [25][26][27][28][29][30][31][32][33]. IV, Southwest China: Ac; Ad, *Angelica dahurica*; Ah, *Arisaema heterophyllum*; Am; Bs; Cc, *Codonopsis cordifolioidea*; Cp; Cs, *Camellia sinensis*; Eu, *Eucommia ulmoides*; Ft, *Fagopyrum tataricum*; Gb; Ge; Gr, *Gentiana rigescens*; Ii; Lb, *Lilium brownii var. viridulum*; Lic, *Ligusticum chuanxiong*; Lyc, *Lysimachia christinae*; Nc, *Nepeta cataria*; Pa, *Plantago asiatica*; Pag; Pb, *Paris bashanensis*; Pc, *Polygonatum cyrtonema*; Pg; Ph, *Pseudostellaria heterophylla*; Pit, *Pinellia ternata*; Pk, *Polygonatum kingianum*; Pn, *Panax notoginseng*; Ps; Pst, *Psammosilene tunicoides*; Ro, *Rheum officinale*; Zo,

Zingiber officinale [34][35][36][37][38][39][40][41][42][43][44][45][46][47]. V, South China: Ae, *Aspidistra elatior*; Alk, *Alpinia katsumadai*; Amv, *Amomum villosum*; Ao, *Alpinia oxyphylla*; Arc, *Areca catechu*; Bis, *Biancaea sappan*; Ds, *Desmodium styracifolium*; Ia, *Ilex asprella*; Sg, *Sarcandra glabra*; Ss, *Spatholobus suberectus*; Tm, *Taxus × media* [48][49][50][51][52][53][54][55]. VI, Inner Mongolia: None. VII, Northwest China: Asm, *Astragalus membranaceus*; Av, *Apocynum venetum*; Bc; Cd, *Cistanche deserticola*; Cp; Ct; Cys, *Cynomorium songaricum*; Eps, *Ephedra sinica*; Eu; Fv, *Foeniculum vulgare*; Gm, *Gentiana macrophylla*; Gu, *Glycyrrhiza uralensis*; Ii; Lc, *Lycium chinense*; Lj; Lr, *Lycium ruthenicum*; Ro; Rp, *Rheum palmatum*; Tc, *Tamarix chinensis*; Zj, *Ziziphus jujuba* [56][57][58]. VIII, Qinghai-Tibet Plateau: Crs, *Crocus sativus*; Gu; Lar, *Lamiophlomis rotata*; Nac, *Nardostachys jatamansi*; Pc, *Pyrola calliantha var. tibetana*; Pis, *Picrorhiza scrophulariiflora*; Sh, *Sinopodophyllum hexandrum* [59][60][61][62].

Rainfall is scarce in the arid inland areas of Northwest China, and water is the main factor limiting agricultural production. When producing perennial medicinal plants, e.g., *Lycium chinense*, *Ephedra sinica*, and *Glycyrrhiza uralensis* [63] (**Figure 1**), in saline fields, NT measures should be adopted to help achieve plant coverage throughout the year, reduce surface evaporation, and prevent secondary soil salinization [64]. NT is beneficial for water storage and moisture preservation, as well as for plant root development and soil water infiltration, so as to reduce runoff erosion. The northwest inland agricultural region suffers from frequent sandstorms and severe wind erosion, where conservation tillage is highly recommended for reducing water/wind erosion and boosting soil fertility [65].

In the Loess Plateau, the runoff and sediment content under CT treatments were greater than those under NT straw mulching [6]. NT straw cover effectively reduced the runoff and erosion of slope farmland and reduced the loss of soil nutrients. Under artificial simulated rainfall conditions, NT straw cover reduced the runoff by 20.3% to 56.2% and sediment yield by 38.1% to 76.8% as compared to CT; it reduced the runoff by 5.0% to 28.5% and sediment yield by 12.9% to 52.3% as compared to NT alone. In winter wheat monoculture in dry areas, when compared to CT, conservation tillage during the fallow period increased precipitation storage efficiency, soil water storage at wheat planting, and wheat yield by 31.0, 6.4, and 7.9%, respectively [66], but did not affect evapotranspiration or water use efficiency (WUE). In the common beans field of Uganda, NT decreased the surface runoff volume and suspended sediment concentration while increasing the infiltration rate and soil moisture content [67]. The effects of tillage and mulching on soil water conservation, crop yield, and water use varied with soil and climate conditions.

3. Effects on Soil Moisture

The positive effects of NT on soil moisture are closely associated with its effects on soil structure and erosion. In Mollisols of Northeast China, NT with stover mulching significantly increased the soil water content and root-associated organic carbon [68] and decreased soil pH. In Henan, China, NT showed better effects on soil moisture conservation and yield increment than ST treatment in dry years [69]. In winter fallow paddy fields in South China, the enzyme activities and total soil porosity in the NT forage wheat and Italian ryegrass fields decreased, and the water content and soil capillary porosity increased when compared to those of the CT field [70]. NT also increased the number of species and aboveground weed biomass. In India, MT and the accumulation of leaf litter result in moisture conservation and low weed infestation [71]. In the trial of wheat-*I. indigotica* rotation, under different rotation modes, NT straw cover significantly increased the soil moisture content of the tillage layer [7]. In the semi-arid Loess Plateau of Gansu, China, the NT straw mulch treatment led to the lowest soil bulk and pH and the highest total nitrogen (TN), NO_3−-N, and available P [72], which were accompanied by higher soil water content as compared with that of CT. In the chickpea field of India, NT60 led to a higher soil moisture content of 22.7% [4].

In the common beans field of Uganda, NT and stubble-mulching improved soil water storage by 46 and 45%, respectively [73], compared with CT in the 0–100 cm soil depth over 14 months. In the study of long-term maize production mode, the NT ↔ ST treatment showed a good water storage effect [2]. Compared to CT, the NT ↔ ST treatment led to good soil moisture status during the growth period of spring maize. In the arid region of Southern Ningxia, ST plowed at 40 cm with straw mulch significantly increased soil water storage by 33.4% compared with plowing 15 cm without mulch [10]. In the tea garden of East Anhui, DT significantly increased soil water storage space and enhanced the water holding capacity of the soil [74]. Compared with NT, the soil moisture of the 15–30 cm soil layer increased by 7.7% under DT. These data suggest that the most appropriate conservation tillage practice varies for different crops and different locations.

4. Effects on Soil Fertility

The positive effects of NT on soil fertility are intricately linked with its impact on the physical/biological properties of soil. It is well accepted that conservation tillage often improves soil fertility in agriculture [75][76] (**Figure 2**). In Sweden, compared with CT for moldboard plowing, NT and non-inversion MT increased the concentrations of SOC, TN, and microbial biomass carbon (MBC) in the upper 20 cm [77]. In Germany, MT increased SOC, TN, and MBC in the top 10 cm, while CT increased MBC contents and SBD between 20 and 30 cm of soil depth. In Romania, MT did not significantly change soil parameters, whose working depth of 25 to 30 cm was similar to that of CT. In Spain, NT pointedly increased the concentrations and stocks of C, N, and MBC. In Southern Italy, in the surface layer (0–15 cm depth), the SOC content and TN were significantly increased by NT [78], but no such effects were observed in the deep layers (30–60 and 60–90 cm). The C/N ratio showed a more equilibrated rate in the NT system, which was accompanied by the best physical characteristics of soil, showing a higher stability index compared to CT and RT. The effectiveness of NT/MT could heavily rely on site conditions, e.g., pH, soil texture, and climate.

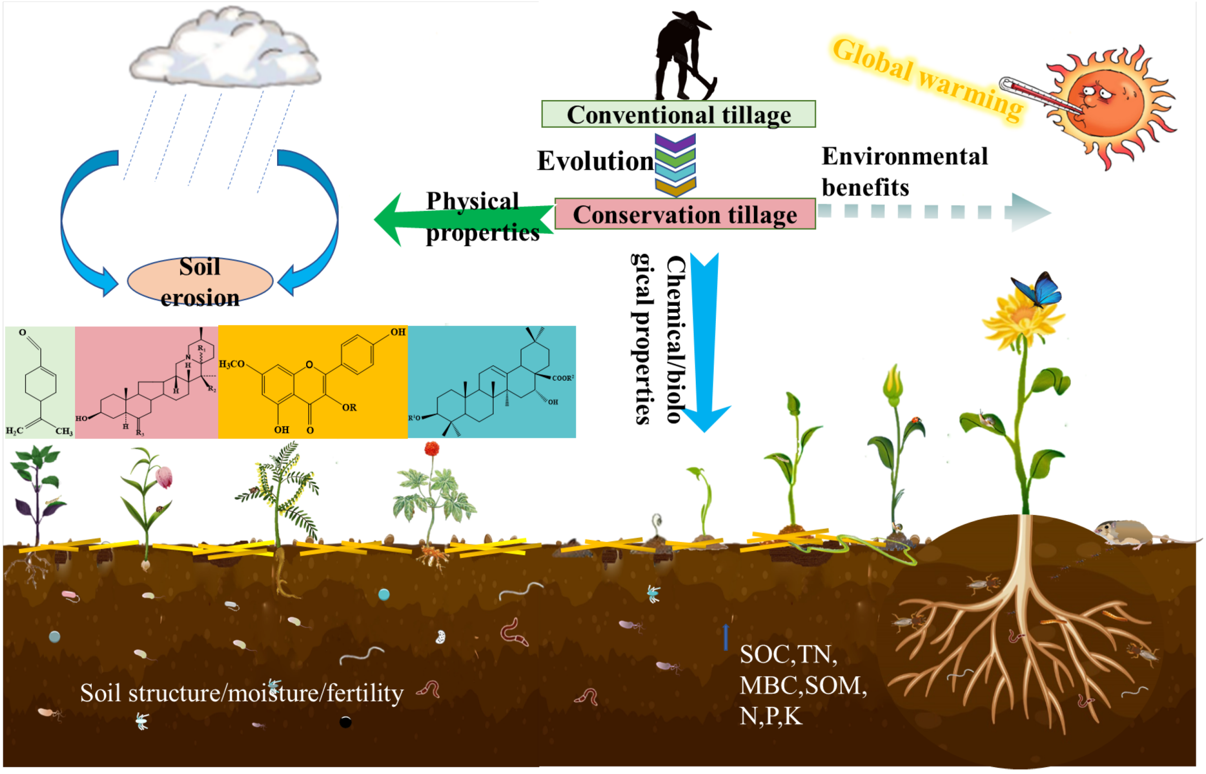

Figure 2. Advantages of conservation tillage in medicinal plant production. The medicinal crops displayed from left to right are *Perilla frutescens* (representative medicinal compound: perillaldehyde), *Fritillaria cirrhosa* (5α-cevanine alkaloids), *Astragalus membranaceus* (rhamnocitrin), *Codonopsis pilosula* (pentacyclic triterpene saponins), and *Chrysanthemum morifolium*. Conservation tillage, which evolved from CT, impacts the entire growth process of medicinal crops and the production of medicinal compounds. NT, RT, and organic mulch have profound effects on soil physical and chemical properties, biodiversity, and soil biota, as well as ecological environments. A variety of biotic and abiotic stress factors act on medicinal plants both aboveground and underground, and moderate stress could stimulate the production of medicinal compounds.

In the Loess Plateau, NT/CT/ST significantly increased the soil TN and SOM contents [1], with reduced soil total phosphorus and total potassium contents. The multi-year average grain yield of spring maize in NT/CT/ST was 10.2% higher than ST and 4.8% higher than ST/CT. In Northeast China, the treatments of NT33 (33% stover mulching ≈ 2500 kg/hm^2) and NT100 (full mulching) increased the polysaccharide content of the top layer and mid-layer soils [79]. NT33 reduced the diversity of carbon components in topsoil, while NT100, if corn stover resources were sufficient, maintained the carbon stability of three soil layers. NT67 increased carbon stability in the deep layer of soil. In the study of long-term maize production mode, the NT ↔ ST treatment effectively increased the organic carbon storage in the 0–60 cm soil layer [2], which was 54.3 t/hm^2. In Moso bamboo forests, the combined intensive management, i.e., DT, fertilization, and organic material mulching, significantly increased the concentrations of available potassium, available nitrogen, available phosphorus, NH_4^+, NO_3^-, SOM, TN, and total phosphorus [80], but decreased pH, which was accompanied by a lowered Shannon diversity of the soil and rhizome/root microbiota and a relatively stable community composition and function.

In the soybean fields of Brazil, the NT systems were more efficient in accumulating labile and stable C fractions with values close to those of native soil [81] and were directly related to lower soil N_2O emissions. NT increased the SOM fractions such as MBC, permanganate-oxidizable carbon, particulate organic carbon, inert carbon, and humic substances. Cover crops, e.g., pea, rapeseed, and wheat, can increase the contents of SOM, alkali-hydrolyzable nitrogen, and enzymatic activities [82], and suppress bacterial wilt. The performance of different cover crops differed in recovering soil properties. For instance, rapeseed inhibited bacterial wilt more effectively than wheat and pea, while wheat was the best at increasing SOM, urease, and invertase, and pea improved catalase better than the other two. The medicinal plant *Perilla frutescens* was used as a cover crop in ginseng farmlands [83]. When compared with the control, the SOM content was increased, the SBD was decreased, and the fertility in the 0–20 cm of soil layer was increased. The soil's microbial diversity improved. Compared to the untreated lands, the survival rate of ginseng seedlings increased by 21.4%, and the physiological indices of ginseng were better than the controls. The application plan for cover crops needs to be carefully considered from various angles, such as technology, economy, and environment.

5. Effects on Biodiversity and Soil Biota

Conventional agriculture contributes worryingly to biodiversity losses, partially due to high stock densities, heavy use of pesticides and fertilizer, monocultures, and the CT approach [84]. Radical changes in tillage modes are required, not only to address the loss of biodiversity but also to ensure food and medicine security in the future. NT/RT and organic mulch could be the “back to basics” solution to improving soil quality and biodiversity while maintaining or improving productivity and profitability. The impact of NT/RT on biodiversity and soil organisms largely determines its success or failure, as soil organisms largely shape the physical and chemical properties of the soil.

5.1. Bacteria and Archaea

In Mollisol, Northeast China, NT without stover mulch (NT0) and NT stover mulch, as low-disturbance practices, manifestly promoted soil bacterial species richness and diversity [68] and enriched potential metabolic diversity. When compared to the bacterial communities in CT, the vertical dissimilarity of bacterial communities in NT0 decreased, but straw mulch enhanced the uniqueness of community composition at each layer. In redundancy analysis (RDA), it was shown that NT and stover mulch had differential effects on the dominant nitrogen metabolism community in black soil [85]. The abundance of the denitrifying gene *nirS* was positively correlated with *Nocardioides* (Actinobacteria), a β-Proteobacteria genus, and an Acidobacteria genus, and was negatively correlated with soil pH, ammonia nitrogen, and a Chloroflexi genus [85]. The soil pH was positively correlated with ammonia nitrogen, TOC (total organic carbon), TN, a Candidatus Rokubacteria genus and a Gemmatimonadetes genus, and was negatively correlated with nitrate nitrogen, *Nocardioides*, and *Solirubrobacter*. In pairwise comparison, a Nitrosopumilales genus and a Thaumarchaeota genus were more abundant in NT0 than in NT100 [85], while the ammonia-oxidizing archaea (AOA) Nitrososphaeraceae genus and *Candidatus nitrosocosmicus* were more abundant in NT100, suggesting the effect of stover mulch on the archaea community.

In the indoor incubation of Mollisol, the moisture/gas regime meaningfully affected the microbial community diversity rather than community richness [86]. The key responsive bacterial classes under different gas conditions were γ-proteobacteria, Bacteroidia, and α-proteobacteria, in contrast to Actinobacteria, α-proteobacteria, and Thermoleophilia under different moisture regimes. The abundance of Piscinibacter, Chujaibacter, Symbiobacteraceae, and Acidobacteriales was positively correlated with moisture and N_2O emission, and denitrification, nitrate reduction to ammonium, nitrification, and nitrogen mineralization/fixation were the dominant processes of the nitrogen cycle in black soil. The hub nodes and connection modes of the microbial nitrogen-cycling network differ under six moisture/gas regimes, and the same species could be active in multiple major nitrogen turnover processes simultaneously. NT and stover mulch may influence the soil's microbial diversity/richness by regulating soil moisture and/or gas conditions.

In the trial of wheat-*I. indigotica* rotation, conservation tillage effectively improved the soil enzyme activity and microbial count [7]. The activities of urease, alkaline phosphatase, sucrase, and catalase in the soils of different depths were expressed as NT straw mulch > NT > CT. The average activities of hydrolases and oxidoreductases in the 0–30 cm soil were also NT straw mulch > NT > CT. The rotation of conservation tillage with *I. indigotica* → wheat improved soil hydrolase and catalase activities. From CT to NT straw mulch, the overall number of microorganisms in each layer of the rotation soil gradually increased. The average number of bacteria, actinomycetes, fungi, and total number of microbes in the 0–30 cm soil were NT straw mulch > NT > CT. The number of soil bacteria and total number of microbes in the wheat field were reduced by about 10 times compared to those in the *I. indigotica* field. In Argentina, soil enzymatic activities were higher in NT than in CT, and enzymatic profiles responded to the changes much earlier than the overall prokaryotic community structure [87]. Comparable β-diversity was observed in both 27 year old NT soils and new NT soils 30 months after switching from CT to NT. The NT responsive bacteria and archaea OTUs were associated with coarse soil fractions, SOC, and C cycle enzymes, while CT responders were related to fine soil fractions and S cycle enzymes. In Uruguay, only after five years of RT + cover crops has soil health improved under intensive vegetable farming systems [88]. RT + cover crop increased soil aggregation, SOC, nutrient availability, and microbial α-diversity, rendering soils more similar to an adjacent undisturbed site.

In Brazil, enzyme activities can be used to estimate the soil quality of the Cerrado biome [89], where cotton, soybeans, and corn are cultivated. Cover crops such as *Brachiaria* grass and NT improved the activities of β-glucosidase, acid phosphatase, and arylsulfatase, suggesting the importance of regenerative management practices for the sustainability of agroecosystems in sandy soils. The cover crop treatments increased the relative abundance of plant-beneficial bacteria, which was negatively correlated with the disease index [82]. Wheat was the best at improving the growth of plant-beneficial bacteria, followed by rapeseed. The pea treatments enriched nitrogen-cycling bacteria. On the other hand, cover crops reduced the relative abundance of pathogens and denitrifying bacteria. The count of bacteria genes involved in nutrient cycling, antibiotic synthesis, and biodegradation of toxic compounds was increased by cover crops, especially wheat. Microbial activity, prokaryotic community, and soil health could be regulated by conservation tillage; meanwhile, water and nitrogen management in the soil need to be coordinated to achieve sustainable production [90].

5.2. Fungi

In agricultural soil, bacteria, archaea, and fungi do not share a common response to land management change [91]. In Spain, the vineyard tillage inhibited the disease-resistant *Trichoderma* populations in the soil [92], which makes us wonder whether NT would boost beneficial fungi to attain the disease-suppressive soil [93]. In the south of West Siberia, half of the identified OTUs (operational taxonomic units) were Ascomycota [94], and the phyla Basidiomycota, Zygomycota, Mortierellomycota, Chytridiomycota, and Glomeromycota showed tillage-related differential abundance. Wheat residues could increase the abundance of dominant genera *Mortierella*, *Chaetomium*, *Clonostachys*, *Gibberella*, *Fusarium*, and *Hypocrea* as compared with undisturbed soil. NT shifted the soil mycobiome composition closer to the undisturbed soil.

In winter wheat fields, around one-third of the fungal genera differed greatly between CT and non-inversion RT [95]. The influences of tillage and pre-crop were much greater than those of fertilization; for example, the phytopathogen *Fusarium* was significantly enriched in the intensively fertilized RT fields with the pre-crop maize, but *Phoma* showed a significant association with CT and pre-crop rapeseed. In another winter wheat study, the non-inversion RT enhanced the effects of the preceding crop on plant growth and fungal communities on plant roots and in the soil [96]. RT increased the abundance of putative phytopathogens such as *Parastagonospora* sp. but reduced *Fusarium culmorum*/*graminearum*, thereby impacting crop health and yield. Many beneficial arbuscular mycorrhizal fungi (AMF) of Glomeromycota also reacted differentially to farming practices [95].

In a 10 year NT mulching experiment, the frequency of stover mulching, rather than its amount, significantly influenced the soil microorganism and nematode communities [97]. The high mulch frequency treatments promoted the correlation between bacterial PLFAs (phospholipid fatty acids) and bacterivores as well as more carbon flow into the soil micro-food web; low mulch frequency increased the correlation between fungal PLFAs and fungivores, and a relatively stable micro-food web was developed. The structure and activity of decomposition pathways are determined by the bottom-up effects of different stover mulching frequencies.

Soil inversion tillage destroys fungal hyphae and negatively influences AMF production of glomalin protein [98]. Even after three years of the NT system, aggregate and glomalin t values were considerably lower as compared to values from continuous pasture for 15 years. With different cover crops, the diversity of AMF, values of spore density, root colonization, and glomalin content were not significantly different. Applying nitrogen fertilizer did not affect the AMF activity in the investigated cover crops.

5.3. Nematode

Many soil nematodes feed on bacteria, fungi, and herbs, all of which are essential parts of the soil micro-food web. Increasing physical disturbance is detrimental to nematode community abundance and diversity, subsequently affecting the stability and sustainability of the edaphic ecosystem. Tillage significantly reduced the overall abundance and richness of nematode communities over time [99]. The abundance and richness of bacterial feeders, predators, and omnivores were reduced. Unlike tillage, minimal disturbance, such as the removal of surface litter, only significantly decreased the abundance of three genera: *Acrobeles*, *Aporcelaimellus*, and *Boleodorus*. Tillage significantly reduced the functional metabolic footprint of nematodes, their metabolic activity, and C inflow and impaired the structures of the soil food web. In 10 European long-term field experiments, tillage, rather than organic matter addition, strongly influenced nematode communities [100]. Compared to CT, RT increased nematode diversity, nematode community stability, structure, fungal decomposition channel, and number of herbivorous nematodes. Total and labile organic carbon, available K, and microbial parameters had a large impact on nematode community structure. Nematode communities are sensitive indicators of soil quality, and molecular profiling helps reveal the effects of conservation tillage on soil quality. In a 12 year NT system, mulching significantly influenced the production and respiration of fungivorous nematodes [101], and the effects of 100% mulching were much stronger than those of no mulching, 33% mulching, and 67% mulching. More basal C flowed into the fungal decomposition pathways, and fungivores contributed more to soil carbon sequestration through the decomposition of recalcitrant nutrients from residue. Residue mulching increased the metabolic footprints of nematode communities and the carbon use efficiency of fungivores and omnivore-predators and enhanced the potential of soil carbon sequestration through the metabolic processes of different nematode trophic groups. The effects of different types of conservation tillage on population densities of various nematode species in monocropping and multicropping systems are being revealed [102], as are the effects of tillage on nematode distribution in the soil profile, as well as the effects of conservation tillage on nematode control. The role of nematology in conservation tillage research should be further highlighted.

5.4. Earthworm

CT decreases the abundance and biomass of earthworms and alters their community structure, and less intensive soil cultivation practices increase earthworm populations and their contributions to ecosystem functioning [103]. In spring corn planting areas of Northeast China, NT and full stover mulching (NT100) significantly increased the number and weight of earthworms per unit area of Mollisols [104], as compared to conventional ridge tillage. In an irrigated maize cropping system in Colorado, conservation tillage enhanced macrofauna, especially earthworm abundance and diversity [105]. Strip tillage led to a higher infiltration rate and higher abundance of macrofauna than CT, while MT had greater species richness than CT (4.1 vs. 2.0 taxa/sample). Residue cover was positively correlated with earthworm abundance, which was also positively correlated with aggregated stability and infiltration. Strip tillage and MT increased the net economic return relative to CT. In forty NT sites and six native Atlantic Forest fragments of Southern Brazil, eighteen earthworm species were found [106], belonging to the families Acanthodrilidae, Glossoscolecidae, Megascolecidae, Rhinodrilidae, and Ocnerodrilidae, of which ten were native and eight exotic. NT agroecosystems had larger earthworm populations and higher species richness than native forests [107], mainly due to the colonization of exotic species in the former.

5.5. Arthropod

Conservation tillage combined with cover crops or mulching may enhance natural enemy (e.g., arthropod) activity in agroecosystems by reducing soil disturbance and increasing habitat structural complexity [108]. Weed seed predation by arthropods can increase with vegetation cover and RT, as they may improve the quality of habitat for weed seed foraging. In Brazil, arthropod diversity and guild composition were similar between NT and CT [109], but their abundance was higher under NT, where residues from the preceding crop were maintained in the field. Thirty-four arthropod species were recorded, and *Hypogastrura* springtails, *Empoasca kraemeri*, *Circulifer* leafhoppers, and *Solenopsis* ants were significantly impacted by NT. The infestation levels of major insect pests, especially leafhoppers, were around seven-fold lower under NT + crop residues, whereas the abundance of predatory ants and springtails was much higher under NT than under CT. There was a significant trophic interaction among crop residues, detritivores, predators, and herbivores, which was associated with higher bean yield under NT. NT and crop residue retention can reduce infestation by foliar insect pests and increase the abundance of predators and detritivores, which are conducive to insect pest management.

The pollinator *Peponapis pruinosa* (squash bee) preferred excavating nests in the most disturbed soil zones, i.e., strip-tilled rows and CT edges [110]. In the RT system, the strip-tilled row had significantly more nests than the NT edge. These suggest that soil tillage practices influence *P. pruinosa* nesting choice, and production practices should be considered to protect pollinators. In a 17 year fertilization experiment, biennial organic amendments were insufficient for promoting soil organisms in the long run [111] and should be combined with NT or RT to attain a beneficial effect on soil quality.

6. Effects on Weeds

Effective control of weeds on farmland is one of the chief indicators for the successful implementation of NT technology. NT/RT and stover mulching/crop residue coverage help inhibit the growth of weeds and reduce the use of chemical herbicides [112][113]. NT causes less soil damage, and weed seeds are rarely exposed and difficult to germinate. The weed control through straw mulch benefits from various physical and chemical factors. Physical factors include shading and lower soil temperature [10], while chemical factors include microbial metabolites, pH changes, and plant allelopathy [114]. Plants produce allelochemicals, which are released into the soil after the decay and leaching of straw and inhibit the germination of weed seeds and the growth of seedlings. These allelochemicals include specialized metabolites such as glucosides, phenols, terpenoids, alkaloids, and hydroxamic acids, which are widely distributed in crop residues/cover plants. For example, benzoxazinone- β- D-glucoside is a typical allelochemical of Poaceae [115].

Ryegrass only releases a small amount of phytotoxic benzoxazinone compounds during its lifespan, but its straw mulch can release up to 1.2–2.0 g/m^2 [115], so it can be used to inhibit weeds before the next crop of corn. Under controlled conditions, rye straw mulch significantly inhibited the broad-leaved weeds; it inhibited the germination and seedling growth of *Amaranthus retroflexus* and *Portulaca oleracea* and strongly inhibited the growth of *Chenopodium album*. Retaining high residues of rye effectively inhibited weeds in NT soybean production [116]. Retaining high stubble significantly increased soybean yield when weed biomass was high [117]. In the Mid-Atlantic United States, cover crop-based, organic rotational NT production systems utilize cover crop surface mulch as the primary within-season weed control tactic [118]. High-residue cultivation reduced total weed biomass across locations; total weed biomass was negatively correlated to soybean yields.

In the soybean field of Iran, the tillage system and weed management regime significantly influenced the seed yield, pod number per plant, seed number per pod, weed density and biomass [119], while their interaction significantly influenced the weed density, weed biomass, and seed number per pod. In NT row crop seeding and NT seed drilling, non-weeding led to the highest weed density, while herbicide + hand weeding led to the lowest one. Thus, moderate weeding may be carried out according to the production purpose. In India, the positive returns from understory MT are attributed to low weed growth and less disturbance to the soil [71].

On the other hand, case studies in the United States suggest that weeds growing in fall-planted cover crops can provide ground cover [120], decrease potential soil losses, and effectively retain nitrogen. In certain circumstances, weeds in cover crops enhance ecosystem service provisioning. If weeds are herbicide-resistant, cover crops should be managed to limit weed biomass and prolificacy. Therefore, the extent to which weeds should be allowed to grow in a cover crop is largely context-dependent. In the northern grain region of Australia, the major weeds before tillage trials were *Polygonum aviculare*, *Sonchus oleraceus*, and *Avena fatua* [121]. Tillage promoted the germination of other weeds, such as *Hibiscus trionum*, *Medicago sativa*, *Vicia* sp., *Phalaris paradoxa*, and *Convolvulus erubescens*. As compared with CT/RT, SB (straw burning) + NT, and NT provided ideal media for weeds to germinate and resulted in heavy infestations of weeds, which might not be good in grain production but might be innocuous in medicinal plant production. Competition between weeds and medicinal plants can produce certain stress effects [122], which may elicit the biosynthesis of specialized metabolites [114][123], which is beneficial for improving the quality of herbal medicine products. The moderate retention of weeds could help maintain high biodiversity in the agroecosystem [124], which is advantageous for pathogen and pest control. A trade-off between weed suppression and the selection of more competitive weed communities by introducing agroecological service crops should be evaluated in the long run. In general, conservation tillage positively impacts crop productivity under adverse climate conditions and in various agroecological conditions [125], despite the increase in weeds.

7. Effects on Pests/Natural Enemies

NT and cover crops help protect annual crops from insect pests by supporting populations of resident arthropod predators [126]. The best pest management consequences may occur when biocontrol is boosted by planting cover crops and broad-spectrum insecticides are disused. Cover crops can promote natural-enemy populations against insect pests. The inclusion of winter and interseeded cover crops in organic agronomic crop rotations is recommended to gain environmental benefits without increasing the risks of damage by insect pests [127]. In reducing the intensity and frequency of tillage in an organic farming system, utilizing ecological processes to manage pests and fertility should be emphasized. At the Pennsylvania NT location, delaying corn planting dates increased the activity/density of predatory arthropods [118], which was conducive to increasing corn yields. The effects of NT + cover crop practices on entomopathogenic fungi, a short-term soil health indicator, and varied and adaptive pest management strategies should be used in NT systems.

In paddy fields in Assam, India, the Oribatida populations of mites were significantly different between the NT and CT systems [128]. Aphididae and Formicidae pests were observed more on foliage, flowers, and pitfall traps of organic Cucurbita in full tillage, while RT methods, such as strip tillage, increased the abundance of natural enemies (e.g., Parasitica) and possibly pollinators [129], which may lead to enhanced biocontrol and pollination, but impacts may vary for different arthropod species and crops.

8. Effects on Yield and Quality of Plants

8.1. Yield and Output

A global meta-analysis showed that CT significantly decreased maize yield by 5% and nitrogen use efficiency by 15% [130], which could be alleviated under good hydrothermal conditions and straw mulching. When compared with traditional ridge cropping, long-term NT with stover mulching could increase maize yield [131]. NT100 had the highest increase rate of 11.4%, followed by NT67 and NT0. NT67 treatment significantly reduced the interannual fluctuation of maize yield and led to better sustainability of yield. NT stover mulching significantly increased soil total carbon and TN contents, which were significantly positively correlated with maize yield. The application of such low-carbon technologies significantly improved the income level of large-scale farmers [132].

In the chickpea fields of India, the maximal grain (2380 kg/ha) and biological output (5762 kg/ha) were attained under RT60 [4]. The net monetary benefit of conservation tillage was 24.3% to 37.7% higher than that of CT. The total N uptake was maximal under RT60, while the total P and K uptake was higher in NT30. In long-term maize production, the NT ↔ ST treatment effectively increased the plant height and dry matter accumulation of spring maize [2]. Compared with CT, NT ↔ ST significantly increased crop yield and WUE in continuous cropping fields of corn. In the common bean fields of Uganda, NT and stubble mulching improved WUE and grain yield [73].

In the trial of wheat-*I. indigotica* rotation, conservation tillage was beneficial for chlorophyll synthesis and delayed chlorophyll a degradation [7]. NT mulching significantly increased the activity of protective enzymes and proline content in the crops, reduced malondialdehyde damage and cell membrane permeability, and protected cell structure integrity, thus promoting crop growth and development. Conservation tillage significantly improved the crop yield as well as the WUE at the leaf level and yield level [7]. In Iowa, USA, the catnip (*Nepeta cataria*) plant height was significantly greater under the oat straw mulch than under other treatments at 4–6 weeks [133]; at 4 to 8 weeks of the second year, catnip plant height and width were significantly lower in the negative control compared with mulch treatments. Catnip yield was significantly higher in the flax straw mat than in other treatments. All organic mulch treatments significantly reduced weeds, with flax straw and wool mat having the best weed control. Meanwhile, the concentrations of medicinal compounds, nepetalactone in catnip and pseudohypericin-hypericin in St. John’s wort (*Hypericum perforatum*), were not affected, and flax straw mulch slightly increased their concentrations. However, there are few reports about the impact of NT/RT and organic mulch on other medicinal crops.

In winter wheat monoculture on dryland, NT performed better on soil water conservation during the fallow period but had a similar effect on wheat yield and WUE as compared to RT and ST [66]. Wheat WUE was improved by straw mulching but not affected by stubble mulching. In the spring wheat field of the Loess Plateau, NT straw mulch led to the highest dry matter accumulation throughout the whole growth stage of spring wheat as compared with CT, NT alone, and CT straw mulch [72]. The average grain yields and WUE of NT straw mulch across three years were 6.0–30.7% and 6.7–40.5% higher than other tillage practices, respectively. These advantages were achieved by improving the edaphic properties and increasing stress-related substances in wheat, e.g., catalase, peroxidase, and soluble protein. In the potato field of Ningxia, higher WUE was obtained in ST 30–40 cm with straw mulch [10], whereas the accumulated temperature use efficiency was increased significantly under different tillage depths with straw mulching. The impact of soil water on the total yield of potatoes was stronger than that of effective accumulated temperature during tuber formation. ST 30–40 cm with straw mulch improved the soil moisture and heat conditions and increased the potato yield and income by more efficiently using water and heat resources, which has application and popularization value in dryland cultivation. In the maize fields of Iraq, the wheat straw mulch increased the plant height, yield components, grain and biomass yield, as well as soil water content [5], and mulching of 8000 kg/ha had the largest positive effects on maize yield.

So far, limited emphasis has been placed on the production of medicinal plants for sustainable harvest and conservation in the understory of degraded forests [71]. In India, Chir pine forests are usually not managed to grow any medicinal plants, leaving a vast space to produce and conserve medicinal plants, which involve sustainable management techniques like MT under the canopy of trees. The medicinal plants were grown with three tillage depths, viz., minimum (0 cm), medium (up to 10 cm), and deep tillage (up to 15 cm), in open and below tree canopy conditions. The good yields of *Andrographis paniculata* [134], *Mucuna pruriens*, *Solanum khasianum*, and *Spilanthes acmella* were attained via MT. The positive average annual returns were achieved in understory conditions, and the system is conducive to utilizing vacant lands and increasing total productivity from them, as well as conserving medicinal varieties in situ. Conservation tillage can also be applied to other medicinal species in blank patches or the understory of degraded forests.

8.2. Medicinal Quality and Nutritional Value

The specialized metabolites are usually defensive weapons of plants (**Figure 2**), which play essential roles in host defense against various biotic and abiotic stresses. Many specialized metabolites display bioactivities and clinical efficacy, and NT-based ecological planting could increase the contents of specialized metabolites in plants [135][136]. The induction and utilization of specialized metabolism in ecological cultivation of medicinal plants could be attained via carrying out biocontrol of pathogens, pests, and weeds, promoting beneficial microbes in soil and plants, optimizing mixed planting, NT/RT, and organic mulch [114]. The biggest difference between the production of medicinal plants and that of food crops is that the specialized metabolism and contents of medicinal compounds must be highlighted in the former; it is also necessary to consider yield and sometimes nutritional indicators, usually involved in primary metabolism, in NT-related ecological agriculture. Compared with CT, the NT system might permit more biotic stresses, such as pathogens, pests, and weeds [123][137], as well as more abiotic stresses, e.g., drought and salinity [64], which could promote the accumulation of specialized metabolites of medicinal plants and improve the quality of medicinal crops [138] (**Figure 1** and **Figure 2**), which is conducive to the prevention and control of diseases, pests, and weeds. However, systematic research on how conservation tillage improves the content of specialized metabolites is still very limited, and the long-term impacts and mechanisms of NT, RT, and organic mulch need to be widely verified and systematically studied in the ecological planting of medicinal plants.

Sustainable management with NT, fertigation, and internal C-inputs via spontaneous weeds and pruning residues was implemented in the olive plantation [136]. NT increased the concentrations of most phytometabolites in the xylem sap (XS) as compared to CT, most of which were involved in plant specialized metabolism, chemical defense, signal transduction, and growth regulation, including alkaloids, terpenoids, phytohormones, steroids, carotenoids, retinoids, and tocopherols, etc. The XS of the tree crop significantly responds to a shift in soil management, and the NT plants showed an upregulated, specialized metabolism. NT could enhance plant physiological status, increase yield, improve quality, safeguard the environment, and ultimately benefit human health. In Poland, NT did not decrease the levels of bioactive phytosterols, tocopherols, and squalene in four varieties of common buckwheat [139]. Functions associated with stress tolerance, including signal transduction and biosynthesis of some secondary metabolites, were significantly increased in Solanaceae plants under intermittent DT treatments (30, 40, and 50 cm) [140].

In Lucknow, India, the application of paddy straw mulch increased the herb and essential oil yields in geranium by 23% and 27%, respectively, as compared with the unmulched control [141]. The straw mulch significantly enhanced the plant response toward 160 kg N/ha and increased nitrogen uptake and apparent N recoveries by geranium crops. Citronellol and geraniol, the quality markers of essential oils, were not affected by organic mulch or nitrogen fertilization, and these components met standards for international trade. In Southeast Spain, NT and cover of *Vicia faba*, *Vicia sativa*, and *Vicia ervilia* improved soil properties [142], e.g., SBD, available water content, aggregate stability, electrical conductivity, SOM, N, P, K, micronutrients, and microbial properties, which increased the antioxidant activity and total polyphenol content of almonds, thus improving their nutritional/medicinal value. In vineyards in Southern Italy, cover crop treatments increased concentrations of ethyl esters, volatile fatty acids, and free terpenes in wines made from *Vitis vinifera* in the humid climate [143]. The leguminous cover crop and its combination with natural zeolites could be promising practices to guarantee yield and quality in olive orchards under rainfed conditions [144].

8.3. Hazardous Substances

To reduce occupying farmland, understory *Panax notoginseng* (UPn) was developed as an ecological planting model with no chemical input [145]. Root and rhizome are more prone to excessive heavy metal levels than other medicinal parts [146]. In Lancang County, Yunnan, the hazard index and target hazard quotient of eight heavy metals in the roots and leaves of UPn were less than one, and Upn showed no human health risk, suggesting that understory cultivation with MT creates a safe and healthy growth environment for medicinal plants, which is worth promoting. More research on how NT/RT affect the content of organic pollutants and heavy metals in medicinal plant products is warranted.

9. Long-Term Ecological Benefits

Besides the abovementioned advantages, NT/RT and organic mulch generally mitigate the spillover effects of pollutants and pesticides as well as the emission of GHG, thereby showing long-term ecological benefits in reducing air pollution, water pollution, and soil pollution, which ultimately benefit the planet and humanity.

9.1. Pollutants and Pesticides

In Mollisol of Northeast China, the mineral nitrogen declined with depth to 60 cm and then increased to its maximum at 250–300 cm under CT and at 120–150 cm under NT0 and NT straw mulch [68]. More mineral nitrogen at 0–150 cm under low-disturbance practices would provide more available nitrogen for crops in the coming growing season, while the accumulated nitrogen at 150–300 cm under CT may leach into the groundwater, which may aggravate the nitrogen contamination in deep groundwater, ultimately threatening the agricultural sustainability in Mollisol regions.

Under natural rainfall conditions, the combination of NT and grass hedgerow measures effectively reduced 69% of runoff loss [147], 62% of nitrogen loss, 77% of phosphorus loss, and 88% of atrazine loss, which were supported by simulation results. On runoff plots with slopes of 5%, 10%, 15%, and 20%, the reduction of agricultural non-point source pollution by combining NT and hedgerow was negatively correlated with the slope. In a meta-analysis of pesticide loss in runoff, the concentrations of atrazine, cyanazine, dicamba, metribuzin, and simazine, instead of alachlor, in runoff were higher under NT than under CT [148]. NT regulates soil properties that control pesticide retention and interactions with soils, and eventually their mobility in the environment. More understandings of pesticide-soil interactions in NT systems should be gained to inform the selection of pesticides by farmers and improve the predictive power of pesticide transport models.

In a cotton-tomato rotation, conservation tillage noticeably decreased dust emissions due to fewer field operations [149], and long-term sampling is necessary to determine the effects of cover crops on dust production.

9.2. GHG Emission

In the North China Plain, when compared to CT, NT significantly reduced the net CO_2 cumulative emissions and water consumption [150][151] but reduced the grain yield. NT decreased the N_2O emission by 22.6% in winter wheat seasons [152] but did not alter it in summer maize seasons. Crop residue retention increased N_2O emissions by 28.1% and 26.7%, respectively, as compared with residue removal in the winter wheat and summer maize seasons. The NT soils took up more CH_4 in the summer maize seasons, and total non-CO_2 GHG emissions at the area scale showed trends similar to those of N_2O emissions. In an organic clover-winter wheat cropping sequence in Switzerland, RT and manure compost application could mitigate GHG as long as SOC is sequestered [153].

In the indoor incubation of black soil, the N_2O/CO_2 emission under six moisture/gas regimes significantly varied [86], the processing time also theoretically influenced the GHG emission, and there were sizable interactions between moisture/gas regime and processing time. The impact of moisture/gas regimes, processing time, and interaction items on ammonia nitrogen and nitrate nitrogen was also conspicuous. NT and stover mulch may influence soil GHG emissions by regulating soil moisture and/or gas conditions. In pot experiments, the N_2O production and nitrifying-denitrifying microbial communities were influenced by the antecedent soil moisture and pattern of the dry-wet cycle [154]. The nitrifying-denitrifying microbial communities, especially members of β-/γ-Proteobacteria, Bacteroidetes, and Gemmatimonadetes, in black soil were important in explaining the variation of N_2O production.

Acidobacteria, Sphingobacteriia, δ-Proteobacteria, Methylobacterium, Gemmatimonas, and Pseudarthrobacter, etc., were the key taxonomic groups in response to the moisture alteration. The nitrite/nitrate reduction to ammonium could be boosted by high moisture. Both nitrifier denitrification and heterotrophic denitrification could be substantially enhanced when the black soil moisture was increased to above 60% water holding capacity. NT and stover mulching may influence soil GHG emissions and relevant microbial communities via the combined effects of early and immediate moisture. Regional assessments of SOC trends and the carbon sequestration potential of NT and organic mulch are crucial in developing climate change mitigation strategies [155]. Developing simplified, scale-adapted assessments is necessary for cross-regional comparisons of conservation tillage and for communication with stakeholders and policymakers.

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