Soil Sickness : Current Status and Future Perspectives

T. CHEN[1,2], S. LIN[1,2], L.K. WU[1,2], W.X. LIN[1,2] and D.A. SAMPIETRO[3]

[1]School of life sciences, Fujian Agriculture and Forestry University
E. Mail: wenxiong181@163.com

CONTENTS

ABSTRACT

In agriculture soil sickness is a major problem, which reduces the crops yield. It is caused by various factors viz., soil nutrients imbalance, autotoxins production and accumulation, changes in soil microbial community structure (development of harmful microbes). Soil sickness is major problenm in Food crops (Rice, wheat, corn, mungbean. soybean etc), Cash ceops (Sugarcane, tobacco, peanut), Vegtetables (Cucumber, eggplant, aspragus, watermelon, muskmelon, tomato, potato, ginger etc), medicinal plants (*Rehmania*, ginseng, *Angelica* etc), Fruit trees (Apple, *Citrus* spp., peach, tea, coffee etc) and forest trees (Chinese fir, *Casuarina* spp). This review discusses the (i). Problem of soil sickness in various crops, medicinal plants, forestry and horticultural trees in terrestrial cropping and hydroponics, (ii). Role of soil physico-chemical properties, allelopathic autotoxins and rhizosphere microflora, (iii). Mechanism of soil sickness and (iv). Suggest methods to overcome this problem.

Keywords: Allelochemicals, *Angelica,* apple, broad bean, *Casuarina,* Chinese fir, *Citrus,* coffee, corn, cowpea, cucumber, eggplant, ginger, ginseng, lettuce, microbes, mungbean, nutrients, peach, parsley, pea, peanut, pepper, plant-soil interactions, potato, *Rehmania,* rice, soil health, soil microbes, soil sickness, soybean, strawberry, sugarcane, taro, tea, tobacco, tomato, watermelon, wheat.

Corresponding author. [2]Provincial Key Laboratory of Agroecological Processing and Safety Monitoring, Fujian Agriculture and Forestry University, China. [3]LABIFITO, National University of Tucumán, Argentina.

1. INTRODUCTION

Soil is the natural medium for seed germination, growth and development of plants. Soil sickness reduces the growth and yield of crops (22,24,27,49,59,113,141). The soil sickness is mainly caused by monoculture of the same plant species continuously in the same field. It is known since ancient times and many approaches have been used to overcome the problem. For example, Jiminyaoshu (ca. 540, an ancient Chinese book), gives detailed description of the importance of suitable cropping sequences for high crop productivity (65). However, scientific work on soil sickness was not initiated until the beginning of 20th Century and has been divided into 3- stages: (i) Pioneer stage (1900s-1950s) focus on phytotoxins, (ii). Second stage (1950s-2000s) focus on phytotoxins and soil microbes and (iii). Third stage (2010s- to date) foccusing on the plant and soil relations (65).

Soil sickness or replant disease has been reviewed several times (10,37,45,49,58, 65,72). In this article, we focus on the recent advances and developing trends in soil sickness research to further understand the underlying mechanisms involved and to develop technology to overcome this problem for sustainable crop production.

2. SOIL SICKNESS IN CROPS

Autotoxicity is one of the causes involved in soil sickness or replanting disease of many crop species. It is a special intraspecific allelopathy phenomenon, where the compounds released by a crop plant inhibits the growth of other crop plants of the same specie. Autotoxicity can lead to plant dysplasia (serious diseases and significant decline in yield and quality) caused by continuous growing of same plant species in the same land for many years. In modern times, continuous cropping has become a need due to more intensive land use, owing to population pressure leading to decreased land. The Table 1 shows the Current Status of soil sickness research in crops, vegetables, medicinal plants and in hydroponics etc.

2.1 Staple Food Crops

Soil sickness has been siudied in monocultures of several staple food crops over the world such as rice (23,25,28,68,131), wheat (73,94,149,164,173), corn (133,139), mungbean (138,145,151) and soybean (63,121,122,123,168).

(i). Rice: In an intensive farming system, the autotoxicity is often ignored. In Taiwan, Chou (25) found that the autotoxicity of rice residues caused 25% reduction in the second crop of rice due to poor water drainage. Usually rice stubbles are left over after harvest of the first season and used in nutrients recycling in the same field. When the rice stubbles are decomposed under anaerobic conditions they release large amounts of autotoxins into the paddy soil, which inhibits rice growth and reduce its grain yield in successive crop (23,28). Various phenolic acids like *p*-coumaric, *p*-hydroxy benzoic, syringic, vanillic, ferulic, *o*- and *p*-hydroxy phenyl acetic, and 2-hydroxyphenylacetic acids have been isolated from the decomposing residues in the soil and root exudates (131).

Table 1. List of crops and fruit plants adversely affected by Soil sickness problem

S.No	Name (English)	Name (Botanical)	Economic use	Crop duration (Annual)	Crop duration (Perennial)	Countries	Nature of soil sickness	References
				Food grains				
1.	Rice	*Oryza sativa* L.	Grains	Annual	-	Asian Countries	Autotoxins, nutrient and microbial imbalance	23,25,28,30, 68,131
2.	Wheat	*Triticum sativum* L.	Grains	Annual	-	Asian, USA Latin American Countries	Autotoxins, microbial and nutrients imbalance	73,94,149,16 4,173
3.	Corn	*Zea mays* L.	Grains	Annual	-	-do-	Autotoxicity, Phytopathogenic microorganisms	133,139
4.	Soybean	*Glycine max* L.	Seeds	Annual	-	China	Autotoxicity, *Penicillum purpurogenum*	4,63,121,122, 123,168
5.	Mungbean	*Vigna radiata* L.	Seeds	Annual	-	India, China	Autotoxicity, Microbial imbalance	138,145,151, 152
				Cash Crops				
6.	Sugarcane	*Saccharum officinarum* L.	Stalks	-	Perennial	Asia, USA, Brazil, Australia	Imbalance in microbes, Soil physico- chemical properties, autotoxins	26,58,78,125, 126,132,137, 146,147,154, 156,157
7.	Tobacco	*Nicotiana tabacum* L.	Leaves	Annual	-	China, USA	Autotoxins, Phytopathogenic fungi	18,107,108
				Vegetables Crops				
8.	Peanut	*Arachys hypogaea* L.	Fruits	Annual	-	China	Microbial imbalance	76
9.	Cucumber	*Cucumis sativus* L.	Fruits	Annual	-	China	Autotoxicity, Microbial imbalance	46,113,114, 116,161,162, 177
10	Eggplant	*Solanum melongena* L.	Fruits	Annual	-	China, Europe	*Verticillum dathiae*, Autotoxicity	19,20,115,18 4, 191

Table 1. Contd.

No.	Common name	Scientific name	Plant part	Annual/Perennial	Region	Problem	References
11	Asparagus	*Asparagus officinalis* L.	Crown buds	Perennial	Europe, Japan, and USA	Autotoxicity, root rot (*Fusarium oxysporum* spp. *asparagi*)	55,100,174,175,177
12	Water melon	*Cucumis lanatus* L.	Fruits	Annual	China	Autotoxicity, Microbial imbalance	54,163,194
13	Muskmelon	*Cucumis melon* L.	Fruits	Annual	China	Autotoxicity, Microbial imbalance	176,178
14	Tomato	*Lycopersicum esculentum* L.	Fruits	Annual	China	Autotoxicity	160,190
15	Potato	*Solanum tuberosum* L.	Tubers	Annual	China, USA, Europe, South america	Soil-borne diseases	42,77
Medicinal Plants							
16	Ginger	*Zingiber officinale* L.	Rhizomes	Perennial	China	Soil-borne diseases Autotoxicity	53
17	Rehmannia	*Rehmannia glutinosa* (Gaertn.) Steud.	Tuberous roots	Perennial	China	Soil-borne diseases Autotoxicity	40,51,52,79, 80,87,88,103, 165,166
18	Angelica	*Angelica sinensis* (Oliv.) Diels	Tuberous roots	Perennial	China	Soil-borne diseases Autotoxicity	187
19	Ginseng	*Panax notoginseng* (Burkill) F. H. Chen	Tuberous roots	Perennial	China	Soil-borne diseases, Autotoxicity	187
20	Asian Ginseng	*Panax ginseng* L.	Tuberous roots	Perennial	China	Soil-borne diseases, Autotoxicity	187
Hydroponics							
21	Cucumber	*Cucumis sativus* L.	Fruits	Annual	Japan	Autotoxicity	2
22	Tomato	*Lycopersicum esculentum* L.	Fruits	Annual	Japan, China	Autotoxicity	2,90
23	Strawberry	*Fragaria* × *ananassa* Duch.	Fruits	Annual	Japan	Autotoxicity	2,4
24	Taro	*Colocasia esculenta* (L.) Schott	Corms	Annual	Japan	Autotoxicity	5,6

Table 1, Contd.

				Fruit/Forest trees				
25.	Apple	*Malus sativus* L.	Fruits	-	Perennial	Europe, American Countries	Phytopathogenic fungi and bacteria	12,14,60,69, 92,1106,132, 140,142,143, 158,159
26.	Peach	*Prunus persica* L.	Fruits	-	Perennial	American Countries	Nematodes, Autotoxicity	98,105
27.	Bitter Orange	*Citrus aurantium* L.	Fruits	-	Perennial	Middle East, Asiatic and American Countries	Autoxicity, Nematodes, phytopthogenic fungi	31,56
28.	Orange	*Citrus sinensis* Osbeck	Fruits	-	Perennial	Middle East, Asiatic and American Countries	Autoxicity, Nematodes, phytopthogenic fung	31,56
29.	Rough Lemon	*Citrus jambhiri* Lush.	Fruits	-	Perennial	United States	Autoxicity, Nematodes, phytopthogenic fung	31,56
30.	Tea	*Camelia sinensis* L.	Leaves	-	Perennial	China, India, Srilanka, Pakistan	Autotoxicity	16,112,136
31.	Coffee	*Coffea arabica* L.	Fruits	-	Perennial	Mexico, Brazil	Autotoxicity	44,149
32.	Chinese fir	*Cunninghamia lanceolata* (Lamb.) Hook	Timber	-	Perennial	China, India	Nutrientsdepletion, proliferation of phytopathogens, soil degradation, autotoxicity	64,182,183
33.	Horsetail beefwood	*Casuarina equisetifolia* L.	Plantations Windbreaks	-	perennial	China, India	Autotoxicity	33,61

Some autotoxins, such as *o*-hydroxylphenylacetic acid reached a peak concentration of 10^{-2} M, in the first week of decomposition while radicle growth of rice seeds is inhibited at 25 ppm concentration (23). The autotoxins in soil reached the highest levels in 6-weeks of decomposition of rice residues, gradually declined thereafter and disappeared after 12-weeks (30). It was also found that autotoxins released from the rice residues showed allelopathic effects on other plant species (68).

Rice is major crop in the rice-wheat cropping system, which has been practiced by farmers of South Asia for more than 1000-years. Continuous cropping of the rice-wheat system for several decades has shown that the yield have stagnated below potential level due to a number of factors including the deterioration of the physical, chemical and biological health of the rice–wheat growing soils. The poor stand establishment of wheat following rice is common. Some findings suggest that residues of aquatic rice weeds have a negative influence on subsequent wheat growth (1). Phenolic compounds (Caffeic acid, chlorogenic acid, ferulic acid, 4-hydroxy-3- methoxybenzoic acid, gallic acid, p-coumaric acid, m-coumaric acid, syringic acid and vanilic acid) were the phytotoxins associated to this effect. Rice allelochemicals might also be involved. Utilization of rice residues in paddy fields has long been recognised as an important source to improve the organic matter status of soil and was also reported to reduce the emergence of weeds. Some experiments, however, indicate that rice straw suppress the germination of oat and wheat (41).

(ii). Wheat: Under reduced or no-tillage farming systems in wheat (*Triticum aestivum* L.), early poor growth and yield performance have been attributed to retention of stubbles and residues (94). The cause of yield reduction is attributed to the phytotoxic chemicals released from the decomposing wheat residues (73,94,149,173). Wu *et. al* (164) evaluated varietal autotoxicity of root exudates and residue extracts in wheat and found that the root exudates and residue extracts inhibited the wheat germination by 2-21%, radicle growth by 15-30%, and coleoptile growth by 5-20%.

(iii). Corn: Corn (*Zea mays* L.) also suffers from serious soil sickness under continuous cropping systems. This is more detrimental in the No-till farming, where corn residues are left on the soil surface. Singh (133) studied the autotoxic effects of maize on some biophysical and biochemical parameters and found that autotoxicity decreased the dry weight, root and shoot length of maize seedlings. There was a significant decrease in total chlorophyll, protein content and nitrate reductase activity, when maize seedlings were treated with the residue extract (133). Corn residues left in the soil for decomposition also alter the rhizospheric microflora, which in turn inhibits the corn growth (139).

(iv) Mungbean (*Vigna radiata* L.): The International Rice Research Institute, Phillipines investigated the effects of 8- years of mungbean monocropping on grain yield of follwing mungbean crop. It was found that yield usually declined 30-60% and in some cases, the crop failed. The inhibitory effects were particularly apparent at early growth stages for mungbean (145). Microbial involvement was confirmed and the old roots remaining in the soil were the primary source of infection to the new mungbean plants. The presence and quantity of crop residues were also related to the appearance of growth inhibitory effects. The phytotoxic activity was found primarily in the stems and other aerial parts (151). Yield

decline of mungbean was related to the production of a number of saponins like soyasaponin-I that are released into the soil from the mung bean seedlings. Glucosyl-flavonoid allelochemicals were also isolated from the inhibitory zone of germinating mungbean (138).

(v) Soybean: Soil subjected to soybean (*Glycine max* L.) monocropping, reduced soybean yields even after sterilization with methyl bromide (121). Mycotoxins released by *Penicillum purpurogenum* Stoll were involved in growth inhibition of soybean plants (63). In hydroponic culture, the addition of activated charcoal decreased the magnitude of mass reduction in continuous soybean (168). These findings suggested that autotoxins were root exudated by soybean plants. Phenolic autotoxins were identified as vanillic, p-coumatic acid, and ferulic acids and *p*-hydroxy phenyl acetic acid, and *m*-hydroxy-phenylacetic acid which are present in decomposed root and soil solutions (122). The application of *m*-hydroxy-phenylacetic acid significantly inhibited the radicle growth and root tips became thicker and brownish. Transmission electron microscopy analysis showed that it affected the soybean root tip, leading to sparse cytoplasm and fewer organelles in root meristematic cell, cell vacuolation and poorly developed irregular amyloplasts in root columella cell. The *m*-hydroxy-phenylacetic acid modified the expression pattern of genes involved in soybean response to several stressing factors (123).

2.2 Main Cash Crops

(i). Sugarcane : Sugarcane (*Saccharum officinarum*) is one of the world's major cash crops. Continuous monocropping of sugarcane including ratooning, is common practice in many regions, which often decreased the sugarcane yield (26,78,155,156,157). Autotoxicity is one major reason for the yield reductions in continuous cropping of sugar cane (125). To prevent soil degradation and soil erosion (122,126), about 600 to 2,400 Kg ha^{-1} of postharvest residues are every year deposited on the field surface and allowed to decompose in the soil (146). The decomposing sugarcane residues release various allelochemicals into the soil (26,58,125,126,132,137,147) and these autotoxins significantly reduces the germination, radical length and seedling dry weight and delay the early leaf development in target plants (125).

(ii). Tobacco: Tobacco (*Nicotiana tabacum* L.) can not be monocultured in successive years, as it suffers from serious replant diseases in continuous monoculture system (18,107,108). Patrick and Koch (107,108) found that the tobacco plant residues could inhibit the respiration, germination and growth of tobacco plants in successive growing seasons and the phytotoxic substances from the plant residues, reduces the resistance of tobacco to black root rot (108). Chen *et al.* (18) in pot experiments studied the effects of continuous monocropping treatment for 0, 3 and 10 years on the growth of flue-cured and burley tobacco plants and the activity of protective enzymes in the leaves. The results showed that the inhibitory effects on the continuously monocropped tobacco were significantly enhanced when the continuous monocropping years extended. It was also found that the growth rates of flue-cured and burley tobacco plants were significantly inhibited, which shortened the plant height and decreased the leaf area. Further, the defense response of tobacco was also triggered in this process, and the activities of

superoxidate dismutase (SOD), peroxidase (POD) and catalase (CAT) in the tobacco leaves were changed, with an initial increase and then a decrease. The malondialdehyde (MDA) content was increased, which in turn significantly reduced the yield and quality of tobacco.

(iii). Peanut (*Arachys hypogaea* L.):   The intensive peanut production is widespread in the subtropical regions of China and other countries. Yield decline in peanut is connected to an increased susceptibility to diseases promoted by root exudation of peanut allelochemicals (76). The root exudates of peanut promote the proliferation of phytopathogenic species such as *Fusarium oxysporum*, *Bionectria ochroleuca* and *Phoma macrostoma*.

2.3. **Vegetables**
         The problem of soil sickness in vegetable crops is known since ancient times. Many vegetables such as Cucumber (*Cucumis sativus* L.) (46,113,114,116,161,162, 177), Eggplant (*Solanum melongena* L.) (19,20,115,184,191), (*Asparagus officinalis* L.) (55,99,174,177), Watermelon (*Citrullus lanatus* Thunb. Matsum.) (54,163,194), Lettuce (*Lactuca sativa* L.) (5,6), Broad bean (*Vicia faba* L.) (4), Cowpea (*Vigna unguiculata* L. Walp) (66), Ginger (*Zingiber officinale* Roscoe) (53), Parsley (*Pastinaca sativa* L.) (48), Pea (*Pisum sativum* L.) (179), Pepper (*Capsicum annuum* L.) (91), Strawberry (*Fragaria ananassa* Duch.) (152), Taro (*Colocasia esculenta* L. Schott) (5,6), Tomato (*Lycopersicon esculentum* Mill.) (180) and have been reported to suffer from serious replanting problem, resulting in poor growth and declined yields in monoculture system.

(i) Cucurbit crops: they are very sensitive to changes in soil physico-chemical properties (176). Autotoxicity of root exudates or decaying residues has been reported in cucumber (*Cucumis sativus*), muskmelon (*Cucumis melon*) and water melon (*Cucumis lanatus*) (178). *In vitro* assays indicated that root exudates of cucumber affect uptake of nitrates, sulfates, potassium, calcium, magnesium and iron by cucumber plants. Phenolic compounds released by cucumber plants such as *p*-coumatic acid seem to influence soil microbial communities which in turn affect the growth of cucumber plants (190). They predisposed plant roots to the attack of *F. oxysporum* fsp *melonis* (171).

(ii) Eggplant (*Solanum melongena* L.): The organic substrates such as peat, bark and sawdust are repeatidily used in eggplant cultivation. Quick humification leads to deterioration of the physical condition of these substrates, with the release of phytotoxic compounds to the soil. The assay of several substrates indicated that a mixture of bark and peat increased water available for eggplant growth and had a low content of phenolic compounds (115). Eggplant roots exudate phenolic compounds such as cinnamic acid and vainillin which in concentrations of 1 and 4 mmol/L inhibit eggplant growth and promote the proliferation of verticillium wilt, a disease caused by *Verticillium dalhiae* (184). Grafting decreased the cinnamic and vanillic acids contents in root exudates by 69% and 100%, respectively (20). Thus grafting changes the phytochemical pattern of root exudates than non-grafted plants and thus confers eggplant resistance to *V. dalhiae* (191).

(iii) Asparagus: The decline in yield of asparagus (*Asparagus officinalis* L.) is attributed to autotoxicity of root tissue as well as its infestation with *Fusarium oxysporum* spp. *asparagi* causing root rot. Asparagus root exudates showed toxicity on asparagus cultivars (175). The addition of shoot and roots, or extracts prepared from them, to soil inhibits asparagus seedling emergence and growth. Phenolic autotoxins were identified as ferulic, iso-ferulic, malic, citric, fumaric, and caffeic acid (55). These autotoxins directly effect the physiological and biochemical processes of asparagus plant and showed synergism with *Fusarium oxysporum* spp. *asparagi* causing increasing the incidence of the root rot disease.

(iv) Tomato (*Lycopersicum esculentum* L.): Eight years of monocropping in greenhouse led to a significant reduction in root vitality and fruit quality of tomato plants (160). Leaf leachates of tomato plants are able to inhibit the root growth of other tomato plants (190). Root exudates in hydroponic culture inhibited the tomato shoot height and fresh weight by 17 and 37%, respectively. Root exudates of tomato plants in hydroponics under controlled climatic conditions were autotoxic and soil factors such as humic and fulvic acids intensified the autotoxicity (90).

(v). Potato: In continuous monoculture, commercial production of potato, numerous soil-borne diseases also persists (42). Current control methods are not always practical or effective for theie control. Therefore integrated, sustainable disease- control options such as biological amendments with crop rotation in a suitable cropping sequence are needed (77).

(vi) Ginger (*Zingiber officinale*): It has been cultivated as a spice and herbal medicine since thousands of years. Consecutive cultivation on the same land retards the emergence and early growth of ginger (53). Its rhizomes are easily infected by soil-borne pathogens [bacterial wilt (*Pseudomonas solanacearum*), soft rot (*Pythium aphanidermatum*) and nematodes (*Meloidogyne* spp.)], which cause severe yield losses. Some allelochemicals such as phenolic acids (vanillic acid, syringic acid, *p*-hydrobenzoic acid, *p*-coumaric acid and ferulic acid) and coumarins (umbelliferone and herniarin) were found in stems, leaves and rhizomes of ginger. Aqueous extracts of these organs inhibited the major leaf antioxidant enzymes of ginger seedlings. The phytotoxicity of extract followed the decreasing order of inhibition: stem > leaf > rhizome (53). These results suggest that ginger has autotoxic potential and its residues (stems, leaves) should be removed from the fields to reduce the autotoxic effects on next ginger crop seedlings.

2.4 Hydroponics: Currently, more developed countries have adopted to the hydroponics and closed type hydroponic systems to grow vegetable and ornamental plants on a commercial scale (4). The allelochemicals accumulate in the re-used nutrient solution during hydroponic culture (4) and accumulations of these allelochemicals result in serious autotoxicity and reduction in yield of succeeding crops. Root exudation of some vegetables leads to autotoxicity in close hydroponic systems. Some examples are strawberry, tomato, taro and cucumber. Scavenging of autotoxins from the nutrient solution (i.e. with supplementation of activated charcoal, by electrodegradation, or with addition of microbial strains) increased the yields and sometimes the quality of the

harvestable organs (2). Asao *et al.* (7) investigated the autotoxicity of 37 ornamentals in hydroponics with or without the addition of activated charcoal (AC) to the nutrient solution. Of the 37 plants species, the growth of Lily, Prairie gentian, Corn, Poppy, Farewell-to-spring, Rocket larkspur, and Carnation was significantly inhibited in the absence of activated charcoal compared with those in its presence. By GC-MS, some allelochemicals were identified, which were adsorbed on activated charcoal from the root exudates of 10 ornamentals (7).

2.5 Medicinal Plants

The problem of soil sickness is most serious in the cultivation of medicinal herbs. About 70% of tuber root medicinal plant species (*Rehmannia glutinosa, Panax notoginseng, Angelica sinensis, Panax ginseng*) and other medicinal plants suffer from varying degrees of soil sickness in continuous monoculture (187). The high-quality herbal drugs are produced in ideal and authentic production areas. Under specific natural conditions and ecological environment, the same medicinal plants in different regions, synthesize different chemical ingredients, thus forming genuine and high quality medicine with obvious regional characteristics. Soil sickness has seriously affected the production and quality of Chinese herbal drugs (188). The underlying mechanisms of continuous monoculture problems of medicinal plants are not known and has become a focal point in China.

2.6 Fruits/Forest trees: In fruit orchards, the productivity decreased rapidly over time after the initial establishment of the fruit gardens (14,15,105,106). Regeneration of fruit trees is also difficult in old plantation, which makes the problem more serious. The replant problems and yield decline in orchards have been often associated to the release of autotoxins, and the proliferation of pests and phytopathogenic microbes. In several situations, other causes of replant problems are autotoxicity or adverse changes in soil microflora inhibting the growth of young trees (64). In forest trees, short rotations have became a common practice. It consists in growing closely spaced forest trees for shorter times than in traditional forestry practice. In this way, more biomass can be harvested over the time, but replant problems occur due to nutrients depletion, specially the phosphorous availability (182).

(i). Apple: In apple replant problem, the initial growth of young plants is suppressed in all apple-growing areas of the world. Utkhede and Li (140,143) identified several pathogenic fungi and bacteria viz., [*Penicillium janthinellum,Costantinella terrestris*, *Trichoderma* sp., *Bacillus subtilis*], which were closely associated with replant problems in continuous monoculture of apple. It was also found that interactions between fungi, bacteria and nematodes contributed towards the occurrence of replant disease in apple soil in British Columbia, Canada. Pythiaceous fungi, parasitic nematodes and actinomycetes have been reported to be associated with apple replant problems in England, Europe and the United States (14,60,69,92,106,132,158,159). Toxicity was also associated to the presence of phenolic compounds like (Phlorizin, phloretin, p-hydroxy hydrocinnamic acid, p-hydroxy benzoic acid, and phloroglucinol) in root bark and released into the orchard soil after microbial decomposition of fallen root bark (12). In addition, abiotic factors including unbalanced nutrition, high or low soil pH, poor soil structure, poor drainage and excess or

lack of soil moisture in continuous monoculture systems, also contribute to replant problems of fruit trees (142).

(ii). Citrus: Citrus replanting soil sickness problem had been observed in the orchards of *C. aurantium*, *C. sinensis* and *C. jambhiri*. It is a syndrome mainly due to the phytotoxic allelochemicals, nematodes such as *Tylenchulus semipenetrans* and the rhizosphere pathogens including *Phytophthora citrophthora*, *P. nicotianae*, *Thielaviopsis basicola*, *Fusarium solani* (31,57). The release of autotoxins occurs from dead and decaying roots left in the soil. Ether extractable substances like homovanillic acid, seselin and xanthyletin, present in the *C. jambiri* roots cause severe toxicity to the young plants (57). The inhibitors stopped the root cell elongation and caused root swelling.

(iv). Peach (*Prunus persica* L.): The bark of old peach roots contains cyanogenic glycoside amygdalin which was related to toxicity to young growing peach plants (98), Microbial degradation of amygdalin in the soil leads to the release of cyanide substances that injury young peach seedlings. The intensity of effect was directly corelated to the amount of roots present in soil. The presence of nematodes in the soil plays an important role in amygdalin release and hydrolization (98).

(v). Tea (*Camellia sinensis* L.): It is perennial, woody and evergreen plant and is major cash crop in the hilly and mountainous area of southern China, India, Srilanka, Pakistan. Due to soil sickness, premature aging and degradation of tea gardens have been critical issues limiting the development of tea industry. Studies have shown that autotoxicity may be the major cause of reduced yield and quality in the later growth stages of tea plants. Caffeine, theobromine, polyphenols, and catechins, which are abundant in tea plants, may be involved in soil acidulation and allelopathic autoxicity (16,136). These allelochemicals significantly inhibits the seed germination and growth of tea plants (16). It is also reported that the catechins influence the growth of both inter- and intraspecific plants and may act as allelopathic autotoxins (112).

(vi) Coffee (*Coffea arabiga* L.): Caffeine may cause autotoxicity in coffee plantations. Coffee seedlings are highly susceptible to caffeine exposure (44). However, coffee seeds developed a mechanism to avoid autotoxicity which allow them to germinate despite their high amount of endogenous caffeine (149).

(vii) Chinese fir (*Cunninghamia lanceolata*): It is a fast-growing conifer planted in China for timber production. Failure of Chinese fir seedlings to grow normally in replant woodlands is due to several factors including nutrient depletion, soil degradation and biotic factors. Extracts of Chinese fir stump roots showed toxicity on Chinese fir seed germination (64). Soil extracts obtained from newer replant rotations are more toxic to Chinese fir seedlings than older ones (182). Decomposing root residues together with pathogenic fungi caused drastic growth reduction of seedlings than the decomposing root residue alone. Further work showed that soil allelopathy is dominant factor regulating the productivity and nutrient cycling in Chinese fir short rotations (183).

(viii) Horsetail beefwood (*Casuarina equisetifolia* Forst & Forst): It is a fast growing,

evergreen, nitrogen fixing multipurpose tree, which is widely cultivated in India and China. It showed a strong allelopathic effect on its understorey vegetation (33) and the spraying of aqueous extracts from its leaf litter showed a high degree of effectiveness in the control of weeds in wheat fields (61). Its seedling roots are sensitive to branchlet leachates and root water extracts of *C. equisetifolia.* Autotoxins responsible for this effects were identified as kaempferol-3-α-rhamnoside, quercetin-3-α- -arabinoside and luteolin-3´,4´- dimethoxy-7-β-rhamnoside (33).

3. MECHANISM OF SOIL SICKNESS

Based on worldwide research, the main reasons for continuous monoculture problems or soil sickness are: (i) Abnormal expression of genes in continuously monocultured plants and their disorderly regulation, which result in an adverse physiological response (87,172); (ii) Deterioration of soil physico-chemical properties and nutrients imbalance (65); (iii) Allelopathic autotoxicity of root exudates (35) and (iv) Imbalance in soil micro-ecosystem (decreased microbial diversity, increased pathogens and pests, the fragile biological interaction), and disruption in rhizosphere soil homeostasis (118).

3.1 Gene expression disorder and soil sickness

In continuous monoculture regime, plants often show dysplasia (decrease in growth rate, shortening of growth period and decline in yield and quality), which is believed to be related to particular physiological responses, gene expression and their regulation (52). Soil sickness in continuous monocultured *R. glutinosa* is seen at the early stage of growth and persists throughout the growth period. Further, the accumulation of free radicals in plant cells, the increase in MDA content and the damage to membrane structure caused by the stressful conditions of continuous monocropping, resulted in the decreased chlorophyll content and stomatal closure (172), which reduces the photosynthetic activity (188). The decrease in root ATPase activity as well as the small capacity of sink, are major reasons for poor growth of continuously monocultured *R. glutinosa* (172,188).

The content of endogenous hormones, such as IAA (Indole acetic acid) and ABA in continuously monocultured *R. glutinosa* plants are also significantly altered (103). At the seedling stage, the content of ABA was significantly higher in the continuously monocultured *R. glutinosa* than in the newly-planted crop. This is not favorable for plant growth, since the high content of ABA in leaves at the early stage often results in closed stoma and decreased photosynthetic activity. However at the root elongation stage, the IAA content of continuously monocultured *R. glutinosa* was significantly lower than in newly-planted plants. Previous studies suggested that the lower level of IAA in leaves accelerated the leaf senescence of *R. glutinosa* at root elongation stage, consequently reducing the transport of photosynthates to the roots. Thus, continuous monoculture destroys the balance of endogenous hormones in *R. glutinosa*, leading to physiological metabolic disorders affecting the normal growth and development of plants.

The changes in specific physiological metabolism or/and endogenous hormones, are a response to environmental stress by regulating the expression of related genes. To

determine the autotoxicity mechanism of rice residues to rice seedlings in rice-rice cropping sequence, Chi *et al.* (21) used microarray assay to analyze the rice root response to ferulic acid (FA), an autotoxin in the rice straw. They found that FA modulates ethylene and jasmonic acid hormone homeostasis, inhibits rice root elongation and the expression of amino acid/auxin permease genes (AAAP) induced by FA. This may play an important role in detoxicification of autotoxin (21). myeloblastosisFang *et al*. (40) used the suppression subtractive hybridization (SSH) technique to construct the forward and reverse subtractive cDNA libraries of *R. glutinosa* and found that the key genes which regulate essential metabolic pathways were restrained or shut down, disrupting their normal expressions in continuously monocultured *R. glutinosa.* The calcium signaling system (such as calcium-dependent protein kinase, calcium channel protein and calmodulin) and ethylene biosynthesis-related genes (such as ACC oxidase and S-adenosylmethionine synthetase) have specific expression resulting in disturbed metabolic process. Li *et al.* (77) applied high throughput Solexa/Illumina sequencing to generate a transcript library of *R. glutinosa* transcriptome and degradome to identify the key miRNAs and their target genes implicated in replanting disease. Their results showed that these miRNAs involved in the regulation of signal transduction, ion transport and cell division (such as miR2931, miR1861, miR7811) were up-regulated in continuously monocultured *R. glutinosa*, which repressed the normal expressions of these target genes and their protein functions. These miRNAs associated with regulating the formation of fibrous roots and early flowering (such as miR165, miR408, miR156/157) were down-regulated leading to up-regulated target genes promoting the formation of fibrous roots, early flowering, shortening the growth period, resulting in typical symptoms of continuous monoculture problems. It is thus obvious that *R. glutinosa* possesses a unique set of perception, transduction and response systems against environmental stress, especially such as the calcium signaling system. A previous study (51) found that two calcium channels away from the cytoplasm [plasma membrane calcium-transporting ATPase 13 and sarcoplasmic reticulum calcium-transporting ATPase 3] were expressed in a down regulated manner in continuously monocultured *R. glutinosa,* while the calcium channels toward the cytoplasm (such as calcium-dependent protein kinase, calcium-binding protein, calcineurin B-Like, calcium ion binding protein, phospholipase C) were expressed in a up-regulated manner (46). Therefore, continuous monoculture of *R. glutinosa* leads to a great increase in cytoplasmic calcium concentration. It was confirmed that calcium signal blockers could inhibit the gene expression of calcium signaling pathway and thus relieve the continuous monoculture problems to some extent, when continuously monocultured *R. glutinosa* plants were treated with different levels of calcium signal blockers such as CBP(CaM-binding protein), CBL (calcineurin B-like protein), CIBP (Calcium- and integrin-binding protein) and PLC (phospholipase C). However, why continuous monoculture induces a disorder in gene expression in crop plants still remains unknown. This however encourages us to further investigate the underlying mechanism of soil sickness from the soil ecosystem point of view.

3.2 Soil physico-chemical properties and soil sickness

The soil physico-chemical properties [soil texture, structure, water content, air, temperature, pH, organic matter, inorganic elements, etc.] have close relationship with plant growth and development. The soil acidification caused by fertilizer application or

allelochemicals released from continuously monocultured crop plants, is also a result of deterioration in soil physico-chemical prpoperties. This is a continuing process in many farming systems and is one of the reasons for soil sickness (109). Usually, plant roots absorb nutrients from soil solutions to satisfy their growth requirements. The uptake of cations and anions is associated with H^+ extrusion and OH^-/HCO_3^- release respectively. If plants absorb more cations than anions, then more H^+ are released around the roots. Inappropriate fertilizer application or accumulated phytotoxins in soil causes serious soil acidification. Excessive application of ammonium fertizers or accumulated catechins, lead to Aluminum toxicity. Unfortunately, many acidified soils are uneconomic to be treated with lime (95). Integrated methods should be used to ameliorate soil acidification, such as application of ground limestone, gypsum, plant residues, animal manure and coal-derived organic materials, combined with biological amelioration through managing cation-anion uptake by crops (139). Continuous monoculture also changes the soil physicochemical properties. Wang *et al*. (153) found that continuous monoculture of cotton significantly affect the composition of soil aggregates and the distribution of organic carbon. Long-term continuous monoculture reduced the mechanical stability of soil aggregates. However reasonable rotation with soybean or corn, could effectively promote the formation of aggregates, improve soil texture, enhance soil fertility and thus promote better growth of cotton.

Plants have certain selectivity and preferences in absorbing soil nutrients and hence, differ in the quantity and type of nutrients taken up especially certain trace elements. In long-term monoculture, due to selective absorption of mineral elements by crops, improper fertilization, water management and other agronomic practices, depletes some nutrients and accumulation of other nutrients leading to occurrence of imbalance in soil nutrients, reducing the plant growth (91). The long-term monoculture of lily caused serious deficiency of soil available potassium, organic matter and soil acidification, which became the major limiting factors in high-yield (181). The decline in soil fertility due to continuous monoculture, cannot be alleviated by increasing fertilizer application. For example in continuously monocultured wheat, despite the adequate level of fertilizer, the yields continued to decrease (185). In capsicum, Zhao *et al*. (189) also found that adding potassium fertilizer did not solve the problem of continuous monoculture.

3.3 Allelopathic autotoxins and soil sickness

Schreiner and Reed proposed in 1907 that some crop secretions contained substances which inhibits the growth of their own seedlings (65). Later many studies have indicated that some metabolites (terpenoids, phenolics, steroids, alkaloids and cyanogenic glycosides) secreted by plant roots cause the crop autotoxicity. This has been now reported in many crops [*Oryza sativa* L., *Triticum aestivum* L., *Fragaria ananassa* Duch., *Solanum tuberosum* L., *Arachis hypogaea* L., *Glycine max* L.Merr., *Medicago sativa* L., *Lolium rigidum* Gaud., *Pyrus malus* Mill., *Rehmanniae* Libosch., *Salvia miltiorrhiza* Bge., *Radix Notoginseng* Burk. and *Angelica sinensis* Oliv (65).

To understand the autotoxicity mechanism in tobacco, Jia *et al*. (71) analysed the allelochemicals in the root exudates of tobacco seedlings using gas chromatography and mass spectrometry (GC/MS). Eighteen compounds were identified in the root exudates of tobacco in continuous monocropping and 20 compounds in rotation cropping systems. Of which 14 compouds were in higher amounts in root exudates of tobacco in continuous

monocropping than in rotation cropping. Among the 14-compounds, phytotoxic effects of phthalate esters (dibutyl phthalate, diisooctyl phthalate and diisobutyl phthalate) were evaluated using tobacco seeds as targets. The inhibitory effect of diisobutyl phthalate was much higher than dibutyl phthalate and diisooctyl phthalate at low concentrations, but there were no differences between them at higher concentrations. These results indicated that the phthalate esters from tobacco root exudates may be the major factor in tobacco autotoxicity in tobacco continuous monocropping.

Recent research on continuous monoculture problems have focussed on isolation, identification, quantification of phytotoxic substances and evaluation of their biological activity on many crops under continuous monoculture regimes. Researchers have isolated and identified several autotoxic allelochemicals [*o*-hydroxyp henylacetic, *p*-hydroxy benzoic acid, coumaric acid, benzoic acid, vanillic acid, vanillin, ferulic acid, cinnamic acid, *p*-hydroxybenzoic acid, benzoic acid, homovanillic acid, seselin, xanthyletin, terpenes, abscisic acid-beta-D-glucopyranosyl ester (ABA-GE), 2,4-dihydroxi-1, 4-benzoxazin-3-one, caffeine, polyphenols and catechins etc], from the tissues, organs and root exudates of rice, *R. glutinosa*, cucumber, watermelon, peanut, tomato, ratoon sugarcane, citrus, tea plants etc. (13,16,21,23,28,31,43,56,125,126,135,147,177,179,187). These allelochemicals may affect water use, nutrients uptake, photosynthesis, gene expressions etc and inhibits the normal plant growth and development.

The root exudates of cucumber contain 11- phenolic acids [2,5-dihydroxy benzoic acid, *p*-hydroxybenzoic acid, benzoic acid, cinnamic acid, etc.(177)]. Of these, all except 2-hydroxybenzothiazole were toxic to the growth of receiver plants (177). Liu *et al.* (88) found that the root exudates and the extracts of leaves and tuberous roots of *R. glutinosa* could inhibit the tuberous root growth of the same plant in continuous monoculture system. The most significant inhibitory effect on the tuberous root expansion was by the root exudates. The phytotoxic substances have been separated from *R. glutinosa* fibrous roots using different polar organic solvents. The ethyl acetate extracts, which had the highest inhibition effect on the receiver plant, were subjected to GC/MS analysis and several phenolic compounds [ferulic acid, vanillin, *p*-hydroxybenzoic acid, benzoic acid, protocatechuic acid and gallic acid] were identified (79). The content of coumaric acid, *p*-hydroxybenzoic acid, syringic acid and ferulic acid in the soil was negatively correlated with tuberous root growth of *R. glutinosa* under continuous monoculture conditions (35).

However some believe, that when toxic substances were secreted by plant roots into the soil, they undergo a series of physical, chemical and biological changes [soil adsorption, microbial decomposition, transformation, etc. (67)]. In other words, the direct phytotoxic effects of root exudates on plants might not happen in conyinuus monoculture regime but the root exudates might be just the inducing factors to indirectly influence the plant performance by changing soil microbial communities. Many believe that the indirect ecological effects of root exudates and soil micro-ecological imbalance are major factors in continuous monoculture problems (86,166).

3.4 Rhizosphere Microflora and Soil Sickness

Yang *et al.* (169) applied the Biolog and T-RFLP methods to analyze the changes in rhizosphere microbial community in the rhisosphere soil of continuously cropped Tobacco. The analysis showed that whether the soil was sterilized or not, the diversity

level of bacterial community in the rhizosphere soil of tobacco decreased as the continuous monocropping years increased and the bacterial community in sterilized soil was highly similar to non-sterilized soil in the same period. These results suggested that the enrichment of exudates and residues from the tobacco had a negative impact on soil bacterial community in continuous monocropping. In addition, it was also found that the monoculture imposed a strong selective pressure on soil microbial flora as the years of continuously monocropped tobacco increased. The pathogens also gradually became a dominant population suggesting that the original balance of soil microbial communities was disrupted and the soil environment was prone to deterioration in continuous monoculture system.

(i). PLFA: Lin *et al.* (84,85) used the methods of soil enzyme, Biolog and phospholipid fatty acid biomarkers (PLFAs) to study the microbial diversity in the rhizosphere soils of 1-, 6- and 20-year-old tea plants. Biolog analysis showed that the ability of microbial flora to use six kinds of carbon sources was highest in 6-year-old tea soil and lowest in the 20-year-old tea soil. Microbial utilization of six kinds of carbon sources was moderate in 1-year-old tea soil. Community diversity analysis showed that the Shannon index, Brillouin index, homogeneity index and richness index of the 6-year-old tea soil were the highest and lowest in the 20-year-old tea soil. In the rhizosphere soil of 6-year-old tea plants, the total amount of PLFAs was the highest and the PLFAs contents of bacteria, actinomycetes, and protozoa were higher than in other rhizosphere soils. The rhizosphere soil of 20-year-old tea plants had a higher content of fungi PLFAs, but lower contents of actinomycetes and protozoa PLFAs than the other rhizosphere soils, whereas the content of bacterial PLFAs was close to rhizosphere soil of 1-year-old tea plants. In the rhizosphere soil of 20-year-old tea plants, the abundance of several microbial groups participating in soil nutrients cycling declined, while the abundance of several microbial groups with low metabolic capacity increased. As compared with those in the rhizosphere soil of 6-year-old tea plants, the activities of urease, phosphomonoesterase and peroxidase in the rhizosphere soil of 20-year-old tea plants were lower, while the activities of invertase and polyphenol oxidase were higher. In the rhizosphere soils of different tea plants of different ages, the PLFAs of different microbial groups were closely correlated with the soil enzyme activities and fertility factors. With increasing years of tea monocropping, the microbial community structure in rhizosphere soils changed greatly, reflecting the decline in microbial diversity and an increase in microbial groups with low metabolic capacity, adapting to poor soil conditions. The activities of some key enzymes had also largely decreased.

Qu *et al.* (119) used the approach of using denaturing gradient gel electrophoresis (DGGE) to detect the effects of different phenolic acids of soybean root exudates on soil microbial populations. The results revealed that two phenolic acids (vanillic acid and 2,4-di-tert-butyl phenol) had   great effect on specific microbial communities, particularly vanillic acid (i.e., *Hymenagaricus* sp., *Cyathus striatus*, etc.), making them dominant population. Similarly, Zhou *et al.* (192) reported that *p*-coumaric acid, an autotoxin in the root exudates of cucumber, played a role in the allelopathic autotoxicity of cucumber by influencing the soil microbial communities. *p*-Coumaric acid could change the structure and composition of bacterial and fungal communities in the rhizosphere, with increases in the relative abundances of Beta proteobacteria, Firmicutes and a decrease in relative

abundances of Deltaproteobacteria, Bacteroidetes and Planctomycetes. In addition, *p*-coumaric acid increased the *Fusarium oxysporum* population densities in the soil.

Increasing number of studies have found various positive and negative plant-plant interactions within or among plant populations, such as amensalism, autotoxicity, stimulation and interspecific facilitation, all being the results of the integrative effect of plant-microbe interactions mediated by root exudates (152) It is therefore felt that root exudates can significantly influence the components and the structure of microbial flora in rhizosphere soil, especially in different cropping sequences.

(ii). Root Exudates: The root exudates have specialized roles in nutrients cycling and signal transduction between a root system and soil, as well as in plant response to environmental stresses (152). They are the key regulators in rhizosphere communication and can modify the biological and physical interactions between the roots and soil organisms. Organic carbon fixed by plants through photosynthesis can be released into the soil by root secretion, which provides the material and energy for the surrounding microorganisms. Soil microorganisms accumulate in the rhizosphere and rhizoplane with abundant rhizodeposition by chemotaxis or quorum sensing (152). Recently, group specificity in microbial use of root-exudate compounds and rhizodeposition has been reported and found that the different components and proportions of root exudates of different plants make the soil microbial community structure to become specific and representative (104). Gschwendtner *et al*. (50) reported that the quality and quantity of root exudates were dependent on the plant genotype and thus influenced the microbial community structure in rhizosphere. Chaparro *et al*. (17) also found that there was significant change in the components and content of root exudates of *Arabidopsis* at different stages of development. Further, meta transcriptome analysis revealed significant correlations between the microbial functional genes involved in the metabolism of root exudates and the corresponding compounds released by the roots at particular stages of plant development (17)

(iii). Soil Microbial Community: Conversely, the structure and functional diversity of soil microbial community also affects the plant growth and development [root secretion, nutrients absorption, utilization, stress /defense response, etc (39)]. As assessed by GC-MS analysis, soil microbial communities affect the biosynthesis of leaf metabolites of host plant, which impacts the feeding behavior of insects (8). Lakshmanan *et al*. (74) demonstrated that foliar infection by pathogens induced malic acid transporter expression, leading to increased malic acid titers in the rhizosphere of *Arabidopsis*. Malic acid secretion in the rhizosphere increased the beneficial rhizobacteria titers causing an induced systemic resistance response in plants against pathogens. Zolla *et al*. (193) found that under drought conditions, a sympatric microbiome (i.e., having a history of exposure to *Arabidopsis* at a natural site) significantly increased the *Arabidopsis* biomass, while the non-sympatric soils did not affected the plant biomass. This was related to the plant growth promoting rhizobacteria (PGPR) in the soil (such as *Bacillus*, *Burkholderia*, *Acinetobacter*, etc.), which could modify the plant's ability to sense abiotic stress and increase plant biomass.

(iv). Rhizosphere: It is the most active region of microbial activity, is a platform for the

frequent material exchanges and signal transmissions between plants and soil microcosms, which are closely related to underground and aboveground plant growth. The collective genomes of rhizosphere microbial communities can be seen as a second genome of the plant (13). Marasco et al. (93) suggest that the plant should not just be seen as single organism, but as a meta-organism, referring to the plant and the surrounding soil microbiome as a whole. Mendes et al. (96) used the PhyloChip-based metagenomics to analyze the microbial community structure in disease-conducive soil and disease-suppressive soil. β-Proteobacteria γ-Proteobacteria and Actinobacteria were consistently associated with disease suppression. In particular, the number of *Pseudomonas* sp. was significantly higher in disease- suppressive soil than in disease-conducive soil.

In-depth rhizosphere ecology research in continuous monoculture problem has focussed on rhizospheric biological processes. The cross-talk between plants and microbes is the key factor for allelopathic autotoxicity or soil sickness. Wu *et al*. (165) found that *R. glutinosa* continuous monoculture changed the rhizospheric microbial community composition and activity, with distinct separation between the control, newly planted plots and the second, third year continuously monocultured plot soils. Under continuous monoculture, the number of bacteria in the rhizosphere of *R. glutinosa* were reduced but the fungal and actinomycetes populations increased (80). Further, the genetic diversity analysis of soil microbial populations showed that *R. glutinosa* continuous monoculture decreased the Shannon diversity index and Margalef index and simplified the bacterial community structure. The dominant group in the newly-planted soil were Bacilli, while the dominant group in the 2-years monocultured soil were class ε–proteobacteria (186). Lin *et al*. (82,83) found that *Pseudostellaria heterophylla* continuous monoculture significantly decreased the number of bacteria and aerobic nitrogen-fixing bacteria in rhizosphere but significantly increased the amounts of anaerobic cellulose- decomposing bacteria, actinomycetes and fungi. Other research on medicinal plants has also shown that continuous monoculture increase the soil-borne pathogens [*F. solani*, *F. tricinctum*, *Aspergillus calidoustus*, *Phytophthora cactorum, Pythium irregulare*, etc. (36,100)]. These findings encourage us to develop Technology to effectively solve the problem of soil sickness in continuous monoculture.

4. CHALLENGES AND PERSPECTIVES IN SOIL SICKNESS RESEARCH

The causes of soil sickness vary among plant species. Within the same plant species, the reasons of soil sickness expression can also vary from one geographical area to another one. This situation is expected due to the diversity of cultural practices, climatic conditions, crop cultivars, soil conditions and microbial populations faced by a crop plant. Several methods have been proposed or are currently used to minimize or partially overcome the soil sickness problem. They are breeding for resistant cultivars, crop rotations and intercropping, soil admendments, appropriate management of crop residues, chemical control, microbial biocontrol and phytotoxin removal.

4.1. Breeding for resistant cultivars: Decades of research showed that many crops have

intraspecific variations in autotoxic potential and in the resistance to pests and diseases. For example, autotoxic potential seems to be a genetic character that vary among the alfalfa and rice cultivars (48,125). High accumulation of phenylpropanoids in the outer layers of the grains and in the stem piths is a genetic character that can be used to improve the resistance of maize inbreds to *Fusarium* spp. and borer pests (129). Hence, crop breeding based on this genetic variability is an attractive strategy to overcome soil sickness. Crop genotypes resistant to pathogens and autotoxins also can be developed as rootstocks for many horticultural crops. This is the case of lemon resistance to *Phytophthora* and the citrus nematode (*Tylenchulus semipenetrans*), due to use of rootstocks of some *Citrus* species or its relatives (i.e. *Poncirus trifoliata*) (135). Nevertheless, crop improvement for resistance to insects and diseases has received more attention than for alleviation of autotoxic feature, probably due to the polygenic nature of autotoxic trait and problems to follow it in laboratory, greenhouse or field experiments (12). Besides the autotoxins are multipurpose compounds that protect the producer plants against many natural enemies. For example, hydroxamic acids in the residues and root exudates of wheat are known allelopathic and autotoxic compounds, but, they are antimicrobials to wheat pathogens and antifeedants to aphids (130). Hence, breeding to decrease the autotoxin production, requires good knowledge of biologically active forms, breakdown products of such compounds and their actual impact at several trophic levels in the agroecosystems.

4.2. Crop rotations and intercropping: They are the oldest and most important methods used to avoid soil sickness. Crop rotations are often restricted by equipment requirements, climatic conditions and the market price of crops (102). They change the contribution of allelochemicals to the soil, avoiding autotoxicity and increase the population of microbial antagonists towards noxious soil borne pathogens and pests. In sugarcane cropping cycle with crops such as soybean or pastures improves the soil fertility and reduces the population of harmful soil microbiota (124). The intercropping increases the soil organic matter and mineral nutrients available for crop growth. For example, green garlic-cucumber intercropping increases the biomass production and improves the mineral nutritional status of the cucumber plants (168). It also can activate microbial disease-suppressive mechanisms such as host dilution and enhanced populations of antagonistic microorganisms. For example, spread of *Rhizoctonia* damping-off in radish-mustard mixture decreases with increasing densities of non-host mustard plants (103). Wheat root infection by *Gaeummanomyces graminis* var. *tritici* was reduced by 25% in wheat-trefoil (*Medicago lupulina*) mixture (33). Many crops exude nematicidal and antimicrobial substances e.g. intercropping of garlic with cowpea or tomato, reduces the occurrence of nematode *Rotylenchulus reniformis* and *Meloidogyne incognita* (39).

4.3. Soil amendments: Continuous monocropping depletes the mineral nutrients in soil and lead to proliferation of noxious microorganisms. In this context, soil amendments with inorganic matter, organic matter or formulated compounds can be used both to control soil born plant pathogens (63). Sometimes biofertilization is better than addition of synthetic fertilizers. An appropriate soil amendment should inhibit the soil borne-pathogens, maintains soil fertility and avoid the detrimental effects in agroecosystems, e.g. the growing and incorporatiing the *Brassica* green manures to the soil in short breaks between vegetable crops viz., potato and carrot (130). This practice suppress the soil borne pathogens

due to the release of biocidal thyocyanates, nitriles and thiocyanates after hydrolysis of glucosinolates contained in the tissues of the *Brassica* species. Some organic materials carry microbial antibiotic-producing antagonists able to suppress the growth of phytopathogenic fungi, e.g. Finnish peat is made of *Sphagnum* mosses, which suppresses the *Fusarium* spp., *Rhizoctonia solani* and *Alternaria brassicola* in horticultural crops (145). It also contains several species of *Streptomyces* (i. e. *Streptomyces griseoviridis*) which produce complex heptaene antibiotics.

4.4. Chemical control: Synthetic pesticides are often used to deal with soil sickness (63). Some examples are the soil treatments with the nematocide nemacur, and the fungicides benomyl or thiram for control of mungbean soil sickness, the fumigation of soil apple orchards with Basamid (dazomet), the seed treatments with metalaxyl that protects germinating pearl millet seedlings from downy mildew infection or the use of methyl bromide as a preplant soil fumigant to control soil born pests and diseases in horticultural crops (102). Nevertheless, the agricultural use of several of these products is currently forbidden due to the increasing public concerns from their harmful effects on the environment and human health.

4.5. Plant Residues Management: Crop residues often release autotoxins and provide appropriate conditions for proliferation of soil borne pathogens, hence, these residues sometimes are partially or totally removed from soil. Methods of removal vary, burning or use of microbes to hasten the degradation of crop residues (9). Solar sterilization is increasingly used to control many soilborne diseases, however, it also kills all soil microflora. Deep ploughing to turn over the soil, summer ploughing and flooding are used to eliminate noxious microorganisms or autotoxins from the soil profile (124).

4.6. Microbial biocontrol: The use of disease-suppressive microorganisms to improve plant health is an efficient way to improve the soil microenvironment and control the soil-borne pathogens. Many types of antagonistic bacteria (*Pseudomonas* sp., *Burkholderia* sp., *Bacillus subtilis*, etc) and fungi (*Trichoderma*, *Gliocladium*, etc) have been isolated from soil and used to control phytopathogens (58). The antagonistic effects of beneficial microbes on pathogens is significant in the laboratory but many of them can not success- fully colonize the rhizosphere soil, suppress soil-borne diseases and improve plant growth.

4.7. Removal of Phytotoxins: Adsorption by activated charcoal (6), degradation by microbial strains (7), electrodegradation and TiO2 photocatalysis can be used to eliminate the autotoxins from root exudates and other plant sources in horticultural crops (6).

Future Areas of Research

Further research on soil sickness is needed on the following Aspects:
(i). To better understand the dynamics of microbial populations in the rhizosphere of crop plants.
(ii). Collective chemical communication between the soil microbial community and the crop plants.
(iii). Real impact of autotoxins on crop plants and microbial communities on whole

cocktail of plant and microbial metabolites exuded into the soil.

(iv). Characterization of new biological agents and organic disease or pest suppressive materials useful for soil sickness control.

ACKNOWLEDGEMENTS

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