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Soil sickness and productivity from ecological aspects

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Abstract
The problem of soil sickness has been emerged in major cropping system of India mostly due to the cultivation of same crop over a long period of time. Even after a good nutritional status in soil, it does not give its potential in crop production due to certain reasons indicating the prevalence of soil sickness. It reduces the amount of yield along with its quality of many agronomic and vegetable crops. The reasons behind the soil sickness could be autotoxicity due to release of allelochemicals by plant species, continuous monocropping, use of agrochemicals and others. These all factors destroy the proper balance of soil nutrients including micronutrients, composition and activities of soil microorganisms, disruption in rhizosphere soil homeostasis, soil physicochemical properties, and infestation of insect-pest and diseases specifically soil borne diseases. Therefore, it’s very imperative to intensify the farming system more sustainably by diversifying crops’ cultivation, preventing use of harmful agrochemicals, and by moderating crop’s autotoxicity.

Keywords: Agrochemicals, Allelochemicals, Autotoxicity, Monocropping, Soil Microbes, Soil Sickness

Introduction
Soil sickness is the reduction in both quantity and quality of crop produce caused by numerous factors. Though, its symptomatic framework is not so far well defined, but scientific studies have shown that it deals with imbalances in soil-plant system. Plants can affect the soil microbial population *via* the ways of variable organic matter supply, or rhizodeposition/ extraction, and so soil microbes can change the performing potential of plant system such as nutritional availability, mutualistic interactions, or pathogenic bustle. In the soil ecosystems, crop plant can alter the biochemical composition of soil through regulating the type and quantity of root deposition, root exudation, and vulnerability to insect-pathogens and symbionts. Subsequently, these alterations can diminish or improve the plant growth and development, which is usually called positive and negative plant-soil feedback, respectively. In the meantime, below-and above-ground herbivores of previous crop species can promotes the changes in prevalence and composition of soil biota, which greatly influence secondary metabolite accumulation, biomass, and aboveground multi-trophic interactions of succeeding plants. Of them, the negative plant-soil feedback is the soil sickness which reduces crop yield and quality and the occurrence of soil borne plant diseases when the same crop or its related species (monocropping) are grown of same piece of land year after year.

Soil sickness in crop plants
Autotoxicity is considered as important factor directly responsible for soil sickness or replanting disease of several crop species. It is a special intraspecific allelopathy phenomenon, in which the secondary metabolites or chemical compounds released by the crop plant hinder the germination, growth, or other biochemical process of other nearby crop plants of the same crop species. Autotoxicity promotes the occurrence of plant dysplasia (serious plant diseases and greatly reduction in amount and quality of crop yield) initiated by repeated cultivation of same crop species on same piece of land over several years. Presently, continuous monoculture has become a need because of intensive land use pattern associated with greater population pressure resulting in decreased land.

Soil sickness of important crops
The type and extent of soil sickness caused by different crop plants are species specific. It may be autotoxicity, nutrient and microbial depletion, and build-up of various nematodes, diseases and pests (Table 1).

Rice
Autotoxic effect of leftover rice stubbles after paddy harvest resulted in about 25% decline in

yield of second rice crop due to lack of adequate drainage. In general, after harvest of first season rice, the residue remains in field and used in nutrients recycling in the same field. The subsequent anaerobic decomposition of these residues resulted in release of large amount of autotoxins into the paddy field, which later on inhibits the growth and yield of successive second crop of rice (Ma *et al*., 2014) [11]. The phenolic acids released from the decomposing rice residues and their root exudates include p-coumaric, p-hydroxy benzoic, syringic, vanilli, ferulic etc.

Wheat

The growth and yield performance of zero-tilled wheat system have been attributed to surface retention crop residues and stubbles. The significant decline in economical yield of wheat crop can reduced due to the phytotoxic chemicals released from the decaying wheat residues. The experimental results also showed the reduced wheat germination, radicle growth, and coleoptile growth by 2-21, 15-20, and 5-20% due to the root exudation and residue extraction (Wu *et al*., 2007) [20].

Table 1: Nature of soil sickness by different crop species

Crop	Nature of soil sickness
Rice	Autotoxins, nutrients and microbial imbalances
Wheat	Autotoxins, nutrients and microbial imbalances
Maize	Autotoxicity, phytopathogenic microbes
Soybean	Autotoxicity, *Penicillum purpurogenum*
Green gram	Autotoxicity, microbial imbalance
Sugarcane	Soil microbial imbalance, soil physio-chemical properties, autotoxins
Tobacco, cucumber	Autotoxicity, phytopathogenic fungi
Groundnut	Microbial imbalance
Brinjal	Autotoxicity, *Verticillum dalhiae*
Apple	Phytopathogenic fungi and bacteria
Peach	Nematode, autotoxicity
Orange, citrus	Autotoxicity, nematode, phytopathogenic fungi
Tea, coffee, tomato	Autotoxicity
Watermelon	Autotoxicity, microbial imbalance
Potato, ginger	Soil borne diseases
Rehmannia	Autotoxicity, soil borne diseases

Maize

Maize is a sensitive crop to the ill-effects of soil sickness under continuous monocropping. This effect becomes more vibrant under no-tillage farming, wherein the maize residues are retained over the surface of soil. In maize, autotoxicity decreases the dry weight, root and shoot length of seedlings and also a substantial reduction in net chlorophyll content, protein content and the activities of nitrate reductase when maize seedlings were treated with residue extracts. Maize residue left in soil for decomposition also alters the rhizospheric micro flora which in turn inhibits maize growth (Singh *et al*., 2010).

Soybean

Soil subjected to soybean mono-cropping, reduced soybean yield even after sterilization with methyl bromide. Mycotoxins released by *Penicillum purpurogenum* were involved in growth inhibition of soybean plant (Jiangchun and Shujin, 1996).

Sugarcane

Continuous mono-cropping of sugarcane including ratoon decreased sugarcane yield. Autotoxicity is also reduces yield of cane in continuous cropping. Allelo-chemicals released from the cane residues inhibit the germination, radicle length and seedling weight of cane (Sampietro, 2006) [16].

Mechanism of soil sickness

There is several mechanism or causes of soil sickness as follow –

1. Abnormal expression of gene order in continuously mono-cultured plants and their disorderly regulation, which result in an adverse physiological response.
2. Deterioration of soil physiochemical properties and nutrient imbalances.
3. Allelopathic autotoxicity of root exudates.
4. Imbalance in soil micro-ecosystem (decreased microbial diversity, increased pathogens and pests, the fragile biological interactions) and disruption in rhizosphere soil homeostasis.
5. Continuous monocropping.
6. Agrochemicals
7. Crop ecosystem

Soil sickness and gene expression disorders

In continuous monoculture cropping, plant shows dysplasia (decrease in growth rate, shortening of growth period and decline in yield and quality), which is related to particular physiological process, gene expression, and their regulation. In continuous mono-cultured *Rehmannia glutinosa* the problem of soil sickness has been seen at initial stage of growth which prolonged during the entire growth period. Supplementary the buildup of free radicals in the cells of crop plant, and the injury to membrane structure due to the ill effects of monocropping becomes the reason for stomata closure and decrease in chlorophyll content. Similarly, monocropping of *R. glutinosa* considerably alters the concentration on indigenous plant hormones i.e. IAA and ABA. Under such conditions, the concentration of ABA hormone increases at the seedling stage of *R. glutinosa* which is unfavorable for the plant growth as higher content of ABA at early growth stage can decreases photosynthetic activity and promotes stomata closure. Although, IAA concentration at root elongation stage of *R. glutinosa* under monoculture was considerably lower than in newly planted plant which accelerated the leaf senescence of plant at the same stage. This imbalance in indigenous hormones in *R. glutinosa* under continuous monoculture disturbs the normal growth and development of plant.

Soil physic-chemical properties and soil sickness

The decline in soil pH or deposition of acidic ions in soil either by chemical fertilization or by release of allelochemicals from plants under continuous monocropping deteriorates the physic-chemical properties of soil. This continuing process in many farming system is the main reasons for soil sickness. To maintain normal growth and development, plant root absorbs cationic and anionic essential plant nutrients from soil solution as a result of H extrusion and OH/HCO_3 release, respectively. The indiscriminate and unbalanced application of synthetic fertilizers enhances the buildup of phytotoxic substances in soil which comes in existence in the form of soil acidification e.g. NH_4^+-fertilization causes Al-toxicity (Kakraliya *et al*., 2017) [7]. In such soils, the physical, chemical and biological properties of soils and, therefore the crop yields get affected strongly (Meena *et al*., 2017a) [14]. The effects of low soil pH on cation availability deteriorate aggregate stability since divalent cations, such as calcium ions, are absent at low soil pH (Kumar *et al*., 2017a) [10]. Although, soil acidity itself is not responsible for restricting plant growth and crop productivity; while the associated chemical changes in the soil can restrict the availability of essential plant nutrients especially nitrogen, phosphorus and potassium (Kumar *et al*., 2017; Varma *et al*., 2017) [9, 18]. In the same way, the cultivation of same crop on same land over a considerable period of time influences the soil properties. For instance, the cultivation of cotton over several years significantly affects the organic carbon distribution and composition and mechanical stability of soil aggregates.

Allelopathic autotoxicity and soil sickness

Numerous autotoxins have been recognized, which exhibits allelopathic property by influencing respiration, water and nutrient uptake, cell division and elongation, ATP synthesis, gene expression, and redox homeostasis. In the meantime, there are great intra-and inter-specific variances in uptake and accumulation of autotoxic substances, resulting in specific changes in plant growth. Notably, these autotoxins also negatively affect the beneficial soil microorganisms which increase the chances of soil sickness. In many cases, autotoxins may enhance soil borne diseases by predisposing the roots to infection by soil borne pathogens through a direct biochemical and physiological effect (Huang *et al*., 2013) [4].

Table 2: List of known autotoxins (Asaduzzaman *et al*., 2013) [2]

Crop	Autotoxic agents	Autotoxins
Alfalfa	Roots	Medicarpin, 4-methoxy medicarpin, sativan, 5-methoxy sativan, coumarin, *trans*-cinnamic, salicylic, *o*-coumaric, chlorogenic and hydro-cinnamic acids
Broad bean	Roots exudates	Lactic, adipic, succinic, malic, benzoic, vanillic, *p*-hydroxybenzoic, glycolic and p-hydroxyphenylacetic acids
Pea	Roots exudates	Benzoic, cinnamic, vanillic, *p*-hydroxybenzoic, 3, 4-dihydroxybenzoic, *p*-coumaric and sinapic acids
Rehmannia	Soil	Phenyl aromatic acid
Rice	Plant decomposition	*p*-coumaric, *p*-hydroxy benzoic, syringic, vanillic, ferulic and *o*-hydroxy phenyl acetic acids
Wheat	Straw residue	Ferulic, *p*-coumaric, *p*-hydroxybenzoic, syringic and vanillic acids
Tomato	Root exudates	4-hydroxybenzoic, vanillic, phenylacetic, ferulic, 2-hydroxy-3-phenylpropanoic caffeic acids
Tea	Soil	Phenolic acids
Coffee	Plant tissue	Caffeine, theophylline, theobromine, paraxanthine, scopoletin, caffeic, coumaric, ferulic,

Rhizospheric micro-flora and soil sickness

Soil also contains some specific group of soil micro-organisms which increase the availability of essential nutrients to plants by mineralizing organic compounds (Kakraliya *et al*., 2017a) [8] such as increased availability of phosphorus by Mycorrhizae (Jakhar *et al*., 2017) [5]. The changes in the composition and activities of these soil microorganisms will significantly influence plant growth as soil microbes are directly involved in the several soil biochemical processes essential for plant nutrition and growth (Meena *et al*., 2016; 2017) [12, 13]. The reasons behind the alteration in population, diversity and functionaries' of soil microorganisms are continuous monocropping, indiscriminate use of agro-chemicals, autotoxins, root exudates and root depositions. The populations of bacteria and overall microbial activity in soil tends to be highest following barley, canola, and sweet corn rotations, and lowest with continuous potato, which is characterized by the greatest proportion of straight chain saturated fatty acids in soils under continuous potato growth. Soil microbial communities are changed after monoculture with a single plant species e.g. peas, soybeans. Continuous monoculture reduces microbial competition in the root zone by lowering biodiversity among root associated fungi and bacteria, thus enabling pathogenic populations to develop, thus increasing disease incidence and subsequent yield losses (Andrews and Harris, 2000) [1]. For example, more than 60% of the strains isolated from healthy soils corresponded to Pseudomonas sp., and 58% of the isolates from sick soils were Bacillus sp., which is able to produce HCN *in vitro* (Benizria *et al*., 2005) [3]. Accordingly, yield reductions following the monoculture of a single crop species also is related to the accumulation of non-pathogenic, deleterious Rhizobacteria.

Continuous Mono-cropping

Since the 1960s, great progress has been made in agricultural science and technology. In many areas, traditional cropping systems with multi-crops have been replaced by mono-cropping with specific crops in many intensive agro-ecosystems. The shift of cropping systems changes the relationship of plant-soil feedbacks and ultimately influences plant growth and sensitivity to soil borne pathogens. At present, soil sickness becomes prevalent in the production of many annual crops with intensive mono-cropping, and it also affects trees and shrubs in orchards (apple, pear, grapes, etc.), coffee and tea plantations, where it causes replant problems for fruit trees and regeneration problems in natural forests.

Agrochemicals

Only 0.1% of applied pesticides are reaches to target organism and the remaining part of a pesticide application usually reaches the soil, even if sprayed on the growing crop, and so may have an effect on organisms living in the soil. These may inhibits the activities of beneficial non-target soil microorganisms, soil enzymes and soil biochemical reactions temporarily. Such possibilities are of particular concern where pesticides are applied at high rates, repeatedly, over many years, as occurs in crops such as maize and cotton which often receive multiple applications of several pesticides during a single growing season. The persistence of insecticides and their effect on the rhizosphere microbial community are more negative as compared with both herbicides and fungicides. Given enough time, the soil ecology appears capable of recovering from applied fungicides and insecticides, although the recovery may take months or years and the economics of crop production may be negatively impacted in the meantime. The experiment conducted by Milošević and Govedarica

(2002) [15] reported that soybean treatment with flumetsulam + trifluralin (Rival), imazethapyr (Pivot), clomazone (Command) and alachlor + linuron (Linuron S-50) reduced the total number of microorganisms in the period of 14 days after application by 15 to 27%. After that period, the numbers of microorganisms in the treated variants reached the level of the control variant while on the 90th day after application the numbers of microorganisms in the variants with clomazone (Command) and alachlor + linuron (Linuron S-50) were increased in relation to the control.

Continuously mono-cropped aerobic rice

Soil sickness related with yield decreases of continuously mono-cropped aerobic rice (CMAR) is the most important constraint to the wide implementation of aerobic rice technology. Root knot nematodes are considered to be the most important contributors of soil sickness because of continuous mono-cropping of aerobic rice, followed by fungi, and other microorganisms.

Dryland rice-based cropping system

In the dryland rice-mung bean rotation, there was a tendency for the nematode genus *Rotylenchulus* to increase in number during mung bean cropping. This may have led to a pathologic effect at later stages of mung bean growth. Continuous cropping of mung bean encouraged a high population of root-infecting *Rotylenchulus*, and may be related to the poor growth of young plants, which is the common but non-specific observed symptom of mung bean soil sickness. There are indications of a similarity in nematode involvement in the soil sickness of cowpea (Ventura *et al*., 1981) [19].

Challenges and outlook of soil sickness

Intensive agriculture as prevalent in many countries and regions may lead to soil sickness in croplands. Soil sickness is a complicated phenomenon, and the detailed mechanisms involved are not fully understood. In general, autotoxicity, disturbed microbial communities, and others are responsible for the observed phenomenon. The interaction between allelochemicals, autotoxins, and microbes is important. There is an increasing interest in the autotoxicity of crops, and more than 50 crops have been shown to have autotoxic potential. In addition, the autotoxic potential of many crops has been established based only on the correlation of phytotoxicity and the dose of extracts in plant tissues, without evidence for autotoxins in the rhizosphere. Allelochemicals or autotoxins in the rhizosphere directly or indirectly affect soil borne pathogens or other detrimental microbes. Biodiversity conservation with different cropping systems will be an increasingly important approach for the sustainable development of agriculture production and pest control. It is important to re-examine the usefulness of traditional agricultural management methods, and this is especially important in developing countries.

Soil is a complex matrix and many autotoxins can be easily modified by soil microbial communities. Special attention should be paid when differentiating the active autotoxins from their inactive conjugates in the soils. In most cases, the concentrations of so-called autotoxins in soils are lower than that at the phytotoxic dose, and these autotoxins also are easily degraded by microbes. It is, therefore, difficult to explain why a 2–7 rotation or fallow period is necessary for these crops based on the fate of autotoxins. We need to find other important autotoxin candidates and study both the additive and synergistic effects of different autotoxins in the soil matrix. In addition, there are suppressive and conducive soils in agroecosystem, but the underlying mechanisms are largely unknown. It will be interesting to compare the microbial communities and the behaviours of autotoxins in these soils.

Future area of research

- To better understand the dynamics of microbial population in the rhizosphere of crop plant.
- Real impacts of autotoxins on crop plant and microbial communities on whole cocktails of plants and microbial metabolites exudates in soil.
- Characterization of new biological agents and organic disease or pest suppressive materials useful for soil sickness control.

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