Fertilizing Crops to Improve Human Health: a Scientific Review

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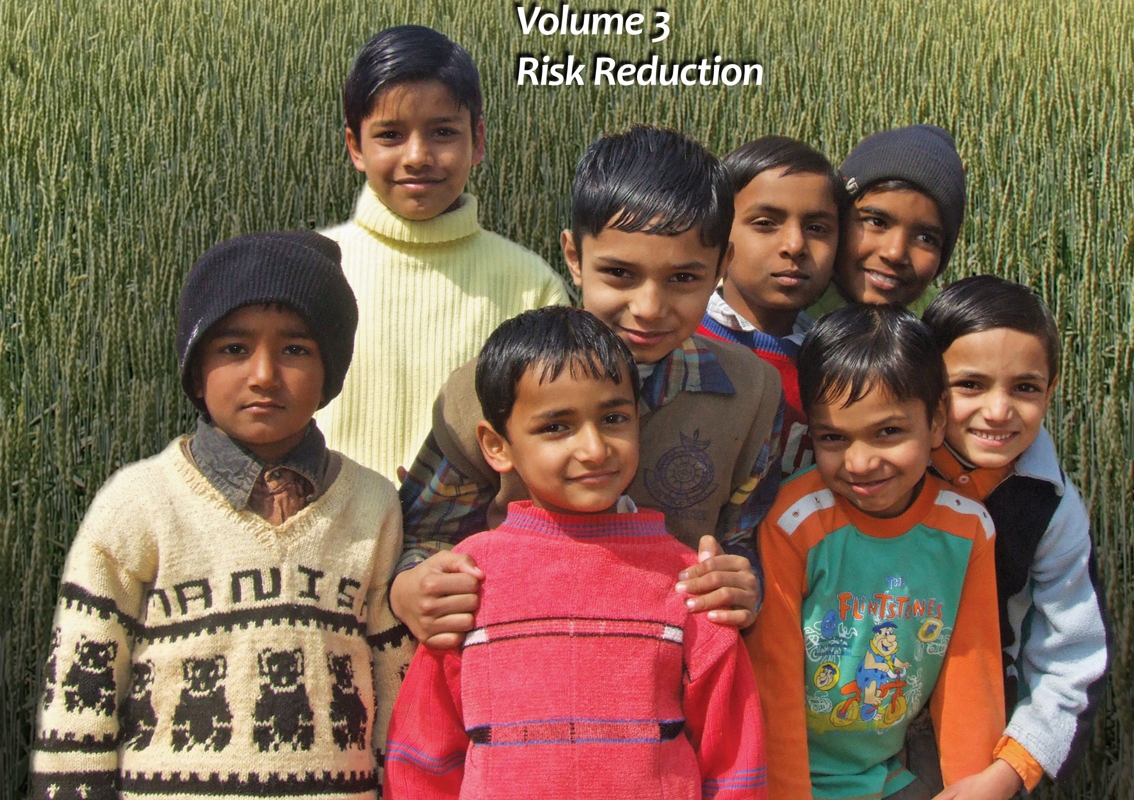

Volume 3
Risk Reduction

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Abbreviations and symbols commonly used throughout this publication

Al	Aluminum
B	Boron
C	Carbon
Ca	Calcium
$CaCO_3$	Calcium carbonate
CaO	Calcium oxide
$CaSO_4{\cdot}2H_2O$	Calcium sulphate (gypsum)
Cd	Cadmium
CH_4	Methane
Cl^-	Chloride
Cu	Copper
$CuSO_4$	Copper sulphate
Cs	Caesium
F	Fluorine
Fe	Iron
Fe^{2+}	Ferrous iron
Fe^{3+}	Ferric iron
H^+	Hydrogen ion
HCO_3^-	Bicarbonate
H_2O	Water
I	Iodine
K	Potassium
KCl	Potassium chloride (also muriate of potash or MOP)
K_2O	Oxide form of K, used in trade to express K content of fertilizer
K_2SO_4	Potassium sulphate (also sulphate of potash or SOP)
Mg	Magnesium
Mn	Manganese
Mo	Molybdenum
N	Nitrogen
Na	Sodium
NaCl	Sodium chloride
N_2	Dinitrogen

NH_3	Ammonia
NH_4^+	Ammonium
Ni	Nickel
NO_2^-	Nitrite
NO_3^-	Nitrate
NO_x	Nitrogen oxides (nitric oxide and nitrogen dioxide)
N_2O	Nitrous oxide
O_2	Dioxygen
P	Phosphorus
Pb	Lead
PO_4^{3-}	Phosphate
P_2O_5	Oxide form of P, used in trade to express P content of fertilizer
Pu	Plutonium
S	Sulphur
Se	Selenium
Si	Silicon
SO_4^{2-}	Sulphate
Sr	Strontium
Y	Yttrium
Zn	Zinc

Chapter 9

Plant Nutrition and Health Risks Associated with Plant Diseases

Don M. Huber[1]

Abstract

Seventeen of the 25 essential elements for humans are also essential for all plants. Three are essential or beneficial for some plants, and most of the remaining five can be found in plants. The availability of a mineral element for plant growth is not only dependent on its abundance in soil, its form and solubility, or the presence of competing or toxic entities, but also on microbial associations, the assimilative capacity of the plant, and environmental factors such as pH, moisture, and temperature. Plant diseases and pests are common causes of disturbed mineral nutrition and limit crop production efficiency, food safety, and nutrient quality. Nutrition has always been a primary component of disease control. Cultural practices such as crop sequence, tillage, organic amendment, soil pH adjustment, and water management often influence disease through nutrient interactions. Nutrient management is important to minimize the impact of diseases on the quantity, nutritional quality, and safety of crops for food and feed. Not only can the severity of many diseases be reduced, but also the chemical, biological, and genetic control of many plant pathogens can be enhanced by proper nutrition. A healthy plant is more efficient and able to balance its nutritional needs more effectively from the limited resources available. This, in turn, results in a greater nutrient sufficiency of the crop and enhances its beneficial use for food and feed purposes.

Introduction

Plants provide the primary source of minerals and other nutrients for animals and humans. Thus, the sufficiency of human nutrition is dependent in large measure on the availability and nutrient sufficiency (quality) of the plants consumed directly, or indirectly through animals. Healthy plants promote healthy people. A varied diet is required to provide a full complement of the essential nutrients since no single plant source contains all of the essential carbohydrates, fats, amino acids, minerals, vitamins, etc. required in their proper ratios or concentrations. Traditionally, each self-sustaining society has cultivated crops and animal sources to provide the energy (carbohydrate), protein, and fat nutrients required

For abbreviations and symbols used commonly throughout this book see page v.

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in the largest quantity; with the essential minerals and vitamins also generally being available through these three primary food groups.

In plants, each element has specific functions as part of an intricate system of delicately balanced physiological interactions. A deficiency or excess of one element greatly influences the activity of others and sometimes can exert catastrophic effects as secondary and tertiary consequences reverberate throughout the entire metabolic network of the plant (Evans et al., 2000). A deficiency of Mn or Mg that limits photosynthesis reduces the efficiency of those physiologic systems requiring energy, while a deficiency of K or Mg essential for sugar movement in the plant results in the accumulation of sugars in photosynthetic tissues and limits the desired accumulation of carbohydrate and protein in developing reproductive structures. The individual elements are required in varying amounts depending on whether they become structural or metabolic components, or function primarily as regulators of metabolic pathways. Nitrogen, P, K, S, Ca, and Mg are required in the largest amounts. However, B, Co, Cu, Cl^-, Fe, Mn, Mo, Ni, and Zn are required in much smaller quantities. Sodium is considered essential for halophytic plants and Si for some grasses and horsetails. Plant essential C, H, and O are supplied through air or water while the remaining elements come from solubilization of various salts and minerals in soil or water. Various crops have different nutrient requirements for optimal growth and productivity (Marschner, 1995).

There are large differences among crops in their efficiency for the uptake and utilization of specific mineral nutrients so that a particular crop species, or even cultivar, may be more or less adapted to a certain environment than another. For example, a soil with 0.5 ppm available Cu may be adequate for pea, corn, rye, and cole crops, but severely limiting for the less efficient wheat, barley, and flax which need 3 to 4 times this level for sufficiency and optimum production (Evans et al., 2000). Root configuration, production of selective root exudates, and physiological efficiency influence whether a plant will be nutrient sufficient or deficient in a particular environment. Generally, as yields have increased, the need for available nutrients also has increased to support the increased physiological activity of the plant and to compensate for the larger amount of nutrients removed with the harvested crop. A different nutritional regime may be required to produce specific crop components such as protein in cereal grain or soybean compared with oil in canola (oilseed rape), soybean, or sunflower. If any one nutrient becomes limiting, yield and quality of the harvested component is often disproportionately reduced because of the intricate interrelationship of each nutrient with physiological processes (Rengel, 1999).

Plant nutrient deficiency is a major limitation to crop production efficiency and nutritional quality, and a predisposing factor for disease. Plant nutrient deficiencies can reduce both the quantity and quality of nutritive components of plants. When plants become deficient in a particular nutrient, other nutrients also may be affected so that the vitamins, protein, carbohydrate, fat and other essential nutritional components that plants are grown for will be affected.

As primary food and feed sources, plants must provide nutrients in adequate quantity, safety and nutritional quality. Factors that result in a nutrient deficiency for plants also affect their nutrient value or nutrient availability for animals or man. Major causes of nutrient deficiency are an inadequate supply, lack of access to forms of nutrients available for absorption, or disease denial of nutrients necessary to maintain plant health and nutrient quality. Nutrient deficiencies can be overcome by increased availability, more efficient plant uptake, increased physiological efficiency, and improved disease control. Benefits of nutrient sufficiency of the plant are achieved through increased production efficiency and greater productivity of more nutritious and safer food. A healthy plant will be more efficient and able to meet its nutrient needs more effectively from the generally limited resources available. The focus of this chapter is on the role of plant nutrition in the management of plant diseases that affect the safety and nutritional value of food crops.

Causes of Plant Nutrient Deficiency

Plant nutrient deficiency is caused by an insufficient level of an essential element at a critical time to maintain normal plant function. This may result from negligible amounts of an element in soil, inaccessibility (solubility, form), unfavorable abiotic soil conditions (pH, aeration, compaction) that limit root function, microbial-induced deficiency in the soil, or the effect of infectious plant disease and impaired physiological function. Balanced nutrition may be as important as the presence of any particular element since the intimate effects of nutrient deficiency occur at the cellular level, but may be manifest in altered growth and nutritional quality of the whole plant. Both abiotic and biotic factors can influence nutrient availability and disease severity.

Abiotic Factors Affecting Plant Nutrition and Disease

Compaction, pH, moisture, temperature, tillage, and biological activity largely determine the availability of nutrients contained in soil, affect root growth, and can predispose plants to various diseases. Soils between pH 6 and 7.5 are considered optimum for most cultivated crops although most crops can be grown well outside this pH range, and some crops are specifically adapted to either acid or alkaline soils. Iron, Mn, Cu, and Zn may reach toxic concentrations in tissues when soil pH is below 5 and be severely deficient at pH above 7.5. Highly acid soils can be limed to reduce toxicity from excess Al, Cu, and Mn, while flooding or applications of S to alkaline soils will increase the availability of B, Cu, Fe, Mn, and Zn that otherwise might be unavailable for plant uptake.

Drought reduces root growth, the solubility of nutrients for plant absorption, and the uptake of nutrients that are poorly mobile in soil. Nitrogen and carbohydrate metabolism and other plant physiological functions are impaired under drought stress, but are impacted less if nutrient sufficiency can be maintained. NO_3^- and NO_2^- reductases are especially impaired by moisture stress and high temperature to result in lower protein and high levels of tissue NO_3^- under otherwise fertile conditions. High NO_3^- in forages fed to ruminant animals can pose a health hazard for them. Symbiotic N-fixation of legumes is reduced under drought stress because Mn and Ni needed for ureide synthesis become less available, and the soil organisms involved in their solubility are less active. In contrast to moisture deficit, excessive moisture limits oxygen in the root zone to inhibit active nutrient uptake.

Coarse-textured (sandy) and highly organic soils pose special situations for maintaining nutrient sufficiency in plants. Coarse-textured soils are subject to leaching and movement of nutrients below the area of active root absorption while organic soils sequester (chelate) cationic nutrients to reduce their availability for plant uptake. Availability of Cu, Mn, and Zn can be disproportionately affected. Although cereal plants can absorb both NO_3^- and NH_4^+ in cool soils, a visible plant response is faster with the more readily translocated NO_3^- than with the NH_4^+ that is translocated primarily as amino acids (glutamine, glutamate, etc.).

Tillage and cultivation mix nutrients in the root zone, break compaction for better aeration, stimulate mineralization, and increase plant access to limited nutrients by facilitating root growth. Reduced-tillage agricultural systems frequently have limited availability of some essential nutrients because of localized distribution (stratification), immobilization in residue, limited root growth, and modified microbial activity affecting nutrient availability. High levels of some nutrients may competitively inhibit the uptake of other elements. Repeated applications of large quantities of organic manures (high in P) can immobilize Cu, Mn, and Zn to reduce their availability for plant uptake from soil. Copper used to control bacterial or fungal diseases can accumulate to toxic levels in soils over years of application.

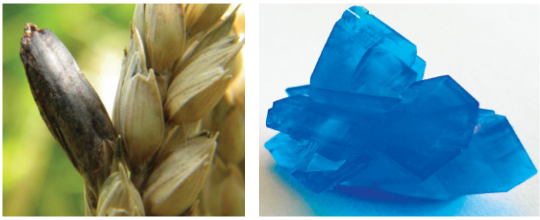
Biological Factors Affecting Plant Nutrition and Disease

Soil microorganisms, as activators in biological nutrient cycles, modify mineral availability and play a critical role in either inducing or alleviating mineral deficiencies and thereby affecting plant resistance and pathogen activity. Biological mineralization of residues releases minerals from their bound state in residues and organic matter, but can also result in a transient immobilization of certain nutrients such as N that are preferentially acquired for microbial growth and activity during decomposition of residues low in N. The dynamics of nutrient cycling can be changed by variations in microbial, environmental and plant factors. Thus, time of nutrient application may be crucial because of changes in the interactions involved. Biological oxidation of N (nitrification) can lead to extensive losses of this essential element through subsequent denitrification or leaching. A characteristic of climax ecosystems is inhibition of nitrification to preserve N for plant availability (Rice, 1984). The biological oxidation of reduced Fe and Mn makes them unavailable for plant uptake, while plants can only use the oxidized form of S. Various synergistic interactions of soil microbes with plants can greatly increase nutrient uptake and reduce disease severity. Examples of the dynamic interactions influencing nutrient availability are the biological fixation of atmospheric N to plant available forms by soil microbes, increased P and Zn uptake by mycorrhizae, biological reduction of Fe and Mn in plant rhizospheres, and the biological oxidation of S.

Effect of Nutrient Deficiency on Plant Disease

Increased susceptibility to infectious disease is a common result of nutrient deficiency (Datnoff et al., 2007; Evans et al., 2000; Huber, 1991; Huber and Graham, 1999). Increased cell permeability from Zn or B deficiency can result in the loss of nutrients through root or leaf exudation to attract various pathogens or enhance infection (Cakmak and Marschner, 1988). This nutrient-enriched rhizosphere environment provides the chemical stimulation and attraction for soilborne pathogens such as *Pythium* and *Phytophthora* (Huber, 1978).

Foliage diseases such as powdery mildew (*Erysiphe graminis*) are more severe on Cu-deficient cereals because maturity of the plants is delayed to extend the infectious period. Copper deficiency predisposes gramineaceous plants to ergot because of pollen sterility that causes the glumes to open so that stigmas are exposed to infection by *Claviceps purpurea*, the cause of ergot. Application of Cu fertilizers can greatly reduce severity of this disease (Evans et al., 2000). Zinc deficiency predisposes plants to *Rhizoctonia solani* and other cortical pathogens because inhibitory carbohydrates are reduced and the energy required for defense is lacking. Early Zn deficiency predisposes winter cereals to winterkill by *Rhizoctonia cerealis* because adequate carbohydrate reserves necessary for resistance are not retained throughout extended periods of snow cover or low photosynthesis. Early seeding of winter wheat to reduce winterkill facilitates root colonization by mycorrhizal fungi and increases Zn uptake to provide a plant that is more resistant to the causal fungus (Bockus et al., 2010). Potassium deficiency predisposes potato and tomato to leaf blight caused by *Alternaria solani*. Manganese deficiency predisposes cereal plants to take-all root and crown rot (*Gaeumannomyces graminis*), potato to common scab (*Streptomyces scabies*), many plants to *Verticillium* wilt (*Verticillium dahliae*), rice to blast (*Magnaporthe griseae*) and numerous other plants to severe debilitating plant diseases because the defense compounds regulated by Mn that inhibit these pathogens are not produced (Huber and Wilelm, 1988; Thompson and Huber, 2007).



Application of Cu fertilizer (CuSO$_4$ crystal on right) has been an effective treatment in ergot-prone soils.

In addition to the lower amino acid content and protein from a deficiency of N, N deficiency will also predispose plants to early senescence and diseases caused by toxigenic *Fusarium* species and other pathogens. Stalk rot describes a symptom of one of the most destructive diseases of maize. It is often referred to as a disease of stress or senescence since actively growing plants at nutrient sufficiency are seldom lodged from infection by *Gibberella zeae* or other stalk rotting pathogens. Stalk rot is especially severe when the available N from the soil reservoir or by recycling stored N compounds from vegetative tissues is inadequate to meet demands of the developing kernels. To meet the needs of developing kernels, most plants will cannibalize photosynthetic enzymes (Rubisco, PEP carboxylase) and glycoproteins (structural proteins) in vegetative tissues as a source of N to meet demands of the developing kernels. This loss of photosynthetic capacity induces early senescence and exposes tissues to maceration by extra-cellular proteolytic, pectolytic, and cellulolytic enzymes of stalk-rotting pathogens (Huber et al., 1986). Maintaining sufficiency of N and other essential elements throughout the grain-fill period is an important control for this disease.

Agricultural herbicides and other biocides (nitrification inhibitors, fungicides, plant growth regulators, etc.) that have chelating properties can immobilize specific secondary and micronutrients (Ca, Cu, Fe, Mg, Mn, Ni, Zn) in the soil or plant to reduce plant uptake, physiological function, or accumulation in reproductive parts of target or non-target plants and predispose plants to various pathogens (Huber, 2010). Fenoxaprop-p-ethyl (Puma® super), trifensulfuron-methyl (Harmony®), clodinefop-propargyl, and picloram (Tordon®) are a few examples of Cu-chelating herbicides that can induce a Cu deficiency in non-target food plants and predispose plants to ergot. Several herbicides that induce a Zn deficiency in plants also predispose plants to winter injury by *Rhizoctonia cerealis*. In contrast to most agricultural compounds that chelate with a single or few metal species, the extensively used herbicide glyphosate (N-(phosphonomethyl) glycine) is a broad-spectrum metal chelator of both primary, secondary, and micronutrients (Ca, Co, Cu, Fe, K, Mg, Mn, Ni, and Zn) and was first patented as such (Stauffer Chemical Co., 1964). This broad-spectrum chelating ability that makes glyphosate a good herbicide and selective anti-microbial agent (Ganson and Jensen, 1988) can also immobilize numerous essential plant nutrients to predispose plants to disease and reduce their mineral content in food or feed products by as much as 45% (Eker et al., 2006; Huber, 2010; Johal and Huber, 2009; Zobiole et al., 2010). Reduced content of amino acids and altered poly-unsaturated fatty acids in seeds of food crops also are observed after glyphosate treatment of glyphosate-tolerant crops (Zobiole et al., 2010). The list of over forty diseases and mineral deficiencies affected by glyphosate is increasing as growers and pathologists recognize the cause-effect relationship with this strong mineral chelator (Johal and Huber, 2009). The accumulation of glyphosate in root tips (meristematic tissues) reduces root growth and further limits plant access to soil nutrients (Huber, 2010). The effect of glyphosate on root growth and nutrient efficiency is similar for genetically modified (glyphosate-tolerant) plants as for their normal parental lines since there is nothing in the genetic engineering technology that impacts glyphosate itself. The technology merely inserts another gene for the EPSPS enzyme that is not sensitive to glyphosate in mature tissues (Huber, 2010).

Infectious diseases intensify nutrient deficiency of plants and further reduce their nutritional value for food or feed. Severe outbreaks of many diseases are an indication of low nutrient availability or mineral deficiency (Datnoff et al., 2009; Englehard, 1989; Evans and Huber, 2000; Huber, 1978, 1980, 1991; Graham and Webb, 1991; Huber and Graham, 1999; Marschner, 1995). Thus, adequate nutrition is an important means of reducing many diseases as will be discussed later.

Disease as a Cause of Plant Nutrient Deficiency

Disturbed mineral nutrition is one of the most common effects of infectious disease. Many primary and secondary symptoms associated with various toxicants and infectious diseases are similar to those expressed by mineral deficiencies and it is not always possible to clearly distinguish symptoms of infectious from non-infectious (abiotic) disease (Huber, 1978). Stunting, chlorosis, wilting, mottle, rosette, witches' broom, dieback, leaf spot, abnormal growth, and other symptoms of specific mineral deficiency are also caused by plant pathogens. Nutrient relationships with disease have been derived from: a) observed effects of mineral amendments on disease severity; b) a comparison of mineral concentrations in resistant compared with susceptible plants or diseased compared with disease-free tissues; c) the correlation of conditions known to influence mineral availability with disease incidence or severity; or d) a combination of these (Huber, 1989; Huber and Haneklaus, 2007). Pathogens impair nutrient uptake (root rots), translocation (vascular wilts), distribution (galls, cankers, and microbial sinks), and utilization (necrosis and toxin producers). Efficient nutrient use by plants is impaired when there is an accumulation of nutrients around the infection site, direct usage of nutrients by pathogens, or a chemical change to render nutrients more or less available for uptake in the rhizosphere or at the infection site (**Table 1**). All of these effects of disease can reduce the nutrient density and quality of edible plant parts.

Table 1. Effect of plant disease on plant nutrition.

Disease type	Effect on nutrition
Microbial growth in soil*	Immobilize (N, Fe, Mn, and S); toxicity (Mn)
Root rots, soil insects, nematodes	Immobilization, absorption, distribution, plunder
Macerating, rotting diseases	Distribution, nutrient sinks, depletion, plunder
Vascular wilts, leaf spots, blights	Translocation, distribution, metabolic efficiency
Viruses, spiroplasmas	Distribution, nutrient sinks, metabolic efficiency
Galls, 'brooms,' over growths	Distribution, nutrient sinks, usage, efficiency
Fruit and storage rots	Nutrient sinks, usage, distribution, low reserves
Toxigenic pathogens	Function, distribution, absorption, safety

(after Huber, 1978; Datnoff, et al., 2007; Evans et al., 2000; Huber and Graham, 1999)

**Referred to as microbially-induced "deficiency" or "toxicity" diseases.*

Reduced Nutrient Uptake and Translocation

Plants absorb nutrients throughout the soil profile by an enormous root system. Destruction of the absorptive capacity of this system through necrosis, malfunction, or reduced growth can severely impair plant functions throughout the entire plant. Soil-borne fungal pathogens, viruses, and nematodes reduce the amount of functional absorptive tissue and have a disproportional effect in reducing uptake of Ca, Mn, P and other relatively immobile elements which require an extensive functional root system to access them. Foliar pathogens (bacteria, fungi, viruses) that affect photosynthesis (rusts, mildews, blights) can create a shortage of energy needed for root growth and mineral uptake. A healthy plant can produce siderophores and other compounds in root exudates to solubilize soil minerals and increase their availability and uptake. Root-rotting pathogens not only severely limit the area of the soil available for nutrient extraction, but also interfere with the production of these root exudates.

Gums, gels, cellular slimes, and other vascular occlusions associated with diseases caused by fungal, bacterial, and viral pathogens interrupt translocation of minerals and water to starve tissues at a distance from the blockage. Deficiencies of N, P, or K that are necessary in large quantities become especially obvious. Absorbed minerals may accumulate below a blockage but are of little benefit unless translocated to all parts of the plant. Pathologically redirected movement and accumulation of sugars, amino acids, and minerals toward infection sites induce a nutrient deficiency in cells that would normally receive those nutrients, and can affect the physiology of the entire plant even though the total quantity of nutrients in the plant may be unchanged. Vascular blockage can have a direct effect or be indirect through imbalances created in various nutrients and localized shortage of water for physiological functions.

Impaired Nutrient Utilization

Plant pathogens impair nutrient utilization through immobilization, alteration of cell permeability, or competitive inhibition. Alteration of cell permeability by pathogen-produced toxins (pericularin, victorin, *Corynebacterium* toxins) can regulate nutrients available for a pathogen at the infection site. These toxins are also strong mineral chelators that can render specific micronutrients, such as Mn, unavailable to the plant, but mobile toward the infection site where they can accumulate to the benefit of the pathogen (Cheng, 2005). Cells adjacent to injured or necrotic tissues become depleted of Mn essential for photosynthesis to create a chlorotic halo around the infected tissue. Cell walls become impermeable to nutrients in some plant-pathogen interactions, while increased cell permeability is observed following infection by obligate (rusts, mildews, etc.) and tumor-inducing (crown gall, fasciations, etc.) pathogens (Huber, 1978). Six of the seven biosynthetic systems unblocked in autonomous tumor cells are activated by specific mineral ions. Tumor tissues are high in auxin and contain high concentrations of micronutrients that activate metabolic systems involved in autonomous growth. The addition of Zn causes a rapid rise in auxin, and large amounts of auxin accumulate in Cu- and Mn-deficient plants because of decreased oxidative enzyme activity.

Modification of cellular permeability contributes to the accumulation of nutrients around an infection site to create a 'sink' effect that immobilizes a nutrient and prevents its normal reuse several times during growth of the plant. Necrosis associated with localized infections common with apple scab (*Venturia inaequalis*), eye spot of wheat (*Pseudocercosporella herpotrichoides*), *Rhizoctonia* canker of potato and cotton, or citrus canker (*Xanthomonas citri*); defoliation by citrus variegated chlorosis (*Xylella fastidiosa*); or impaired translocation makes nutrients accumulated in some areas inaccessible to new growth or other parts of the plant. Obligate pathogens create very powerful nutrient sinks where minerals and plant metabolites are mobilized to the infection site as permeability and metabolic activity are increased (Horsfall and Cowling, 1978). Pathogen metabolism may also maintain a concentration gradient and higher osmotic pressure to ensure a continuous flow of materials to the infection site and thereby deprive the rest of the plant of those essential nutrients. Nitrogen, P, S, other elements and plant metabolites accumulate in plant tissues at the infection site of viruses, rusts, mildews, and potato late blight (*Phytophthora infestans*) (Huber, 1978; Horsfall and Cowling, 1978).

The ability to induce a localized mineral deficiency can be a virulence factor for some pathogens. Only isolates of *Gaeumannomyces graminis* (take-all root and crown rot of cereals), *Streptomyces scabies* (common scab of potato), and *Magnaporthe grisea* (rice blast) that can oxidize Mn from the reduced, plant-available form to the oxidized, non-available form are able to cause disease. By immobilizing Mn in plant tissues at the infection site, these pathogens turn off plant defense mechanisms regulated through the shikimate pathway (Cheng, 2005; Huber and Thompson, 2007; Thompson and Huber, 2007). Nutrients accumulating around infection sites are unavailable to the plant as are those that accumulate in hyperplasia (growths from an abnormal increase in cells) induced by certain bacteria, fungi, and nematodes. Restricted root growth from necrosis or girdling can directly reduce nutrient absorption and predispose plants to more severe infection or susceptibility to other pathogens. A malfunctioning vascular system or changes in membrane permeability can induce a systemic or localized nutrient deficiency. All of these effects of infectious diseases can reduce the mineral content, nutritional quality, and safety of the food or feed products produced.

Effect of Plant Pathogens on Food Safety

In addition to causing a direct loss in yield and nutritional quality, some plant pathogens produce chemically diverse toxins that threaten food safety. These toxins can cause gastrointestinal disturbances, intestinal necrosis, hemorrhage, vomiting, cancer, kidney damage, liver damage, hepatic changes, reduced feed and production efficiency, immune suppression, infertility, and death in animals and man. They can be produced during crop development prior to harvest, in transport, in storage, and during processing so that raw or processed foods and feeds may contain them (CAST, 1989). Factors influencing microbial toxin production include crop substrate, moisture, temperature, pH, drought, disease, nutrient stress, damage by other pests, and several commonly used agricultural chemicals. Some of the major crops affected include barley, maize, cotton, peanuts, wheat, and nut crops. The primary toxin-producing fungi include various species of *Aspergillus, Acremonium, Claviceps, Fusarium, and Penicillium.*

Risks Due to Pathogen-Produced Toxins

Contamination of milk, eggs, and meat can result if animals consume mycotoxin-contaminated feed. Since mycotoxins are naturally occurring compounds, some level of mycotoxin is unavoidable in various crops such as peanuts, cotton, corn, wheat, and nut crops. The usual route of exposure to mycotoxins is through ingestion of contaminated feed or food; however, dermal or inhalation exposure also may be significant (CAST, 1989). Wheat straw used as bedding for pigs or cattle can leave them infertile from absorption or consumption of estrogenic zearalenone produced by *Fusarium graminearum* (*Gibberella zeae*) or other toxins produced by *Fusarium* species that cause cereal head scab/blight, root and crown rot, stalk rot, or ear rot (Rottinghaus et al., 2009).

The presence of a potential toxin-producing fungus in the crop does not automatically establish the presence of mycotoxins, just as the absence of the fungus from the harvested product does not ensure absence of a toxin. Both deoxynivalenol and zearalenone produced by *Fusarium* in cereal root and crown tissues are translocated and accumulate in the grain and other plant parts (Rottinghaus et al., 2009). A few mycotoxins, such as those associated with ergot, are produced exclusively in the field, while many other mycotoxins also are produced in storage or later in processed food products (CAST, 1989).

Factors Influencing Mycotoxin Production

During plant growth, any condition favoring fungal infection can predispose to mycotoxin production. Abiotic stress (chemical, moisture, temperature), reduced vigor from nutrient deficiency, weed competition, and insect or other wounds are especially favorable conditions for toxin production. Heavily lodged grain is often damaged more by fungal and bacterial pathogens (also dense planted crops) because of the more conducive microenvironment. Post-harvest production of toxins is favoured by high temperature and moisture during storage or processing (CAST, 1989). Many pests predispose plants to infectious disease as vectors or by providing avenues for entry that breach natural defense barriers.

Aflatoxins - Infection of grain, peanuts, and cottonseed by *Aspergillus* species, and their subsequent production of highly carcinogenic aflatoxins, is associated with insect damage and environmental stress. Drought, high temperature and other environmental stresses weaken a plant's resistance to infection and provide an environment conducive for infection. Use of insecticides to control seed infesting insects can prevent fungal infection and toxin production in fruiting structures.

***Fusarium* toxins** - The production of trichothecene, zearalenone, and other toxins by various species of *Fusarium* is favoured by nutrient deficiency, environmental stress, and insect damage. Control of root and stem insects, and maintaining structural integrity through proper plant nutrition can reduce pest damage to improve both the quality and quantity of the crop produced. Less dense populations, wide rows that permit air circulation, and full nutrient sufficiency also can provide a less conducive environment for infection or pathogenesis (disease development).

Ergot - Ergot (*Claviceps* species) is the oldest recognized mycotoxicosis of man. The ergot toxins are produced during grain growth as the fungus replaces the grain (seed) with a sclerotium containing the mycotoxins. Infection occurs by wind blown spores of *Claviceps* species in open-pollinated cereals and has limited the production of hybrids of self-pollinated species when glumes are opened to receive outside pollen. Late spring frosts that kill the anther, or Cu deficiency of cereals grown on low Cu soils or induced by certain Cu-chelating herbicides, can result in heavy infection and contamination by ergot sclerotia. Application of adequate Cu fertilizers for physiological plant sufficiency provides a significant measure of control of ergot (Evans et al., 2000).

Agricultural chemicals - Although of significant benefit in reducing pest damage, some agricultural chemicals can reduce crop nutritional quality and predispose plants to pathogens and toxigenic organisms (Johal and Huber, 2009). *Fusarium* species causing head blight (also referred to as scab) are common root and crown rot pathogens of cereals everywhere; however, *Fusarium* head blight (FHB) has generally been a serious disease of wheat and barley only in warm temperate regions of the world. *Fusarium* head blight and the mycotoxins produced by these fungi are greatly increased with the extensive use of the glyphosate herbicide (*N*-(phosphonomethyl)glycine) that is a strong micronutrient chelator. With the extensive use of glyphosate, FHB is now of epidemic proportions and prevalent throughout most of the cereal producing areas of the world. Canadian research has shown that the application of glyphosate one or more times in the three years previous to planting wheat or barley was the most important agronomic factor associated with high FHB in wheat, with a 75% increase in FHB for all crops and a 122% increase for crops under minimum-till where more glyphosate is used (Fernandez et al., 2005, 2007, 2009). The most severe FHB occurs where a glyphosate-tolerant crop precedes wheat or barley in the rotation for the same reason. Glyphosate-altered plant physiology (C and N metabolism) increases susceptibility of wheat and barley to FHB and increased toxin production from heading to maturity of the crop.

The increased FHB with glyphosate results in a dramatic increase in tricothecene 'vomitoxins' (deoxynivalenol and nivalenol) and estrogenic (zearalenone) mycotoxins in grain. The high concentrations of mycotoxin in grain are not always associated with *Fusarium* infection of kernels. Quite often overlooked is the increase in *Fusarium* root and crown rot with glyphosate usage and the production of mycotoxins in root and crown tissues that are subsequently translocated to stems, chaff, and grain. Caution has been expressed in using straw and chaff as bedding for pigs, or roughage for cattle, because of mycotoxin levels that can exceed clinically significant levels for animal infertility and toxicity (Sweets and McKendry, 2009).

Other Health and Safety Concerns

Potential pest and disease damage have necessitated the use of various chemical biocides (herbicides, insecticides, fungicides, etc.) to reduce their economic impact on agriculture. Many of these products can be of great benefit in reducing nutrient competition, crop damage and toxin production, but may pose a toxicological health risk of their own if they accumulate in the harvested product used for feed or food. Such concerns have been expressed most recently with the unrestricted use of the herbicide glyphosate because of relatively high concentrations of this micronutrient-chelating herbicide that can accumulate in many foods and food products to enter the food chain directly (Watts, 2009). The level of glyphosate in feed and foods has increased significantly with the use of glyphosate tolerant crops and the direct application of glyphosate to food and feed plants (Antoniou, et al., 2010; Watts, 2009). In addition to increased mycotoxins and chemical residues in feed, food, and water, glyphosate reduces the content of essential micronutrients (Co, Cu, Fe, Mn, Ni, and Zn) in the harvested food product (Bellaloui, 2009; Huber, 2010; Zobiole et al., 2010). Recent studies have found levels of glyphosate in manure from chickens fed grain of glyphosate-tolerant crops equivalent to one-tenth the labeled herbicidal rate of this material per ton (Dr. M. McNeil, personal communication).

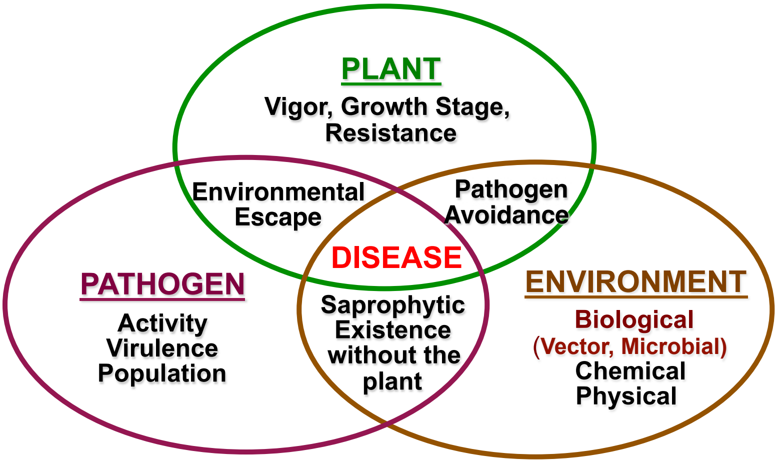


Figure 1. Interacting components of plant, environment, and pathogen affecting disease and nutrient quality.

Interacting Factors of Nutrition and Disease

Infectious plant disease is the expression of the interaction of the plant, a pathogen, and the environment over time (**Figure 1**). Disease control is most effectively achieved when the interacting factors of these three primary components are recognized and understood to make them less conducive for disease development. All interactions between the plant, pathogen, and environment are affected by nutrition, and all of the essential mineral elements are reported to influence disease incidence or severity (Datnoff et al., 2007; Englehard, 1989; Huber, 1980, 1991; Huber and Graham, 1999; Huber and Haneklaus, 2007). Although nutrients, as a component of the environment, influence the plant's resistance, and a pathogen's virulence, each of the three primary components also influences the availability of nutrients. As previously discussed, nutrition of the plant can be drastically altered by many disease organisms through their effect on the uptake, translocation and distribution, or utilization of nutrients, and it is frequently difficult to clearly differentiate between the biotic and abiotic factors that interact to "cause" a plant nutrient deficiency or excess.

Recognizing Plant Nutrient Deficiency

All nutrients have specific metabolic functions, and impaired nutrient status of a plant may be indicated by symptoms associated with the malfunction of particular metabolic pathways. The manifestation of nutrient deficiency may be very subtle ('hidden hunger') or quite pronounced and distinct depending on the level of deficiency or severity of disease. Visible symptoms, however, are often late manifestations of metabolic disruptions that occurred much earlier. Detailed descriptions and colour photographs of mineral deficiency symptoms (and toxicity) are available and useful for this purpose (Bennett, 1993; Grundon, 1987; Plank, 1988). Reduced productivity as measured by yield or quality may have multiple causes such as weather, management practices, infectious diseases and the soil environment so that correcting the problem may require multiple approaches. With multiple deficiencies, some symptoms may be alleviated only after all elements are available in sufficient quantity. Analytical tests of soil or plant tissue provide a basis to prevent or remedy potential deficiency conditions. Nutrient amendment (fertilization) or modification of the soil environment influencing a particular nutrient's availability are important techniques to provide nutrient sufficiency to plants. The root cause of many nutrient deficiencies may be in the roots, and a plant will balance many nutritional needs if it has access to nutrients through a fully functional and healthy root system.

When a nutrient is deficient, its content in the plant is usually reduced. Soil and tissue analysis can be used as a general guide to the availability and nutrient status of plants. Chemical analyses for the mineral nutrients provide a quantitative evaluation of nutrient status capable of revealing mild deficiencies or excesses in a range where symptoms are not expressed. A number of analytical techniques have been developed to establish the relative availability of nutrients in soil or water, or the sufficiency status of a plant (Page et al., 1982; Mills and Jones, 1996). Most commercial laboratories use standardized procedures to provide consistency between laboratories; however, interpretation and recommendations from the data differ widely between areas because of innate differences in environment, local experience, or sales incentives. These techniques can help to achieve optimal conditions since internal requirements for most essential nutrients (critical levels) have been determined for many crop plants (Graham, 1983; Mills and Jones, 1996; Plank, 1988). Such diagnostics indicate the current nutritional status of the plant, but do not necessarily give a prognosis for sufficiency through to harvest because they are limited in scope to the time of sampling. For example, an assay of ear-leaf tissue N at tasseling may be accurate for predicting N sufficiency of maize hybrids which absorb 90-95 % of their required N prior to tasseling, and then recycle this N during grain formation; but grossly underestimate N required for 'high yielding' hybrids which are dependent on 40-50 % of their N uptake after flowering, or for cultivars that recycle little of their vegetative N sources to grain ("stay green" hybrids) (Tsai et al., 1983). Tissue analysis also gives little indication of the dynamics of microbial intervention in nutrient availability and uptake.

Managing Nutrition to Control Plant Diseases

Each of the 14 plant-essential mineral elements and several functional elements are known to influence disease severity. Disease suppression through manipulation of nutrient availability may be achieved by direct application of a nutrient to enhance resistance, by cultural practices which modify abiotic and biotic environments influencing nutrient availability, and by modifying the plant genotype relative to its nutrient uptake or interaction with the abiotic or biotic environment. A well-balanced nutrition program, integrated with other crop production practices, permits a broad utilization of this cultural disease control, and generally provides the best opportunity for maximum disease suppression.

Strategies to Reduce Disease through Nutrient Interactions

Six key strategies to manage disease through nutrition include: 1) selection of cultivars with the highest genetic disease resistance and nutrient efficiency; 2) provide a balanced nutrition for full nutrient sufficiency; 3) apply a form of nutrient that is not conducive to disease; 4) apply the nutrient at a time when conditions for disease are least conducive; 5) use nutrient sources which suppress rather than enhance disease; and 6) integrate nutrition with other management practices that influence nutrient availability or function in the agricultural production system (Datnoff et al., 2007; Graham and Webb, 1991; Huber and Graham, 1999; Huber and Haneklaus, 2007). The greatest response to nutrition in reducing disease is generally observed when going from deficiency to sufficiency and excess application may increase sensitivity to some diseases.

Selection of adapted, nutrient-efficient cultivars. The availability of genetic resistance to disease has permitted the production of many crops in areas that would otherwise be non-profitable because of certain diseases; however, nutrient sufficiency is a primary component for the full expression of genetic resistance. Resistance of wheat and flax to rust, and maize to Stewart's wilt may be lost under K-deficient conditions (Huber and Arny, 1985). Cultivars that are resistant or tolerant to disease are generally more responsive to nutrient manipulation than highly susceptible cultivars. Rye is resistant to take-all by its high efficiency for the uptake of Mn and other micronutrients essential for resistance to this pathogen that is mediated through the shikimate pathway. In contrast to rye, wheat is inefficient in micronutrient uptake and highly susceptible to take-all. Rye-wheat interspecific hybrid lines (triticale) that contain rye's efficiency for nutrient uptake are as resistant to take-all as the rye parent, while lines that do not contain this genetically controlled nutrient efficiency are as susceptible to take-all as wheat (Huber and McCay-Bius, 1993). Oats that are resistant to gray speck (Mn deficiency) produce root exudates that inhibit Mn-oxidizing organisms in the rhizosphere to increase Mn availability in soil and are resistant to take-all compared to gray speck susceptible varieties (**Table 3**). This change in soil biology to increase the availability of Mn also protects a subsequent wheat crop from take-all while rye, as a preceding crop to wheat, has no effect in reducing susceptibility of the wheat that follows it. (Huber and McCay-Bius, 1993).

Provide a balanced nutrition for full nutrient sufficiency. The greatest response to nutrition is observed when going from deficiency to plant sufficiency. The needs and uptake of nutrients depend on the stage of plant growth, availability of nutrients in the soil, time of application, microbial activity, and general health of the plant. The severity of take-all and tan spot of wheat and stalk rot of corn decrease as N approaches full sufficiency (Bockus and Davis, 1993; Bockus et al., 2010; Huber et al., 1986, 1987). A similar effect is observed with Alternaria leaf blight of potato and tomato as rates of K approach physiologic sufficiency (Prabhu et al., 2007). When disease decreases with rates above physiological sufficiency for the plant, it is usually because of changes in the environment or interactions with other elements. Nutrient imbalance may be as detrimental to plant growth and disease resistance as a deficiency. Excess N can increase stalk rot because physiological sufficiency of other nutrients is not in balance (Huber et al., 1986). Potassium decreases take-all of wheat if N and P are sufficient, but increases this disease if they are deficient (Huber and Thompson, 2007). *Fusarium* wilt of cotton, clubroot of crucifers and late blight of potato have been correlated with the ratio of K to Mg and N rather than the actual amount of either element individually (Engelhard, 1989). An excess of some nutrients is toxic and can predispose plants to disease while a disease may be reduced by the same nutrient up to the sufficiency needs of the plant. Liming to reduce toxicity and availability of Mn can provide effective control of hyperplasia (gall) diseases.

Use a form of nutrient that is not conducive to disease. Different forms of some nutrients often influence disease differently because of differences in plant uptake, physiological pathways involving specific defense mechanisms, or pathogen activation. Elements such as N, Fe, Mn, and S are readily oxidized or reduced in most soils by soil microorganisms to affect their availability for plant uptake. Both the cation (NH_4^+) and the anion (NO_3^-) forms of N may be assimilated by plants, but they frequently have opposite effects on disease (**Table 2**) because they are metabolized differently. Practical control of some diseases can be achieved by manipulating the environment to favor one or the other forms of N. Application of NO_3^- and liming has proven to be a practical control of *Fusarium* wilt diseases of melons, tomatoes, and other crops, while NH_4^+ decreases the severity of take-all of cereals, *Verticillium* wilt of potato, common scab of potato, and rice blast. Diseases that are reduced by NH_4^+ are also reduced by environmental conditions that slow or inhibit nitrification and increase the availability of Mn (**Table 3**). In contrast, diseases such as *Fusarium* wilt of fruit and vegetable crops, clubroot of crucifers, and *Rhizoctonia* canker that are reduced by NO_3^- also are less severe with supplemental Ca and environmental conditions that favor nitrification.

Table 2. Some diseases influenced by the form of N and pH.

Crop	Disease	Pathogen
Diseases decreased by NO_3^- fertilization and alkaline pH:		
Asparagus	Wilt	*Fusarium oxysporum*
Bean (*Phaseolus vulgaris*)	Chocolate spot	*Botrytis*
	Root and hypocotyls rot	*Fusarium solani*
	Root and hypocotyls rot	*Rhizoctonia solani*
Beet	Damping off	*Pythium* species
Cabbage	Club root	*Plasmodiophora brassica*
	Yellows	*Fusarium oxysporum*
Celery	Yellows	*Fusarium oxysporum*
Cucumber	Wilt	*Fusarium oxysporum*
Ornamental plants	Crown gall	*Agrobacterium tumefaciens*
Pea (*Pisum sativum*)	Damping off	*Rhizoctonia solani*
Pepper	Wilt	*Fusarium oxysporum*
Potato	Stem canker	*Rhizoctonia solani*
Tobacco	Frenching	*Bacillus cereus*
Tomato (and others)	Gray mold	*Sclerotinia sclerotiorum*
	Sclerotium blight	*Sclerotium rolfsii*
	Wilt	*Fusarium oxysporum*
Wheat	Eye spot	*Pseudocercosporella herpotrichoides*
Diseases decreased by NH_4^+ fertilization and acid pH:		
Bean (*P. vulgaris*)	Root rot	*Thielaviopsis basicola*
	Root knot	*Meloidogyne*
Carrot	Root rot	*Sclerotium rolfsii*
Eggplant	Wilt	*Fusarium oxysporum*
Maize	Stalk rot	*Gibberella zeae*
Onion	white rot	*Sclerotium rolfsii*
Pea (*P. sativum*)	Root rot	*Pythium* species
Potato	Common scab	*Streptomyces scabies*
	Wilt	*Verticillium dahliae*
	Virus	Potato virus X
Rice	Blast	*Magnaporthe oryzae*
Tomato	Southern wilt	*Pseudomonas solanacearum*
	Anthracnose	*Colletotrichum*
	Wilt	*Virticillium dahliae*
	Virus	Potato virus X
Wheat	Take-all	*Gaeumannomyces graminis*

(After Huber and Graham, 1999)

Table 3. Some conditions affecting N form, Mn availability, and disease severity.

Condition or cultural practice	Effect on:		
	Nitrification	Mn availability	Disease severity*
Low soil pH	Decrease	Increase	Decrease
Green manure crops (some)	Decrease	Increase	Decrease
Oat pre-crop	—	Increase	Decrease
Ammonium fertilizers	Increase	Increase	Decrease
Irrigation (some)	Decrease	Increase	Decrease
Firm seedbed	Decrease	Increase	Decrease
Nitrification inhibitors	Decrease	Increase	Decrease
Soil fumigants	Decrease	Increase	Decrease
Metal sulfides	Decrease	Increase	Decrease
Glyphosate	Increase	Decrease	Increase
High soil pH	Increase	Decrease	Increase
Liming the soil	Increase	Decrease	Increase
NO_3^- fertilizers	—	Decrease	Increase
Animal manure	Increase	Decrease	Increase
Low soil moisture	Increase	Decrease	Increase
Loose seed bed	Increase	Decrease	Increase

**Common scab of potato, take-all of cereals, rice blast, maize stalk rot (after Huber and Haneklaus, 2007)*

Apply nutrients at a time when conditions for disease are least conducive. Mineral nutrients are applied to meet the potential needs for efficient crop production in an economically and environmentally sound manner. The time of fertilization is important to minimize periods of irreversible nutrient deficiency without stimulating pathogenic activity. Fall application of N to winter wheat (under non-leaching conditions) can provide full sufficiency throughout the crop season without affecting eyespot (*Pseudocercosporella herpotrichoides*), whereas N applied in the spring increases disease severity by stimulating growth and virulence of the pathogen. Sharp eyespot and winter-kill (*Rhizoctonia cerealis*) of wheat are increased when N is applied during cool, wet conditions favorable for disease, but not if applied later to actively growing wheat under less conducive conditions for disease (Bockus et al., 2010). Liquid N increases these diseases more than granular fertilizers because of enhanced contact with the pathogen to increase its virulence.

Use nutrient sources that suppress disease. The associated ion applied with a fertilizer salt or in an organic fertilizer may have an effect on disease independent of the primary ion. Zinc in barnyard manure is primarily responsible for reduced *Rhizoctonia* spring blight rather than the more abundant N, P, or K that are also available with this source of nutrient. Stalk rot of maize, take-all of cereals (*Gaeumannomyces tritici*), northern leaf blight of maize (*Setosphaeria turcica*), and rusts (*Puccinia* spp.) on wheat are reduced by high rates of KCl, but not with K_2SO_4, possibly as a result of the Cl^- decreasing nitrification and increasing Mn availability (Christensen et al., 1986; Elmer, 2007).

Integration of nutrition with management systems. Many of the cultural practices used to control plant diseases function through their influence on plant nutrition (**Table 3**). Crop rotation, green manure cover crops, and fallowing practices have made crop production efficient in many areas of the world by increasing the supply of readily available nutrients and controlling weeds that compete for nutrients and moisture. Long-term monocropping can provide biological stability in soil and reduce diseases such as take-all of wheat through a phenomenon referred to as take-all decline involving enhanced N conservation and increased Mn availability (Hornby et al., 1998). Maize is a preferred crop to precede potatoes because it provides almost twice the available Mn as other cereals (Smith, 2006) and suppresses *Verticillium* wilt (Thompson and Huber, 2007). Integration of nutrient amendment with cultural practices such as tillage, seeding rate and date, and pH adjustment can accentuate the benefits of nutrient amendment by modifying the environment for plant growth or microbial activity. Tillage distributes nutrients in the root zone for easier access, prevents nutrient stratification in soil, facilitates root growth, and changes microbial activity that affects specific nutrient forms or availability.

Time of tillage and seed bed preparation are important because of their effect on soil microorganisms involved in mineralization of residues and nutrient availability. Seed bed preparation and uniform planting depth for quick emergence can shorten the infection period for seedling diseases and establish a vigorous plant with a well developed root system that can sustain the nutrient needs of the plant throughout vegetative growth and reproduction. A firm seedbed provides an environment conducive to Mn reducing microbes to increase availability of Mn for plant uptake (Huber and McCay-Buis, 1993). This has been a long-standing recommendation for reducing take-all root and crown rot of cereals (Hornby et al., 1998) and results in 9-15 ppm higher tissue Mn at the tillering stage of growth to enhance resistance to take-all through callose production around penetration hypha of the fungal pathogen.

The first 30 days after planting is an especially critical period to ensure stand establishment, early vigour, and optimum physiological function for subsequent growth and reproduction. An early deficiency of nutrients can stress the plant to cause irreversible effects on crop yield and nutrient quality so it is important that adequate levels of the essential nutrients are available throughout the various stages of crop growth in order to maintain disease and stress resistance as well as optimum nutrient content in harvested crop parts. Seed treatments can minimize early root damage from seed-borne pathogens and protect tender tissues from early colonization and deleterious effects of soilborne pathogens. Root configuration (architecture) can also impact the nutrient efficiency of a cultivar.

A deep taproot provides access to deeper soil moisture for drought tolerance, but may be less efficient for uptake of micronutrients located near the top of the soil profile. Soil temperature influences root configuration of crops like maize so that early planting in cooler soils produces a shallower, more fibrous root system efficient for nutrient uptake from shallow soils or with nutrient stratification as occurs with non-tillage practices.

Inoculation of seed or soil with N-fixing, mycorrhizae, and plant growth promoting rhizosphere (PGPR) organisms can increase nutrient availability and sufficiency for many plants, with the reduction in disease as an additional benefit. Soil fumigation may be required to reduce the population of plant parasitic nematodes and other soilborne pathogens. Most chemical soil fumigants also inhibit nitrification so that selection of the fertilizer N may be used to enhance the control of other diseases through the form of N. Success of the nutritional program for disease control will depend on its integration with the overall management practices to maximize crop productivity and quality. A well-balanced nutrition program, integrated with other crop production practices, permits a broad utilization of this cultural disease control.

Mechanisms of Disease Control with Nutrition

Disease resistance is a property of the plant that describes the relative incompatibility of the plant-pathogen interaction, while tolerance describes the ability of the plant to produce even though diseased (compatible plant-pathogen relationship). Virulence is a characteristic of the pathogen to cause disease, and disease escape refers to environmental conditions that are not conducive to disease even though the pathogen and plant might be present (**Figure 1**). Nutrition influences all of these interactions. Nutrients suppress disease by maximizing the inherent genetic resistance of plants, by facilitating disease escape and shortening the infection period, increasing tolerance through stimulating plant growth and yield in the presence of a pathogen, and by modifying the abiotic or biotic environment to reduce the survival or activity of pathogens (**Table 4**).

Table 4. Effects of plant nutrition on disease severity and nutritional quality.

Nutrient mechanism	Effect on disease
Compensate for disease damage	Restore mineral nutrient quantity and quality
Facilitating disease escape	Increased root and leaf growth, shorter infective period
Increasing tolerance to disease	Compensate for reduced efficiency or disease damage
Increasing physiologic resistance	Less susceptible tissue, production of physical and chemical defenses to limit damage
Modifying the environment	Less conducive environment for disease, nutrient compensation, enhance rhizosphere biological interactions
Reducing pathogen activity	Reduce survival, growth, virulence, pathogenesis

Nutrient Effects on Plant Resistance

Mineral elements are directly involved in all mechanisms of a plant's defense to disease as integral components of cells, substrates, enzymes, and electron carriers; or as activators, inhibitors, and regulators of metabolism. Resistance to disease is generally a dynamic process involving the principles of metabolic regulation by substrate feedback, enzyme repression, and enzyme induction that are all controlled through mineral factors (Datnoff et al., 2007; Graham, 1983; Huber, 1980, Huber and Graham, 1999). Nutrient-sufficient plants contain preformed antimicrobial compounds and have active response mechanisms where inhibitory phytoalexins, phenols, flavonoids, proteins, and other defense compounds accumulate around infection sites. An adequate supply of Mn, Cu, and other nutrients is important in most of the defense mechanisms mediated through the shikimate pathway. Production of glycoproteins (lectins) associated with disease resistance also requires Mn. Calcium and Mg suppress tissue-macerating diseases caused by bacteria and fungi by increasing the structural integrity of the middle lamella, cell wall components, and cell membranes to resist the extra-cellular enzymes produced by these pathogens. Silicon, combined with other components, gives cell walls greater strength as a physical barrier to fungal penetration (Datnoff et al., 2007). The rapid walling off of pathogens around a wound or infection site can limit potential damage by various pathogens.

All aspects of disease resistance are intimately related to the nutritional status of the plant and reflect either a modified nutritional environment for a pathogen or the production or accumulation of compounds inhibitory to pathogenesis. The nutritional environment is especially critical for obligate pathogens and the concentration of many viruses is inversely proportional to the growth status of the plant. Resistance based on regulation of amino acid or protein synthesis is greatly affected by the Cu, N, Mg, Mn, Ni, and Zn status of the plant. Resistance of potato to *Phytophthora* is associated with the K-induced accumulation of fungistatic levels of arginine in leaves while the decreased levels of glutamine and glutamic acid in leaves is associated with resistance to *Alternaria, Cercospora*, and *Sclerotinia* (Huber and Graham, 1999). Physiological responses may deny obligate pathogens of essential metabolic intermediate compounds needed for pathogenesis, survival, or reproduction. Providing adequate N throughout the grain-fill period minimizes cannibalization of physiological and structural proteins that are required for stalk rot resistance of maize plants (Huber et al., 1986).

Nutrient sufficiency provides a general form of disease resistance by maintaining a high level of inhibitory compounds in tissue, and energy for a quick response to invasion by a pathogen. Nutrient seed treatments can promote a well-established, vigorous seedling with an efficient root system for maximum nutrient uptake and expression of resistance.

Nutrient Effects on Disease Tolerance

Disease severity, and subsequent yield loss, may be limited by supplying sufficient nutrient quantity to offset the deleterious effects of a pathogen. Phosphorus, N, and Zn stimulate root growth of cereal plants to compensate for tissue lost through root rots such as take-all. Increased availability of nutrients can compensate for reduced uptake efficiency caused by soilborne pathogens. Although N rates required for nutrient sufficiency can increase powdery mildew (*Blumeria graminis*) in cereal plants by 10-20%, yield is increased 50% to show that the vigorous, N-fertilized plants are able to tolerate the increased disease burden (Huber and Thompson, 2007; Last, 1962). Phosphorus, N, and Zn stimulate root growth to promote more efficient nutrient uptake and translocation to promote disease resistance.

Nutrient Effects on Disease Escape

A response to fertilization by increased growth may constitute a form of disease escape, especially if a susceptible growth stage is shortened for some plant-pathogen interactions. Plants adequately fertilized with B and Zn have fewer root and leaf exudates to break spore dormancy (fungistasis) or stimulate fungal pathogens (Marschner, 1995).

Nutrient Effects on Pathogen Survival and Virulence

Mineral nutrients may reduce the ability of a pathogen to cause disease by inhibiting germination, growth, virulence or survival directly or through plant exudates. The need for an external source of nutrients for saprophytic growth of fungi prior to infection is common. *Botrytis cinerea, Typhula* species, *Fusarium* species, *Sclerotinia*, and *Armillaria mellea* infect healthy plants slowly unless an external source of nutrients is available from soil or decaying organic matter. Exogenous C and N are required for germination of dormant *Fusarium* chlamydospores. Zinc is required for appressorium formation of *Puccinia coronata* on oat leaves and infection of broadbean by *Botrytis*. Leaf exudation of arginine from K and N sufficient plants inhibits germination of *Phytophthora infestans* sporangia, and the levels of arginine generally increase as the sufficiency for K increases. Calcium suppresses extra-cellular macerating enzymes of pathogens required for pathogenesis. Iron, Mg, Mn, and Zn also suppress macerating pathogen enzymes (Huber, 1980). By reducing tissue maceration, there also are fewer nutrient sources available to pathogens.

Detailed discussion of specific nutrient interactions with plant disease can be found in Datnoff et al. (2007), Englehard (1989), Graham and Webb (1991), Huber (1978, 1980, 1991), Huber and Graham (1999), Huber and Haneklaus (2007), Johal and Huber (2009), Marschner (1995), and Rengel (1999).

Importance of Pest and Disease Control on Nutritional Quality and Food Safety

Economic forces operating over a long period of time have produced a highly efficient agricultural system. The benefits to society through efficient crop production include lower prices, reliable supplies, employment opportunities, environmental improvements, and higher nutritional quality food and feed. Nutritional quality is markedly reduced by disease and pest damage, and sometimes before a yield reduction is observed. Greatest losses are sustained in protein, vitamin, and mineral composition, and least in carbohydrates. The need for increased processing required to compensate for pest losses or contamination may of itself reduce nutritional value. Mycotoxin production initiated during crop production can continue in storage to expose large segments of a population to highly toxic or carcinogenic compounds.

Good animal and human health is dependent on healthy plants that are only available from fertile soils. Disease resistance is genetically controlled but mediated through physiological or biochemical processes interrelated with the nutritional status of the plant, pathogen, and environment. The nutritional status of a plant determines its histological or morphological structure and properties, the function of tissues to hasten or slow penetration and disease development, and its nutritional value for feed or food. The severity of most diseases can be greatly decreased by proper nutrient management (Datnoff et al., 2007). It is not possible to generalize the effects of any particular nutrient on all plant diseases because it is the sum of many interacting factors of the plant, pathogen, and environment over time that determine how a specific disease is affected by nutrition. The disease response may be independent of vigour or other generalized growth responses since nutrients can limit pathogenesis or toxin production through passive and active mechanisms of defense that are activated through effective nutrient management.

Pest and disease damage are generally greatest with plants that are nutritionally or environmentally stressed. A balanced nutrition increases plant vigour, competitive advantage, and ability to successfully respond to limit infection. Disease control by cultural practices—crop rotation, organic amendment, irrigation, liming to adjust soil pH, and tillage—frequently influences disease through effects of these practices on nutrient availability, and this often involves altered microbial activity (**Table 3**). Disease and pest control are integral aspects to reducing mycotoxin contamination during crop production and storage. Since crop residues provide the primary inoculum for non-soil inhabiting and mycotoxigenic fungi, removal or management of crop residues to hasten their decomposition can reduce mycotoxin levels significantly. Tillage that buries infected crop residues not only hastens their demise as inoculum sources, but also makes nutrients contained in them available for subsequent crops much sooner. Thus, crop rotation or tillage to facilitate degradation of infected residues and lower inoculum of plant pathogens can supplement other control practices. Nutrient availability for microbial activity is especially important for surface decomposition of plant residues. Increased levels of genetic resistance or chemical controls are required when residue burial is limited by the need to reduce soil erosion. Aflatoxin contamination of both maize and peanuts is more severe with prolonged late-season drought. Adequate Ca nutrition can minimize aflatoxin contamination of peanut but requires moisture for plant uptake. Control of pink bollworm and stinkbug damage that predispose cottonseed to aflatoxin is important in reducing levels of this carcinogen in feed. Although *A. flavus* can infect corn silks at temperatures above 30°C, it is more likely to colonize insect-damaged kernels. In contrast to the warm conditions that favour *Aspergillus* infection, cool, wet conditions during grain fill favour infection by toxigenic *Fusarium* species. (CAST, 1989)

The advent of readily available inorganic fertilizers has brought about the demise of many diseases through improved plant resistance, disease escape, altered pathogenicity, or microbial interactions influencing these. Efficient fertility programs can enhance plant resistance to pathogens, reduce the impact of environmental stress, and increase the nutritional quality of the food and feed that are produced. Effective disease and pest management improves crop quality and quantity to result in surplus food production, lower prices for consumers, and an abundance of quality food products. Ensuring nutrient sufficiency to maintain resistance to pathogens and abiotic stress is necessary to provide food safety, abundance, and nutrient quality. An abundant supply of affordable, safe and nutritious food and feed is essential to meet society's needs. FCHH

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Chapter 10

Human Health Issues Associated with Nutrient Use in Organic and Conventional Crop Production

Holger Kirchmann and Lars Bergström[1]

Abstract

In recent years, there have been intensive discussions about agricultural systems that can produce sufficient amounts of nutritious and healthy food. This chapter focuses on crop quality of organic and conventional systems in relation to human health. A number of field studies and national agricultural statistics clearly indicate that organic crop production cannot provide sufficient food for the current and growing population in the world. Crop yields are too low, mainly due to lack of nutrient supply, especially of N. We reviewed crop quality variables related to N supply. The compilation showed that contents of protein, NO_3^-, and A and B vitamins were often increased in conventionally grown crops by the use of mineral N fertilizer but vitamin C contents were slightly higher in organically grown crops. The results are in agreement with knowledge based on plant physiology. Higher levels of NO_3^- in conventionally grown crops should not be misinterpreted as poor quality since a beneficial effect of NO_3^- for the human immune system was discovered. The hypothesis of the founders of organic agriculture that NPK fertilizers may lead to a dilution of non-added minerals in crops seems plausible. However, earlier reviews and recent studies do not indicate that concentrations of trace elements in organically and conventionally grown crops differ systematically. A recent theory that enhanced levels of secondary metabolites in crops are a quality indicator is doubtful, considering that they are non-essential and can also be harmful. Published reports on mycotoxin contents in crops from organic and conventional systems revealed no differences. Our review provided no evidence that organically grown crops are of superior quality or that the use of mineral fertilizers deteriorates food quality. In contrast, controlled application of

Abbreviations specific to this chapter: FAO = Food and Agriculture Organization of the United Nations; UN = United Nations; EU = European Union; SCB = Statistics Sweden; IFOAM = International Federation of Organic Agriculture Movements.
For abbreviations and symbols used commonly throughout this book see page v.

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L. Bergström is Professor, Department of Soil Sciences, Section of Water Quality Management, Swedish University of Agricultural Sciences, Department of Soil and Environment, Uppsala, Sweden; e-mail: lars.bergstrom@mv.slu.se plant nutrients in mineral form enables improvement of crop quality. Despite the great interest in food quality among supporters of organic agriculture, we conclude that focussing on food supply and dietary composition is most important for human health.

Principal Considerations

Cropping systems can affect human health in several ways: through production of insufficient amounts of food and products of insufficient quality. If the amounts of crops produced by agricultural systems are not sufficient to cover human needs, this will result in malnutrition, starvation, and ultimately shortened lifespan. This aspect is so fundamental that humans who are able to buy sufficient amounts of food may not necessarily consider this a major health concern in the world. However, lack of food is a reality in many developing countries worldwide (e.g. Sanchez and Swaminathan, 2005). According to the world summit on food security (FAO, 2009), about one billion people suffer from malnutrition, a main cause of disease and disability of children (World Health Organization, 2000). Food shortage is definitely one of the most important aspects when discussing health issues relating to food, although excessive diets, over-consumption and obesity can be a main cause of untimely death in rich countries.

The other major issue is the quality of the food produced. Crops may contain too little of the nutrients essential for animal and human well-being, reduced levels of protective antioxidants and anticancer compounds, high levels of unwanted elements, pesticide residues, toxic microorganisms or high concentrations of natural toxins. It should be borne in mind that organic agriculture was founded on the conviction that this type of agriculture assures superior food quality (Steiner, 1924; Balfour, 1943; Rusch, 1978).

In this chapter, we compare food supply and food quality issues in organic and conventional cropping systems, the former considered to be superior by many. The main difference between organic and conventional cropping systems is the principal exclusion of processed inorganic N and P fertilizers and synthetic pesticides in organic agriculture. The impact of these systems on food quantity and quality is reviewed. Quality refers to nutrients essential for the human body.

Food Supply

Crop Yields in Organic and Conventional Systems

Providing sufficient and healthy food for everyone is probably one of the most important survival issues for mankind in the future. Already today, the global production of food is unable to keep pace with consumption and the demand for food, feed, fuel, and fibre will greatly increase during coming decades (Evans, 1998; FAO, 2007), driven by a growing population (Bruinsma, 2003; GeoHive, 2007). Human population has doubled over the last 40 years, to around 6.5 billion people in 2006, while food plus feed production has tripled during the same period (FAO, 2007). By 2030, the global population may reach 8 to 9 billion, of which 6.8 billion may be living in developing countries (Bruinsma, 2003). As the projected increase will mainly take place in developing countries (i.e. Africa would need to increase food production by 300%, Latin America by 80%, Asia by 70%) still even North America would require a 30% increase. Assuming that the additional population consumes only vegetarian food, a minimum of 50% more crop product would be needed by 2030 to ensure sufficient food supply.

The recommended daily intake of total protein is 63 g per person per day (National Research Council, 1989) but opinions differ on the minimum intake of animal proteins required for a satisfactory diet. However, as protein of animal origin has an amino-acid composition closer to human physiological need than vegetable proteins, an optimal diet has been defined to consist of 40 g animal protein per person per day (see overview by Gilland, 2002). As diets throughout the world are changing with the rise in income towards more meat and dairy products irrespective of culture, there will be a need to actually increase food plus feed production by 60 to 70%. For example, meat consumption in developing countries amounted to 71 g per person per day between 1997 and 1999 and is projected to further increase to 100 g per person per day in 2030 (Bruinsma, 2003). In developed countries, meat consumption is estimated to be 180 g per person per day in 2030. Since the largest proportion of meat consumption is expected to come from pork, poultry, and aquaculture, meeting future demand will depend on achieving increases in cereal yields (Bradford, 1999). A doubling in cereal yields may be necessary by 2030 if one does not want to increase cultivated area, which, however, is hard due to many different constraints.

Food production is coupled to a moral imperative, as adequate food supply is a cornerstone of human welfare. Development of agricultural practices ensuring food sufficiency is a basic human requirement, a precondition for satisfactory social conditions and a necessity for civilizations to flourish. Lack of food, on the other hand, is a tragedy leading not only to suffering and loss of life but also to inhumane behaviour, political instability and war (Borlaug, 1970). In fact, eradication of famine and malnutrition has been identified as the most important task on Earth (UN Millennium Project, 2005). Thus, when discussing different forms of crop production, it is of the utmost importance to examine without prejudice the forms of agriculture that can contribute to food sufficiency and security, at present and in the future. Separation of facts and wishful thinking is absolutely necessary and only an unbiased review of the scientific literature can provide objective answers to the questions put forward below.

In terms of crop yields, a number of reviews have shown that organic crop yields are consistently lower than conventional yields (e.g. Badgley et al., 2007; Kirchmann et al., 2008a; Korsaeth, 2008; Goulding et al., 2009). However, the magnitude of the yield decrease attributed to organic cultivation differs. For example, in the review by Badgley et al. (2007), a biased selection of experimental data from a limited number of studies with small yield differences were chosen, which is not representative. The conclusions have been criticized by Connor (2008) and Goulding et al. (2009), pointing out that if one considers the whole existing literature it is obvious that organic agriculture cannot feed the world.

To avoid reliance on experimental data only, crop yields given in national statistics of organic and conventional agriculture were examined. One may argue that national statistics may be biased because organic farming may be carried out mainly on land with lower production potential and thereby not representative for arable soils in general. However, the Swedish experience seems not to corroborate this view. The majority of organic farmers in Sweden are milk and meat producers maintaining grass/clover leys in rotation and having access to manure. This means conditions to maintain reasonable crop yields in organic production in Sweden are therefore given.

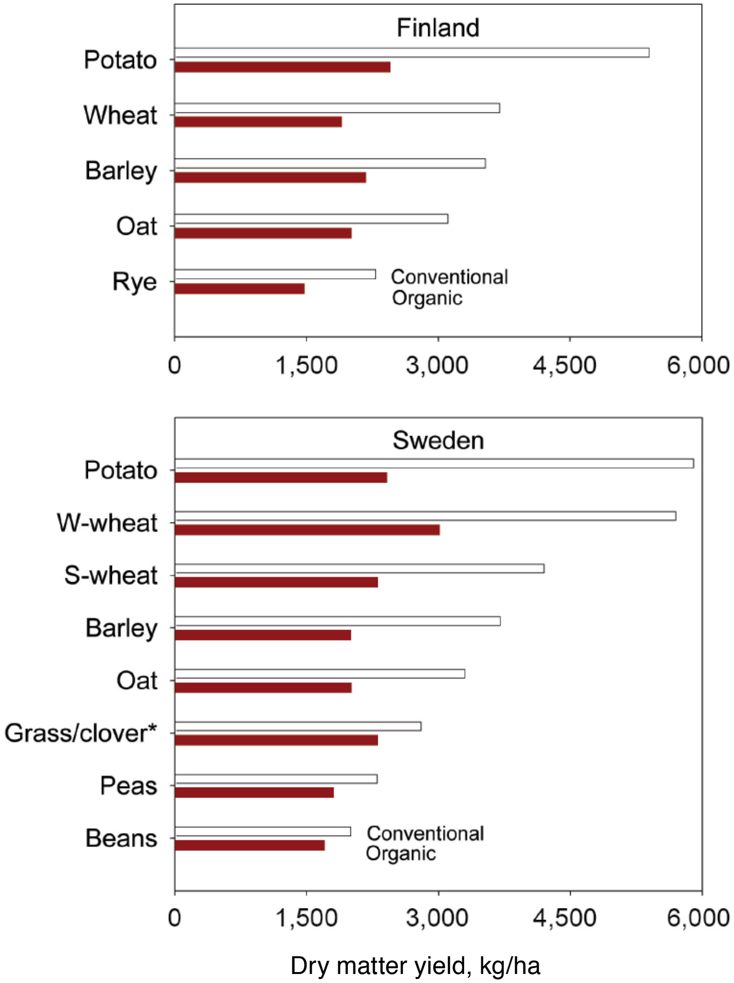

Figure 1. Official yield data for organically and conventionally grown crops in Finland and Sweden, 2005. *Only the first of two or three cuts is represented by the data.

A search in agricultural statistical databases of EU countries, the USA, Canada, and Australia revealed that information on organic crop yields is very scarce. No crop yield data were found except for Sweden and Finland. Official Swedish statistics (SCB, 2008) reveal that yields of organically grown crops are 20 to 60% lower than those of conventionally grown crops. Yields of organically grown legumes (peas and beans) and grass/clover leys are, on average, 20% lower (**Figure 1**), as they are sufficiently supplied with N, whereas yields of cereals are 46% lower and yields of potatoes as much as 60% lower than in conventional production. National statistics for Finland (Finnish Food Safety Authority, 2006; Statistics Finland, 2007) show a similar picture with yields of organically produced cereals being 41% lower and yields of potatoes 55% lower (**Figure 1**).

Organic farming requires large areas for legume production (N-fixing crops); for example in Sweden, the area used for the legumes such as peas and beans is twice as high in organic as in conventional production. Also the proportion of agricultural land used for forage production (grass/clover leys) is much higher in organic than conventional production systems, 69 versus 49%, respectively (see **Table 1**). However, the production of digestible energy for ruminants is lower in grass/clover leys than in winter wheat or in alfalfa than in maize. Thus, increasing legume production substituting cereals means that productivity of land is reduced.

Table 1. Proportion of crops grown in conventional and organic agriculture in Sweden (SCB, 2008).

Crop	Portion of agricultural land, %	
	Conventional	Organic
Forage	49	69
Legumes	1.2	2.3
Cereals	43	27
Oilseed rape	3.8	1.0
Potatoes	1.2	0.3

In summary, there is on average a 40% reduction in crop yields through conversion from conventional to organic crop production according to the statistics. This estimate is in good agreement with the assessment of Smil (2001), who claimed that industrial N-fixation (N fertilizer production) provides the means for 40% of global food production. This implies that the greatest part of the yield difference between organic and conventional production is due to N. In fact, insufficient N supply to crops has been identified as being the main yield-limiting element in organic crop production (Kirchmann et al., 2008b). Deficiency of K has also been pointed out as a reason for decreased yield especially in potato (Torstensson et al., 2006). Thus, the exclusion of synthetic fertilizers and lack of approved and cheap nutrients for organic agriculture limit organic yields to such an extent that shortage of food, or alternatively, the conversion of new land to agricultural production, will be the immediate consequence of large-scale adoption of organic crop production.

Some advocates of organic agriculture claim that the lower yields produced in organic systems can be compensated for by a shift to a more vegetable-based diet (e.g. Woodward, 1995; Tudge, 2005). In other words, it is proposed that the shortcoming of organic production to supply sufficient food for humans should be resolved through a change to a more vegetarian diet. However, it must be borne in mind that if such a shift is recommended due to benefits for human health, the most efficient solution would be to grow conventional crops and use the surplus set-aside land for other forms of production or return to natural land including forest.

Lower Yields in Organic Crop Production Due to Non-Scientific Fertilization Rules

Low yields of organically grown crops are the result of the organic farming approach to supply the soil with nutrients but not to feed the crop with soluble nutrients and the fact that total input of nutrients is often too low for high-yielding crops. In organic systems, plant nutrients are added in organic forms or as untreated minerals with low solubility and plants are expected to obtain balanced nutrition through the actions of roots and soil microbes and through weathering of minerals. Furthermore, there is a widespread conception, as proposed by Steiner (1924), that organic and self-sustaining farms constitute the real core of sound agricultural production. The need to import nutrients to a farm is considered a sign of failure of the system (Steiner, 1924). A common view is that on-farm recycling of nutrients, with any small losses balanced by soil weathering, will maintain soil fertility (IFOAM, 2006). However, the view of a farm as a self-sustaining unit contradicts the ‘law of nutrient replacement’, where nutrient removal must be restored to maintain soil fertility and avoid nutrient mining of soils.

In contrast, in conventional agriculture, the focus is on crop demand and on optimizing the nutrient supply. Since von Liebig (1840) showed that plant roots take up nutrients in the form of ions dissolved in water, the exclusion of water-soluble mineral fertilizers in organic agriculture is contrary to these basic findings and to modern plant nutrient research. Even though plant nutrients are added as organic manures or untreated minerals in organic crop production, uptake by crops is mainly in the form of ions, dissolved or mineralized into the soil solution from minerals or organic manures. In other words, the source of plant nutrients does not affect the uptake mechanism but nutrient sources of low solubility cannot increase yields.

For optimal growth, crops require a minimum of nutrients consisting of macro- and microelements. A number of these elements are supplied through inorganic fertilizers to complement nutrient release from soils. Complete and sufficient nutrient supply to crops is the rationale to apply macro- and micronutrients in conventional agriculture. In addition, organic manures, recycled wastes, and mineral fertilizers are used in conventional agriculture to cover crop demand. A further difference between organic and conventional agriculture is that plant nutrients removed through sale of crops and animal products from the farm are principally replaced in conventional agriculture - the 'law of replacement' is adopted. If the nutrients lost or sold are not replaced, the soils used in any cropping system will become depleted and soil fertility will decline.

Although organic farmers recognize farm animal manures as a valuable source of nutrients and place much emphasis on proper use of manures in a crop rotation, the rules given by the founders of organic agriculture have to be followed, even when they are not necessarily in accordance with best management practices. For example, in biological dynamic agriculture (Steiner, 1924) farmers must compost animal wastes. However, losses of N in the form of NH_3 are higher during composting than when manure or slurry is properly stored under anaerobic conditions (Kirchmann, 1985). In biological organic farming (Rusch, 1978), surface application of manure or green manure crops is prescribed, also leading to high losses of NH_3-N. These practices, which are central to two main schools of organic agriculture in Europe, lead to less efficient recycling of N and organic matter compared with other forms of manure treatment such as anaerobic storage of solid or liquid manure, protection against rain during storage, and incorporation of animal wastes into soil directly upon spreading.

Different Proportions of Crops in Organic and Conventional Systems and Implications for Human Diet

One of the most distinct differences between organic and conventional agriculture is the type of crops grown in a crop rotation. According to official Swedish statistics (SCB, 2008), the production of forage crops for ruminants (grass/clover leys) increases considerably in organic systems as pointed out above (**Table 1**). Why are proportionally more forage crops grown in organic than conventional rotations? The reason is that N-fixing forage crops show less yield reduction than other organically grown crops and can fulfil several functions: N supply, weed control, and manure production. There is simply lack of other organic methods to produce reasonable yields. In other words, organic agricultural systems in many parts of Europe will be mainly based on forage-ruminant systems.

In addition, the proportion of legumes (peas and beans) in organic rotations is almost doubled due to their ability to fix N, and similar yields are obtained as compared to conventionally grown legumes (**Table 1**). A logical consequence of growing more N-fixing crops in organic rotations is that other crops decrease proportionally. The biggest change when converting to organic agriculture in Sweden is the decline of cereal, potato, and oilseed rape production. According to figures in **Table 1**, only 63% of cereals and 25% of potato and oilseed rape would be produced as compared to conventional agriculture. In addition, assuming yield reductions shown in (**Figure 1**), supply of these products will be further reduced. Actually only 13% of present production of oilseed rape and potatoes would remain.

If one assumes that the statistical data (**Table 1**) are representative even for a full-scale conversion to organic agriculture in Sweden, some changes of the dietary composition are foreseeable. One probable consequence of large-scale organic production is that the increase in forage production (from 49 to 69% on arable land substituting cereal growth) may not lead to a large decline in milk and red meat supply. Furthermore, reduced cultivation of cereals and oilseed rape from 47 to 28% on organically managed land, will reduce the fodder supply for pigs and poultry. Simply, less eggs, poultry, and pork will be produced.

Differences in the proportion of crops grown and decline in yields in organic production systems can have a great impact on food supply and the composition of the human diet. Despite many uncertainties, some general conclusions can be drawn. Firstly, it is not likely that organic agriculture will result in a vegetarian diet. Organic food production in cold temperate climate is mainly based on a forage-ruminant system, which seems to be the only system proved that can maintain reasonable organic yields through a large proportion of legumes in rotation and control of weeds. Secondly, less pig and poultry products in the diet requires replacement through other food. However, it is not likely that ruminant products will substitute eggs, poultry, and pork as ruminant production is less energy-efficient and requires more water per calorie unit. The constraint put on human diets through organic agriculture to cover protein and energy need is likely to be overcome through an increased intake of vegetable proteins and carbohydrates (i.e. more legumes and cereals in the diet). A third consequence can be that the domestic demand for these staple legumes and cereals will be difficult to cover through organic crop production and shortage of some vegetable products is possible.

Food Quality

A large number of environmental factors influence food quality. They include parent material of soils, geographical location, climate, weather conditions, exposure to industrial, traffic or natural emissions, etc. Crop variety, storage, refinement and food amendments may further impact quality. None of these factors were considered in the present review. Our focus was solely on the effect of organic and conventional agricultural practices on crop composition. The aim of this literature compilation was to answer the ultimate question whether organic products contribute to health benefits for the consumer.

One objective of this review was to quantify the extent of changes in nutrient composition in crops caused by conventional and organic practices. Another objective was to discuss how apparent differences in crop nutrient composition can be coupled to organic and conventional practices and which mechanisms that may be responsible for the differences found. A third objective was to put crop nutrient composition in perspective to the nutritional demand of humans.

The View on Food Quality in Organic Agriculture

The founders of organic agriculture stressed the superior nutritional quality of organically produced food. For example, Steiner (1924) stated that use of mineral fertilizers would degrade crop quality to such an extent that food would become a worthless filler of the abdomen. The view of the founders of the Soil Association (Howard, 1947; Balfour, 1943) was that only a healthy soil produces healthy food. Howard (1947) believed that only plant nutrients made available through a kind of living bridge between life in soil and plants can feed plants properly.

Today, organic farming organizations (e.g. Soil Association; Organic Food Information Net; the Organic Center) are of the opinion that organic food is of higher quality. The common understanding within organic agriculture is that addition of mineral fertilizers enhances plant growth, which means production of more sugar, proteins, and fats, but yield increases are not accompanied by corresponding increases in mineral uptake, vitamin, and antioxidant production. Only the exclusion of synthetic fertilizers will guarantee high contents of trace elements, vitamins, and beneficial non-nutrient compounds. Benbrook et al. (2008) conclude in their report that organically grown plants are better for health, having about 25% more nutrients than conventionally grown plants. A decline in nutrient density of crops over time (Mayer, 1997; Davis et al., 2004) is sometimes mentioned as a proof for the ‘dilution’ of nutrients through mineral fertilizers.

Existing Comparative Studies

Numerous studies comparing the nutritional quality of organic and conventional food have been published since 1924. The intention of this chapter is not to re-examine the existing literature but to understand the consistent differences found in existing review papers and discuss the possible principles that may explain these differences. Food quality is a poorly defined concept—for instance, taste and appearance are personal assessments—and our purpose was to focus only on the nutritional composition of food.

Reviews by Woese et al. (1997), Bourne and Prescott (2002), Magkos et al. (2003), and Dangour et al. (2009) show that there are consistent differences in the composition of organically and conventionally produced food (**Table 2**). Woese et al. (1997) found clear evidence of higher NO_3^- concentrations in vegetables and higher protein content in cereals if grown conventionally, whereas vitamin C was higher in vegetables grown organically. Bourne and Prescott (2002) found only a significant difference in NO_3^- contents being higher in conventional food. Magkos et al. (2003) found higher levels of vitamin C and lower protein contents in organically produced vegetables. Finally, the review by Dangour et al. (2009) found significantly higher N contents in conventional crops and higher contents of titratable acid (i.e. vitamin C) and P in organic crops. A similar summary was presented by Tinker (2000).

Differences in Crop Composition Due to Organic and Conventional Cultivation

Organic agriculture excludes synthetic fertilizers, and it is well-known that different nutrient supply can cause major shifts in plant composition, especially N application. Nitrogen is the most important plant nutrient in terms of increasing crop yields (Mengel and Kirkby, 2001). Furthermore, N fertilizer application stimulates growth-enhancing shoot elongation and increasing shoot/root ratios, and alters plant composition more than any other mineral nutrient (Marschner, 1995). An increasing supply of N to crops stimulates the synthesis of crop

Table 2. Compilation of significant differences in crop composition reported in reviews between organically and conventionally grown crops and possible mechanisms.

Significant differences found in reviews	**Possible mechanisms**
Woese et al. (1997)	
Higher NO_3^- content in conventionally grown vegetables	More plant-available N in soil
Higher protein content in conventionally grown cereals	More plant-available N in soil
Bourne and Prescott (2002)	
Higher NO_3^- content in conventionally grown crops	More plant-available N in soil
Magkos et al. (2003)	
Higher dry matter content in organically grown crops	Smaller cells with proportionally less water
Higher protein content in conventionally grown crops	More plant-available N in soil
Higher vitamin C content in organically grown crops	More light per unit leaf area (less mutual shading)
Dangour et al. (2009)	
Higher N content in conventionally grown crops	More plant-available N in soil
Higher titratable acid content in organically grown crops	More light per unit leaf area (less mutual shading)
Higher P content in organically grown crops	More light per unit leaf area (less mutual shading)

biomass, which leads to more chloroplast formation (part of leaf that contains chlorophyll) and higher concentrations of the constituents in chloroplasts such as chlorophyll, proteins, and lipids. An increase in total N in crops or crude protein (total N multiplied with 6.25) representing the sum of proteins, amino acids, amides, and NO_3^- (often not fully included in total N analysis) is normally found. Nitrogen fertilizer application can also increase the biosynthesis of carotene and B vitamins in crops (Marschner, 1995).

Dry matter contents are normally somewhat lower in N-fertilized crops probably because of larger cells that store proportionally more water than smaller cells of unfertilized crops. In many studies, no moisture-adjusted concentrations of nutrients and vitamins are used. For instance, declines of nutrient contents in food over time are less significant if increases in water content are made as shown in recalculation of data by Davis et al., (2004).

Changes in crop composition due to exclusion and application of N fertilizer are discussed in detail below.

Total Nitrogen and Nitrate

In organic agriculture, exclusion of N fertilizer and reliance on biological N-fixation as a N source has resulted not only in yield losses but also lower N and NO_3^- contents in crops (**Table 2**). Organic farming organizations (e.g. Benbrook et al., 2008) regard lower N and NO_3^- contents in organically grown crops to be a quality indicator. The general argumentation is that there is less but higher quality of N compounds in organic products. Elevated NO_3^- contents are regarded to be undesirable for plants and humans.

Nitrogen is an essential component of amino acids, the building blocks of proteins. Protein concentrations in crops are highly dependent on N supply and high protein concentrations, for example in grains, and are associated with good nutritional and commercial quality. The ten essential amino acids that cannot be synthesized by humans (arginine, histidine, valine, leucine, isoleucine, threonine, methionine, lysine, phenylalanine, tryptophan) must be part of the diet and must at least partially be obtained from ingested crops. Application of N fertilizer during late stages of crop growth can be effective to increase protein concentrations.

However, late application of N fertilizer to barley and wheat can also increase the content of non-essential proteins, which improve baking properties but not the nutritional value. On the other hand, late application of N to oats increased the nutritional quality of protein (Mengel and Kirby, 2001).

Studies on protein quality showed that the portion of essential amino acids of the total protein content was not significantly different in organically and conventionally grown cereals (e.g. Dloughý, 1981) or vegetables (Eppendorfer and Bille, 1996). As there is no scientific evidence that the content of essential amino acids and protein quality is reduced through N fertilizer, but only additional proteins and amino acids are formed, lower protein contents in organically grown cereals are of no advantage. A review by Wang et al. (2008) summarizes information on the effects of inorganic N fertilizer on crop quality, and generally finds them to be positive.

There is still a misunderstanding on the NO_3^- issue in crops requiring a comprehensive explanation. NO_3^- is abundant in our diet, and levels found in many vegetables range from as low as 1 mg/kg in peas (*Pisum sativum* L.) and Brussels sprouts (*Brassica oleracea* L.) to as high as 4,800 mg/kg in rucola (*Eruca sativa* L.), see review by Lundberg et al. (2004) and EFSA (2008). High NO_3^- contents in crops have traditionally been considered to be a health risk as NO_3^- was thought to be a potential cancer-causing chemical in the gastro-intestinal tract. Consequently, lower NO_3^- contents in organically grown crops were believed to be a nutritional advantage. This perspective is still dominating among many scientists including interest organizations for organic food (e.g. Benbrook et al., 2008). However, in 1994 the standpoint on NO_3^- started to change. It was observed that the human stomach contains large amounts of nitric oxide (NO) and that the gas was able to kill bacteria in the stomach (see overview by Minkel, 2004). Bacteria in the mouth were found to convert NO_3^- to NO_2^-, and when swallowed, production of NO in the stomach was induced. The NO_3^- - NO_2^- - NO pathway in physiology was detected and the role of NO_3^- as an important mammalian resistance mechanism against infectious diseases was discovered (see review by Lundberg et al., 2008). In addition, no epidemiological evidence for an increased risk of gastric and intestinal cancer in population groups with high NO_3^- intake was found (Duncan et al., 1997) and positive effects of dietary NO_3^- were reported (Leifert and Golden, 2000). The European Food Safety Authority concluded in a review (EFSA, 2008) that "Overall, the estimated exposures to NO_3^- from vegetables are unlikely to result in appreciable health risks, therefore the recognized beneficial effects of consumption of vegetables prevail."

In summary, to consider lower protein and NO_3^- contents in crops to be of nutritional advantages in the human diet has no scientific basis. From the view point of human health, it is of great importance to increase the content of essential nutrients in crops.

Vitamin A

According to plant physiological knowledge, an increasing supply of N enhances the synthesis of proteins and chloroplasts in crops (e.g. Marschner, 1995; Mengel and Kirkby, 2001). An increase of chloroplasts means that also chloroplast constituents such as chlorophyll and carotenoids (for instance β-carotene the precursor for vitamin A) increase in crops. Carotenoids are integrated together with chlorophyll into membrane proteins forming light-harvesting centers. Carotenoids act as light interceptors for more energy-rich radiation than chlorophyll. The most frequently occurring carotenoid in higher plants is β-carotene. Carotenoids are lipid-soluble pigments synthesized by plants, fungi, algae, and bacteria being responsible for the yellow, orange, and red colours of fruits and vegetables.

Over 600 carotenoids have been identified so far (Bendich, 1993) and significant differences in carotenoid accumulation among different vegetable crop species have been reported (Kopsell and Kopsell, 2006). In the human diet, fruits and vegetables are the main sources of carotenoids (Rao and Rao, 2007) and the daily requirement for vitamin A is estimated to be 800 retinol equivalents (1 retinol equivalent = 12 μg β-carotene). Carotenoids have received attention for their antioxidant properties.

A review by Mozafar (1993) compiling about 180 studies on the effect of mineral N fertilizer on vitamins in plants showed clearly that carotenoids in crops increased when fertilized with increasing rates of mineral N, which is in accordance with plant physiological understanding outlined above, and he found no contradictory studies. A compilation of some recent references (**Table 3**) show that mineral N fertilization can increase β-carotene concentrations in a number of crops. In comparative studies, organically grown crops had lower β-carotene concentrations than crops fertilized with mineral N fertilizer. However, apparently contradictory results published by Caris-Veyrat et al. (2004) are in fact in line with our understanding because N fertilization rates were 340 kg/ha in organic and 160 kg/ha in conventional production in this specific study. Increasing rates of green manure N applied to crops also resulted in significantly increasing β-carotene concentrations in carrots (Kaack et al., 2001). At very high N application rates, concentrations of carotenoids declined somewhat if expressed on a fresh-weight basis due to more water storage in plant cells (Kopsell et al., 2007a). However, on a dry-weight basis, concentrations of carotenoids continued to increase with increasing N fertilizer applications (Kopsell et al., 2007b; Lefsrud et al., 2007).

The above-cited studies corroborate that N supply is a major determining factor for carotenoid synthesis in crops. An earlier study by Trudel and Ozbun (1971) showed that also the supply of K fertilizer had a positive effect on carotenoid formation in tomatoes. Thus, increasing the nutrient supply to crops and thereby gaining higher yields is also followed by an increased production of carotenoids per unit crop biomass. As less N is normally applied in organic cultivation (see review by Kirchmann et al. 2008 a,b), a greater supply of nutrients to conventionally grown crops will result in at least similar or higher carotenoid contents than in organically produced ones.

B-vitamins

Humans and mono-gastric animals rely on the supply of B-vitamins with the diet. Microbial biosynthesis of B-vitamins is well-known and fermented food can be a significant source. Although comparative studies between organically and conventionally grown crops showed no significant differences concerning certain B vitamins (e.g. Woese et al., 1997; Bourn and Prescott, 2002), it is of interest to discuss how N supply may affect the synthesis of B vitamins in crops. The review by Mozafar (1993) included B vitamins and showed that application of N fertilizer resulted in higher vitamin concentrations in crops. According to Mengel and Kirkby (2001), there is a close relationship between protein concentrations in cereal grains and concentrations of B vitamins. Late application of N to cereals increased concentrations of B vitamins. According to Marschner (1995) the content of lipids in green leaves is closely related to N supply. An enhancement of protein synthesis through N application also leads to an increase in the lipid layers of leaves. In the lipid metabolism, vitamin B_1 (thiamine) plays a key role as thiamine pyrophosphate together with coenzyme A.

Table 3. Review of mean concentrations of β-carotene in crops as affected by N supply. References cover studies between 2001 and 2010.

Reference and crops	β-carotene concentration#, mg/kg fresh weight			Relative increase with N supply,
	Increase with N level	Mineral	Organic	
		fertilization		%
Kaack et al. (2001)				
Carrot (green manure, 10 rates, 2 yrs)	110-150	-		+10
*Caris-Veyrat et al. (2004)**				
Tomato (320 kg organic N vs. 116 kg mineral N, 3 cultivars)	-	8.7	12.3	+70
Chenard et al. (2005)				
Parsley (N fertilizer, 5 rates)	39.7-78.5	-		+98
Kopsell et al. (2007b)				
Kale (N fertilizer, 5 rates, 3 cultivars)	61.6-65.3	-		NS
Lefsrud et al. (2007)				
Spinach (N fertilizer, 4 rates, 2 cultivars)	57.9-69.6	-		+15
	47.0-51.4	-		NS
del Amor (2007)				
Sweet pepper (low organic N vs. high mineral N)	-	a		+24
Kopsell et al. (2007a)				
Watercress (N fertilizer, 3 rates)	3.3-9.3	-		+182
Juroszek et al. (2009)				
Tomato (3 paired farms, organic vs. conventional, 2 cultivars)	-	5.2	5.8	NS
Behera and Rautaray (2010)				
Durum wheat (N fertilizer, 2 rates)	4.0-4.7	-		+17
Mean difference				+42

 # 12 µg of "dietary" beta-carotene correspond to 1 µg vitamin A being 1 retinol activity equivalent (RAE).
** Note that more N was applied with organic manure than mineral fertilizer.*
NS = not significant.
a = no absolute values given.

Although knowledge about the synthesis of several B vitamins in crops is limited, it seems that an enhanced protein formation is followed by the syntheses of B vitamins. It is therefore most likely that the content of B vitamins is equal or higher in conventionally, due to a higher N supply, than in organically grown crops. The B vitamin content in foods of plant origin would likely be relevant to human nutrition mainly in vegetarian diets, since in other diets, fish and animal products supply much larger relative amounts.

Vitamin C (Ascorbic Acid)

Humans cannot synthesize vitamin C in the body and an adequate and regular intake with the diet is therefore necessary. The recommended dietary intake of vitamin C is 75 mg per day for adults. In Western diets, vitamin C is mainly provided through fruits and vegetables (including potatoes) and deficiencies are rare.

Vitamin C is a water-soluble plant metabolite linked to carbohydrate metabolism formed from glucose as a precursor (Wheeler et al., 1998). A high production rate of glucose promotes vitamin C synthesis. Among factors determining the level of vitamin C in crops, radiation interception is the most important one. This means that intensive light and high photosynthetic activity favors the synthesis of vitamin C in crops (Mengel and Kirkby, 2001). Vitamin C is needed by the crop in three reactions during photosynthesis and is also protecting crops against oxidative stress (Smirnoff, 1996). However, N fertilizers at high application rates seem to decrease the concentration of vitamin C in fruits and vegetables. The review by Mozafar (1993) showed that the content of vitamin C decreased in plants at high N fertilization. Similarly, a review by Nagy (1980) on citrus fruits showed that an increasing application of N fertilizer resulted in higher N contents and lower vitamin C contents. The same finding is obvious from **Table 4**, which shows that higher total N contents in conventionally grown crops are followed by lower vitamin C contents and vice versa for organically grown crops.

A relevant question to ask is what mechanism may cause lower concentrations of vitamin C in plants with higher N supply? The most probable explanation is that application of N fertilizer results in denser crop canopies affecting the leaf area exposure to light and thereby the rate of photosynthesis. Knowing that N fertilization increases the amount of biomass produced and knowing that vitamin C formation increases with light intensity, it is most likely to assume that a dense crop canopy can cause mutual shading, which means reduced light penetration to certain parts of the crops. In other words, although total photosynthesis per plant or area increases due to more leaves, a larger and denser crop canopy can reduce photosynthesis per leaf area compared to sparse-leafed crops. As a result, a lower vitamin C production is related to dense canopies and vice versa. This mechanism can also explain instances where vitamin C concentrations do not decline with N fertilizer application (see **Table 3**). For example, vegetables grown in pots with sufficient light not affected through mutual shading did not show lower vitamin C content with increasing N supply (e.g. Müller and Hippe, 1987). Similarly, cabbage and sweet corn, which are most likely less affected by mutual shading showed no decline in vitamin C contents between conventionally and organically grown plants (Warman et al., 1997, 1998) as well as peas (Fjelkner-Modig et al., 2000) to which no N fertilizer is applied.

An important question to be answered is how large declines in vitamin C that have been reported upon N application? An earlier study by Åberg and Ekdahl (1948) showed that the difference in vitamin C content was less than 10% between low and high N application rates for different plants. Lisiewska and Kmiecik (1996) found a reduction in the vitamin C content of 7% when increasing

Table 4. Vitamin C contents in crops from comparative organic and conventional cropping.

Reference and crops	Vitamin C concentration, mg/kg fresh weight		Organic relative to conventional, %
	Conventional	Organic	
Leclerc et al. (1991)			
Carrot (6 farms, 2 yrs)	38	45	+18
Celeriac (6 farms, 2 yrs)	73	81	+11
Cayuela et al. (1997)			
Strawberry (11 sampling dates, 1 yr)	700	720	+3
Warman and Havard (1997)			
Carrot (3 yrs)	26	25	-4
Cabbage (3 yrs)	538	479	-11
Warman and Havard (1998)			
Potato (2 yrs)	275	262	-5
Sweet corn (3 yrs)	67	64	-4
Fjelkner-Modig et al. (2000)			
Cabbage (6 yrs)	376	370	-2
Carrot (6 yrs)	53	58	+9
Onion (6 yrs)	80	90	+12
Pea (2 cultivars, 6 yrs)	165	160	-3
Potato (3 cultivars, 4 yrs)	213	223	+5
Asami et al. (2003)			
Corn (1 yr)	28	32	+14
Caris-Veyrat et al. (2004)			
Tomato (3 cultivars, 1 yr)	121	154	+27
Chassy et al. (2006)			
Tomato (2 cultivars, 3 yrs)	168	203	+21
Bell pepper (2 cultivars, 3 yrs)	518	554	+7
Mean difference			+6.1

fertilizer application from 80 to 120 kg N to cauliflower. Although these studies do not deal with the comparison of organic and conventional agriculture, it is interesting to note that the reported decline is of the same order of magnitude as in the review of Dangour et al. (2009), who found a 6.8% lower content of titratable acidity including ascorbic acid. The compilation of data in **Table 4** derived from paired studies over the last 20 years shows that the mean decline of vitamin C in conventional products is 6.1% as compared to organic ones. In summary, a small decline of vitamin C in conventionally produced crops can be expected. The dietary impact may not be very severe as the difference is small in comparison to the varying contents among fruits and vegetables of different species. Sparing application of N to fruits and vegetables will help to produce high vitamin C crops.

Trace Elements

Another important crop quality aspect is the trace element composition. Principally, plant availability of nutrients and trace elements in soil affects the composition of crops. If for example NPK fertilizers are applied to soil, a larger amount of these nutrients in soil solution enables crops to take up more of these and yields increase. However, if the addition of mineral NPK fertilizer may not be followed by a sufficient amount of trace elements, less trace elements in proportion to applied nutrients may be taken up. As a result, concentrations of trace elements in crops may become diluted (Jarrell and Beverly, 1981). Dilution of trace elements through application of mineral NPK fertilizers has been pointed out as one reason why mineral fertilizers could reduce crop quality. According to Rusch (1978), one of the founders of organic agriculture, high crop quality can only be achieved when easily soluble mineral fertilizers are excluded. In fact, decreasing contents of some plant nutrients in vegetables and fruits available on the market over a period of 50 years have been observed (Mayer, 1997; Davis et al., 2004).

The study by Mayer (1997) showed that there are significant reductions of Ca, Mg, Cu, and Na in vegetables; and Mg, Fe, Cu, and K in fruits over time. A similar study by Davis et al. (2004) in the USA revealed a decline in Ca, P, and Fe in garden crops although observations of sometimes increased levels of nutrients were found. However, the nutrients mentioned are both macro- (K, P, Mg, Ca) and micronutrients (Fe, Cu) and a systematic decline of only micronutrients was not obvious. Furthermore, one may not expect K, P, and Ca, which have been applied in agriculture as mineral fertilizer and lime on a regular basis, to be declining. Other factors than dilution due to fertilizer application were also pointed out by Davis et al. (2004). Selection of cultivars with a high yield potential, and unpredictable genetic variability of cultivars, were given as possible explanations (Davis et al., 2004). Comparisons of trace element contents in organic and conventional food based on recent publications reveal no definite results for a dilution effect in the latter (Gundersen et al., 2000; Lorhem and Slania, 2000; Ryan et al., 2004; Hajšlová et al., 2005; L-Bäckström et al., 2006; Kristensen et al., 2008). In most cases there were no differences in mineral contents and in the remaining cases both higher and lower concentrations can be found in organic and conventional food. For example, one study found that Cu concentrations were higher in conventional than organic food, while another study found the opposite and yet another study found no difference between the two (**Table 5**).

Table 5. Review of studies comparing concentrations of trace elements in organically and conventionally grown crops.

Trace element	1 Experiment, 18 maize samples	19 Farms, 190 pea samples	2 Experiments, 39 cereal samples	1 Experiment, 18 cereal samples	2 Experiments, vegetables
Cr	n.a.	org = conv	n.a.	n.a.	n.a.
Co	n.a.	org = conv	n.a.	org = conv	org = conv
Se	n.a.	org = conv	n.a.	org > conv	n.a.
Ni	n.a.	org = conv	n.a.	conv > org	org = conv
Mo	n.a.	org = conv	n.a.	n.a.	org > conv
Cu	conv > org	org = conv	org > conv	n.a.	org = conv
Fe	org > conv	org = conv	org = conv	org > conv	org = conv
Zn	org > conv	org = conv	org > conv	n.a.	org = conv
Mn	n.a.	org = conv	org = conv	n.a.	org = conv
Reference	Warman and Havard (1998)	Gundersen et al. (2000)	Ryan et al. (2004)	L-Bäckström et al. (2006)	Kristensen et al. (2008)

n.a. = not analyzed

Furthermore, absolute concentrations in crops differed more between studies than between organic and conventional systems in the same study. This means that location, soil, soil-crop management, etc. seem to have a major influence on the micronutrient composition of crops. As data in the literature are inconclusive or conflicting and do not support a mineral depletion hypothesis caused by NPK fertilizers, other factors may influence trace element concentrations in organically and conventionally grown crops, which are discussed below.

The major source for trace elements is agricultural soil. Native concentrations of trace elements in soil may vary due to differences in parent material. As a consequence, differences in the supply of trace elements from soil can have a greater impact on concentrations in crops than the type of cropping. For example, low Se content in a soil will lead to low Se contents in crops, regardless of the type of production. Furthermore, flows of micronutrients and trace elements to soils and crops will greatly affect crop composition. Micronutrients and trace elements are added to soil with mineral P fertilizers, untreated minerals, or purchased manures, or are applied as such to cover crop demand. Even purchased animal feed being enriched with mineral nutrients can lead to enrichment in soils that receive manure on a regular basis. Information on flows of trace elements must be provided and considered when comparing crops from different cultivation systems. Unfortunately, this information is often not available and therefore seldom mentioned.

Atmospheric deposition of trace elements can have a significant effect on contents in crops as shown by concentrations of unwanted elements (Pb and Cd) that have decreased in crops over the last two decades (Kirchmann et al., 2009) due to reduced emissions.

One may conclude that the hypothesis that organically produced crops have higher concentrations of trace elements than conventional crops is not supported by scientific data. In fact, use of synthetic fertilizers allows controlled application of trace elements to achieve defined concentrations in crops. Fertilization with Se in Finland since 1984 is an example of controlled application to achieve defined concentrations in crops, animal products and human blood (Eurola et al., 2003).

Non-essential Secondary Metabolites

Secondary crop metabolites (other than essential vitamins) consist of different groups of compounds such as phenolic acids, polyphenols, terpenoids, alkaloids, flavonoids, estrogens, glucosinolates, etc., in total 5,000 to 10,000 different substances whose role in plants is not fully known, including functions such as protection against light, control of oxidative stress, defence against insect and pathogen infestation, and herbivore grazing. Also their dietary role and function in humans is not well understood. The antioxidant function of some metabolites, reducing free radicals and their preventive role in cancer has been pointed out (Hasler, 1998). However, one may be reminded that if a secondary metabolite would be essential, the compound would be defined as a vitamin. Identified vitamins and micronutrients such as vitamin A, C, Se, etc. act also as antioxidants. In fact, polyphenols were proposed as vitamin P more than 70 years ago (Kroon and Williamson, 2005), but evidence for essentiality was lacking.

Some commonly occurring secondary compounds, for example solanine (alkaloid) in potatoes and cyanide in cassava are occurring at concentrations in crops harmful for humans. Some secondary metabolites have the potential to cause cancer (Ames, 1983; Ames et al., 1990). It seems that the large number of secondary compounds present in plants can make it difficult to know which are beneficial or harmful for human health. However, several epidemiological studies have shown that a higher daily intake of vegetables and fruits, being the major source of secondary metabolites, reduce the risk for cardiovascular disease (Ness and Powles, 1997) and cancer (Block et al., 1992).

Despite their non-essentiality for humans, supporters of organic agriculture consider secondary crop metabolites as key substances for human health (e.g. Lundegårdh and Mårtensson, 2003; Caris-Veyrat et al., 2004; Mitchell et al., 2007; Benbrook et al., 2008). In fact, the beneficial health effects of fruit and vegetable consumption have been attributed to a higher intake of secondary metabolites (Brandt and Mølgaard, 2001) and not of essential vitamins and micronutrients. However, the grounds for considering secondary metabolites an extremely important health component in the diet are not supported by scientific evidence. Ames and Wakimoto (2002) point out that the health-promoting and cancer-reducing effect of a higher fruit and vegetable consumption is attributed to a sufficient level of vitamin and mineral intake avoiding suboptimal conditions and dietary deficiencies. To explain elevated levels of secondary crop metabolites as a crop quality indicator can be a misinterpretation.

It is therefore highly questionable to consider secondary metabolites (e.g. phenolic compounds in berries) (Asami et al., 2003), and chlorogenic acid (Caris-Veyrat et al., 2004) and kaempferol in tomatoes (Mitchell et al., 2007), as being as beneficial as contents of vitamin C. These compounds are not known to be essential and in addition have been shown in some studies to be harmful (Ames, 1983; Sahu and Gray, 1994).

Recent comparative studies with onions, carrots, and potatoes showed that organic or conventional production had no significant and systematic effects on polyphenol and flavonoid content (Sølhoft et al., 2010 b) or polyacetylene in carrots (Sølhoft et al., 2010 a)—a group of less abundant compounds in crops also ascribed a health promoting effect (Christensen and Brandt, 2006). Testing the source of N fertilizer (organic or inorganic N) on possible changes of the most common flavonoid in onion (quercitin) resulted in no significant differences (Mogren et al., 2007; 2008). A meta-analysis done by Koricheva et al. (1998) investigating six environmental factors on contents of some secondary metabolites in plants showed that phenols and terpenoid concentrations responded marginally to N fertilization, P fertilization, shading, drought, ozone and CO_2-enrichment.

In summary, based on the fact that our understanding of the reactions of secondary crop metabolites in human metabolism is poor, and that they can be both harmful and beneficial, it may be incorrect to interpret elevated levels as a quality improvement. In the discussion of secondary plant components, it may be useful to remember that humans only use a limited number of plants as food crops simply because many plants contain high contents of unwanted secondary metabolites making them unsuitable as food.

Mycotoxins in Organically and Conventionally Grown Crops

A further quality aspect of crops is the presence of toxins produced when fungi colonize food crops, the so-called mycotoxins. There are large numbers of mycotoxins synthesized by fungi, but only a few pose a potential health risk (Murphy et al., 2006). A distinction can be made between mycotoxins formed before harvest such as deoxynivalenol, zearalenone, and derivatives originating from *Fusarium* species; and those formed after harvest such as aflatoxins and ochratoxins originating from *Aspergillus* species. Thus, when examining the effect of cropping system on mycotoxin formation, only toxins produced before harvest are of interest. Our examination focuses solely on deoxynivalenol (DON), since it is the most frequently detected *Fusarium* toxin in wheat (Edwards, 2009).

In principal, inorganic N fertilization can increase the occurrence of fungi and mycotoxin formation as a result of higher moisture conditions in crops (Clevström et al., 1986; 1987). It is well-known that N fertilization results in denser crops, which can lead to less air flow and cause a higher relative humidity in crop canopies. Furthermore, use of N fertilizer can lead to higher water contents in crops as compared to unfertilized. In addition, fertilizer use can prolong the maturity period of crops and may also increase the risk for lodging. Fungal infections are favoured by high levels of moisture from flowering to the end of the maturation period. In other words, intensive conventional agriculture may indirectly increase the problem of fungi infestations.

While some studies showed no significant increase of mycotoxin contamination with N fertilization (e.g. Teich and Hamilton, 1985; Schaafsma et al., 2001; Blandino et al., 2008), others indicate an increase in deoxynivalenol contents (e.g. Lemmens et al., 2004; Heier et al., 2005; Oldenburg et al., 2007). Although high N fertilization can favour mycotoxin formation, a number of additional factors can also have an influence, such as infection pressure, weather conditions and the susceptibility of crop varieties. Furthermore, it seems that only very high N application rates exceeding crop demand increase the risk for mycotoxin contamination (Blandino et al., 2008). Main factors having a depressive effect on mycotoxin formation were K fertilization and a high pH in soil (Teich and Hamilton, 1985).

In summary, there is no clear evidence that conventional crops grown with inorganic N fertilizer will be more contaminated. In addition, the use of synthetic fungicides in conventional agriculture can be a powerful tool to control fungal infestation in crops and thereby maintain low mycotoxin levels. Whether organic or conventional crop production is favouring mycotoxin formation is reviewed below in which a number of experiments and field studies are compared.

Data on grain concentrations of deoxynivalenol were compiled (**Table 6**) to examine whether there are indications of the concentrations being higher in any particular system. Only grain samples prior to storage and processing were selected, while commercially available grain products (e.g. Malmauret et al., 2002; Schollenberger et al., 2003, 2005; Cirillo et al., 2003; Jestoi et al., 2004) were excluded in order to avoid the possible influence of different conditions related to processing.

Concentrations in grain showed large variations in organic crops (25 to 760 μg deoxynivalenol/kg grain) and in conventionally grown crops (16 to 1,540 μg dexonivalenol/kg grain). Mean dexonivalenol values of the data compiled (organic 225 μg/kg grain and conventional 215 μg/kg grain) were not significantly different. In some studies, variations between years were larger than variations between systems (Birzele et al., 2002; Champeil et al., 2004). Fungicide treatment of growing crops decreased the level of deoxynivalenol in the grain. However, the treatment was less effective for low to moderate disease infections than for a high infection rate (Birzele et al., 2002; Champeil et al., 2004). Minimum tillage generally resulted in higher levels of deoxynivalenol in grain than more intensive tillage (Champeil et al., 2004). From the data compilation above, we can conclude that conventionally grown crops will not lead to a greater contamination than organically grown crops.

Table 6. Review of mean concentrations of the *Fusarium* mycotoxin deoxynivalenol measured in grain samples obtained from organic and conventional crop production.

Type of crop	No. of samples	Concentration of deoxynivalenol in grain prior to storage[†], mean µg/kg grain		Reference
		Organic	Conventional	
Wheat	35 in total	—	54	Teich and Hamilton, 1985
Wheat	51 and 50	484	420	Marx et al., 1995
Rye	50 and 50	427	160	
Wheat	37 in total	26	20	Olsen and Möller, 1995
Rye	10 in total	20	15	
Wheat	n.g.[††]	50	16	Eltun, 1996
Oat	n.g.	36	19	
Wheat	169	—	16	Langseth and Rundberget, 1999
Oat	178	—	32	
Wheat	46 and 150	760	1,540	Döll et al., 2000
Wheat	47	111	—	Birzele et al., 2002
Wheat	58	280	—	
Wheat	n.g.	205	150	Birzele et al., 2002
Oat	9 and 14	25	24	Schollenberger et al., 2003
Wheat	24 and 36	126	394	
Wheat	8 and 8	123.5	37.5	Finamore et al., 2004
Wheat	75 and 75	500	450	Champeil et al., 2004
Wheat	31 and 40	160	200	Hoogenboom et al., 2008
Wheat	247 and 1,377	230	230	Edwards, 2009
Wheat	13 and 13	310	132	Solarska et al., 2009
Wheat	4 and 4	201	46	McKenzie and Whittingham, 2010
	4 and 4	201	323	
Mean values		**225**	**215**	

† The maximum permissible deoxynivalenol concentration in grain is 500 µg/kg for direct human consumption and 100 µg/kg for infants and young children.

†† Not given.

Concluding Remarks

A number of representative reviews have shown that adopting organic agriculture on a world-wide scale would lead to severe shortages of food (Smil, 2001; Kirchmann et al., 2008a; Goulding et al., 2009). However, some advocates of organic agriculture have been quick to respond that this is not a problem as we should change to a more vegetarian diet. In other words, the world should adapt to organic systems that produce less food (Badgley and Perfecto, 2007). The recommendation given is that lack of food as a result of conversion to organic production should be compensated for by a change in diet. However, if the aim is to produce more vegetarian food owing to nutritional recommendations based on science, the most efficient and environmentally friendly way would be to cultivate crops through conventional practices. Large land areas used for agriculture today could then be re-converted to natural ecosystems, forests or used for production of bioenergy. The environmental impact of agriculture would be minimized.

Worryingly, it is foreseeable how organic food production on a large scale will endanger food security. Based on statistics from Sweden, organic crop production would imply a shift towards milk and red meat production requiring much more land for forage utilized by ruminants. Yield reductions of about 50% and declines of 75% less land used for organic potato and oilseed rape production would not be sufficient to cover demands in Sweden.

Since it was stated by the founders of organic agriculture that organic food is superior, quality has been a key argument to promote this type of agriculture. Numerous studies on food quality have been performed, but stringent reviews subjecting results to extensive comparisons or rigorous statistical procedures (e.g. Magkos et al., 2006; Dangour et al., 2009) reveal few differences showing that food quality of organic products is not necessarily better. In this review, an understanding of enhanced or decreased contents of vitamins, protein, NO_3^-, and trace elements in crops due to different fertilization was aimed for. It seems that only vitamin C is reduced by conventional cropping (mutual shading in crop canopies fertilized with N), whereas the synthesis of other vitamins (A and B) are favoured by N fertilization. The literature data reviewed in this chapter provides no evidence for a systematic dilution of trace elements in conventionally grown crops and no difference in mycotoxin contents between the cropping systems were found. We conclude that the quality of organically grown crops does not seem superior.

Food Supply, Dietary Composition and Food Quality

Many people want to supply their body with the best food available and choose organic food. Lady Eve Balfour, the British founder of the Soil Association, wrote that she changed to a diet based on organically produced food (Balfour, 1943). However, she also shifted to whole grain instead of refined flour products, a high proportion of vegetables and fruits and abolishment of meat in her diet. She lived a long life. Her experience may lead to the conclusion that organically produced food supports a long and healthy life. However, to be able to evaluate health effects, the distinction between dietary composition and food quality is necessary.

Many human health problems in the world are the result of malnutrition or obesity (i.e. shortage of nutrition or excessive food consumption). Furthermore, an imbalanced dietary composition can cause health problems as a result of insufficient supply of essential nutrients. Finally, differences in food quality may have an impact on human health. In other words, one has to distinguish three aspects related to food intake: amount of food eaten, dietary composition, and nutritional quality.

Our analysis indicated that large-scale organic production will bring about two major changes—food supply may not be secured and shortage of certain foods will affect the dietary composition. Although claims about nutritional benefits are used as an argument for organic products, our review corroborated earlier studies also showing that organic products do not have a superior quality. Considering the dietary composition (i.e. proportions of carbohydrates to fats, intake of products with sugar and white flour, consumption of fruits and vegetables, amount of fish or meat eaten, etc.) has a great impact on human health (Willet, 1994; Taubes, 2001; Trichopoulou and Critselis, 2004). Focus should be on proper nourishment first of all. It seems that any possible differences in product quality may actually be of minor importance for health as long as the supply of essential nutrients is sufficient, which can be regarded to be a healthy diet (Ames and Wakimoto, 2002). For example, a daily intake of five conventionally grown fruits and no cake per day will supply more vitamins than two organically grown fruits plus cakes. We conclude that food shortage and consequences for the dietary composition are of uttermost importance when discussing health aspects of organic production rather than food quality.

Belief in the Superior Quality of Organic Food

A frequent statement of advocates of organic agriculture is that organically produced crops are more nutrient dense. A late example is a report from the organic center in Boulder, Colorado by Benbrook et al. (2008) stating that organic plant-based food contains 25% more nutrients than the same food produced conventionally. The evaluation of this report by Rosen (2008) showed that: i) the selection of references indicate exclusion of results favourable to conventional food; ii) the revised standpoint on dietary NO_3^- actually being essential for the human immune system was completely ignored; and iii) the magnitude of 25% higher contents cannot be derived from the literature studies cited.

This recent example shows that conviction in the superiority of the nutritional benefits of organic food rather than search for the understanding of the complexity and factors controlling food quality seems to be a driving force for supporters of organic agriculture. The wide-spread belief that organic products must be superior is based on a view idealizing nature. The slogans 'nature knows best´ and 'nature makes it good' are examples characterizing this view. However, not to idealize nature but to recognize the wholeness of nature is in accordance with natural science. FCHH

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Chapter 11

Fertilization as a Remediation Measure on Soils Contaminated with Radionuclides ^{137}Cs and ^{90}Sr

By Iossif Bogdevitch, Natallia Mikhailouskaya
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Abstract

A wide range of countermeasures has been used to mitigate the consequences of the Chernobyl accident in affected regions of Belarus. Radical improvement of grassland, liming, fertilizers, and manure application are the most widespread, applicable, and effective countermeasures to restrict soil-to-plant radionuclide transfer. Efficiency of fertilization depends on radionuclide deposition, texture and chemical properties of the soils, and biological characteristics of plants. Soil fertility improvements through liming, manure, and NPK application are the basic remediation measures in the long-term period after the Chernobyl accident. This paper reviews existing experimental data on the efficiency of agrochemical countermeasures on land contaminated by ^{137}Cs and ^{90}Sr.

Introduction

Radiocaesium (^{137}Cs) and radiostrontium (^{90}Sr), the important products of nuclear fission, have been introduced into the terrestrial environment by nuclear weapons testing, nuclear waste disposal, and by nuclear accidents such as those at Chernobyl and Fukushima. Following a large-scale release of radioactivity into the environment, inhabited land and food production systems may be contaminated for many years. Radiocaesium in the environment can affect human health following exposure via various pathways. The consumption of agricultural

Abbreviations specific to this chapter: BRISSA = Belarus Research Institute for Soil Science and Agrochemistry; LSD = least significant difference; RF = reduction factor; PL = permissible level of radionuclide concentration; FYM = farmyard manure; SD = standard deviation; Bq = Becquerel; Tag = Aggregated transfer factor [the ratio of the mass activity density (Bq/kg) in a specified object to the unit area activity density in Bq/m^2] = m^2/kg.
For abbreviations and symbols used commonly throughout this book see page v.

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V. Mikulich is a Postgraduate Student, Research Institute for Soil Science and Agrochemistry, Minsk, Belarus; e-mail: roni24@tut.by products contaminated with ^{137}Cs and ^{90}Sr represents the main long-term exposure pathway of the population (Alexakhin, 1993; Shaw and Bell, 1994). There is considerable variation in the soil-to-plant transfer of radionuclides. This is due to differences in soil pH, K status, and the contents of clay and organic matter (Absalom et al., 1995, Arapis and Perepelyatnikova, 1995, Sanzharova et al., 1996). Prister et al., 2003 proposed a comprehensive model for prediction of ^{137}Cs and ^{90}Sr transfer from soil to plants in relation to deposition, time of incubation, and main soil properties: pH, absorbing capacity of cations, content of organic matter, and exchangeable K and Ca.

An accident in the Chernobyl nuclear power plant on 26 April 1986 resulted in a massive radioactive contamination of territories in Republic of Belarus, Russian Federation, and in Ukraine. As a consequence, large-scale countermeasures in agriculture of the affected countries have appeared to be necessary. Such countermeasures have been intensively applied in the post-accident period. More details on implementation of remediation strategies in the areas affected by the Chernobyl accident—especially in terms of costs and averted doses, efficiency, and also the possibility to involve stakeholders in the remediation process—can be found elsewhere (Jacob et al., 2009). The primary aim of agrochemical countermeasures on contaminated land is to reduce radionuclide transfer into the human food chain. Liming and extra rates of K and P fertilizers are basic elements of plant production technology in radioactive contaminated land, which result in essential change of soil agrochemical properties and radionuclide behaviour in the soil-plant chain.

The aim of our work was to determine parameters of radionuclide transfer from soil to plants depending on soil fertility status and fertilizers, based on the background of our research experience in the post Chernobyl period in Belarus. These parameters are the basis for the development of protective measures in the long-term post-accident period to decrease the transfer of ^{137}Cs and ^{90}Sr in the food chain with minimal expenses, using conventional methods of fertilization.

The Chernobyl accident in Belarus has resulted in a radioactive contamination covering about 23% of the territory and affecting 2.2 M people. An area of 265,000 ha has been excluded from agricultural use due to deposition of ^{137}Cs over 1,480 kBq/m^2, ^{90}Sr over 111 kBq/m^2, and plutonium (Pu) isotopes over 3.7 kBq/m^2. At present, agricultural production is conducted on 1.0 M ha of land contaminated by ^{137}Cs with deposition of 37 to 1,480 kBq/m^2. A portion of this land, 0.34 M ha, is simultaneously contaminated with ^{90}Sr as well (6 to 111 kBq/m^2). The agricultural sector has been the area of the economy most affected by the accident. The Government has provided significant financial support for the rehabilitation of contaminated territories. However new efforts are needed for development of reliable experimental background for the choice of efficient remediation measures. In relatively favorable climatic conditions, the level of soil fertility is the most important parameter for limiting the contamination of harvested crop product.

Materials and Methods

Studies on the influence of soil fertility on ^{137}Cs and ^{90}Sr transfer to plants were carried out with randomized plots 1 m^2 in size on crop fields of the Gomel region. The efficiency of fertilizers was studied on Luvisol loamy sand soil under conventional agricultural conditions. The soil agrochemical properties were as follows: 2.2% humus, 6.0 pH (KCl), 170 mg P_2O_5/kg, and 160 mg K_2O/kg. Radionuclide deposition on soil (mean ± SD) was rather high at 350 ± 18.0 kBq $^{137}Cs/m^2$ and 48 ± 5.2 kBq $^{90}Sr/m^2$. Treatments included rates of K fertilizer (60, 120, and 180 kg K_2O/ha) along with 90 kg N and 60 kg P_2O_5, which were compared to no treatment. The fertilizer treatments (four replications) were laid out on 3 blocks receiving 0, 8, and 16 t/ha of manure within the crop rotation of maize, spring wheat, vetch-oat mixture, winter wheat, and lupin for grain. Associative N_2-fixing bacteria (local strain *Azospirillum brasilense*) were tested in field trials by the inoculation of perennial grass seeds. The experiments in the Mozyr district of the Gomel region were conducted on poor Luvisol loamy sand soil with the following characteristics: 1.2% humus, 6.0 to 6.2 pH, 160 to 180 mg P_2O_5/kg, and 180 to 190 mg K_2O/kg. Deposition of ^{137}Cs and ^{90}Sr was 185 kBq/m^2 and 12 kBq/m^2, respectively. Timothy grass (*Phleum pratense*), fescue (*Festuca pratensis*), brome grass (*Bromus Inermus*) and cocksfoot (*Dactylis Glomerata*) were grown on small experimental plots (6.4 m^2) using four replications and background fertilization of 30-60-90 kg N-P_2O_5-K_2O/ha.

Soil analyses were conducted using conventional methods. Available P_2O_5 and K_2O were determined by extraction in 0.2 M HC1 using a 1:5 soil to water ratio. ^{137}Cs activity concentration in plant and soil samples was measured using gamma spectrometry (HP-Ge detector Canberra GC4019). ^{90}Sr activity concentration was determined in plant and soil samples ashed at 600°C, using the oxalate method with separation of radioyttrium (^{90}Y) (Cherenkov counting). Results were calculated for each soil sample both as Bq/kg and as kBq/m^2. Then aggregate transfer coefficients of radionuclides from soil into crop production, Tag values ($m^2/kg \times 10^{-3}$) for ^{137}Cs and ^{90}Sr were calculated. Conventional dispersive and regression statistical analysis for the experimental data was carried out using MS Excel (Clever and Scarisbrick, 2001).

Remediation Measures

Liming

Plants absorb Cs and Sr by the same uptake mechanisms as their competitor ions (K and Ca, respectively). Both K and Ca are important plant nutrients and are therefore actively taken up by the plant. Where their competitor ions are abundant and bioavailable, ^{137}Cs and ^{90}Sr accumulation by plants is expected to be relatively low.

Soil acidity influences the availability of dissolved nuclides and their uptake in plants. The liming of acid soils is an effective way of reducing ^{90}Sr transfer to plant products. This countermeasure, based on decreasing soil acidity and a relation of Sr^{2+}/Ca^{2+} in soil solution, was known a long time before the Chernobyl accident (Wiklander, 1964). During the post-accident period numerous trials with Ca amendments were done. A priority was given to such chemical amendments to try to reduce the level of radionuclides in soil solution by increasing the concentration of competitive species, such as Ca and K (Alexakhin, 1993; Nisbet et al., 1993).

It was found that Ca addition may significantly reduce both the transfer of ^{137}Cs and ^{90}Sr to plant production only on acid soils, relatively low in exchangeable Ca (about 2 cmol of exchangeable Ca per kg soil) (Nisbet et al., 1993). The most appropriate liming material for coarse-textured soils of Belarus was finely-ground dolomite containing 22% Ca and 13% Mg.

The pH (KCl) values for maximum yield of growing plants on Podzoluvisol loamy sand soil were different: 6.7 for barley, 5.9 for potatoes, and 4.9 for lupine. The priority criterion for choosing a countermeasure treatment needs to consider the value of extra yield obtained (Bogdevitch, 2003). An example of combined radiological and economic justification is the optimal liming treatment for potato plants presented in **Table 1**.

Table 1. Effect of liming on potato yield and radionuclide accumulation on Podzoluvisol loamy sand soil (Deposition of ^{137}Cs – 370 and ^{90}Sr – 37 kBq/m², ^{137}Cs activity of potato tubers on Control treatment – 10.2 Bq/kg, ^{90}Sr activity of tubers – 11 Bq/kg).

Dolomite applied, t/ha	Fertilizer applied ($N-P_2O_5-K_2O$), kg/ha	Soil pH	Soil exchangeable Ca, cmol/kg	Yield of potato, t/ha	Net return, €/ha	^{137}Cs activity RF (reduction factor)	^{90}Sr activity RF
0	0-0-0	4.9	2.5	16.2	-	1.0	1.0
6	0-0-0	5.9	4.2	17.6	67	1.6	-
18	0-0-0	6.7	5.8	15.4	-95	1.7	-
0	70-60-150	4.9	2.5	24.3	403	1.8	1.2
6	70-60-150	5.9	4.2	26.4	509	2.1	1.5
18	70-60-150	6.7	5.8	23.1	298	2.3	1.7
$LSD_{0.05}$				1.4			

The highest yield of potatoes in the experiment was achieved with application of 6 t of dolomite and an application of 70-60-160 kg of fertilizer $N-P_2O_5-K_2O$ per ha. This treatment resulted in the highest net profit per hectare, while substantially reducing the plant accumulation of ^{137}Cs and ^{90}Sr. Increasing the rate of dolomite to 18 t/ha provided a neutral soil reaction (pH 6.7), slightly less plant accumulation of ^{137}Cs and ^{90}Sr, but resulted also in decrease of yield and net profit. It is well known that large additions of lime to acid soils that raise pH above 6.5 often lead to depressed yield owing to low availability of micronutrients such as Fe, Mn, Cu, and Zn (Bergmann, 1992). Combined applications of lime and fertilizer were able to increase yields and profits while reducing plant accumulation of radionuclides.

Perennial grasses accumulate the highest concentrations of radionuclides for both ^{137}Cs and ^{90}Sr, which is most problematic for grazing cattle, especially for dairy stock. Soil acidity influences the availability of dissolved nuclides and their accumulation in plants. Our investigation on farm fields showed that liming changed the reaction of Luvisol soils from pH (KCl) 4.2-4.5 to pH 6.5-7.0, and strongly reduced ^{90}Sr accumulation in clover (*Trifolium pratense*) (**Figure 1**).

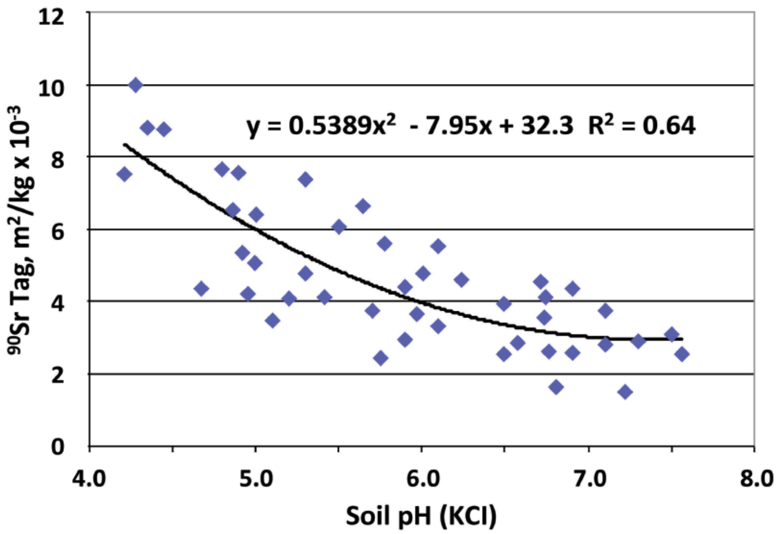

Figure 1. ^{90}Sr transfer (Tag m^2/kg x 10^{-3}) to clover biomass in relation to the reaction (pH KCl) of Podzoluvisol loamy sand soil.

The results of the present study can be simply described by an empirical regression using a negative power function. Similar relations have been established for other crops. Such negative power functions have been widely used in Belarus for the prediction of ^{137}Cs and ^{90}Sr plant uptake from soil. The mean reduction factors of ^{137}Cs and ^{90}Sr accumulation in plants due to liming of contaminated soils with different pH (KCl) in Belarus, Russia, and Ukraine varied from 1.3 to 2.6 times (Deville-Cavelin et al., 2001). However in the case of highly acidic Podzoluvisol and peat soils (pH < 4.0 to 4.5), liming in our experiments reduced radionuclide accumulation in perennial grass by up to 10 times.

The recommended lime rates were differentiated according to soil type, texture, and initial degree of acidity to achieve the optimal pH level for main crops grown on contaminated land (BRISSA, 2003). The target levels of pH (KCl) for Podzoluvisol texture groups were: clay and loam 6.0 to 6.7, loamy sand 5.8 to 6.2, sand 5.6 to 5.8. The target pH range for liming of drained Histosols (peat-boggy soils) was 5.0 to 5.3. Liming of contaminated acid soils is a mandatory prerequisite of agriculture practice in contaminated areas.

Potassium Fertilizer

The application of K fertilizer is a main agrochemical measure for restriction of ^{137}Cs accumulation in crop products. It is well known that K, as a chemical analog of Cs, could effectively inhibit the transfer of ^{137}Cs from soil to plants (Andersen, 1963; Evans and Dekker, 1963). However, the inhibitory effect is strongly dependent on the K concentration in soil solution, which determines the effect of K fertilization as a countermeasure to reduce the Cs contamination of crop products (Menzel, 1954; Shaw and Bell, 1991). The genotypic differences in ^{137}Cs uptake between the various crops are very important; however, they also depend on exchangeable K content in soil (Bogdevitch, 1999). Exchanges of K nutrition of plants result in essential change of intensity of accumulation both of ^{137}Cs and ^{90}Sr in plants. Insufficient soil K supply leads to the intensive involvement of ^{137}Cs in the biological chain on contaminated soils (Alexakhin, 1993; Prister et al., 1993; Fesenko et al., 2007).

Our field experiments were carried out on soil with three prepared blocks characterized by different levels of soil K supply. Increasing doses of K, balanced with NP fertilizers, were applied on each level of soil K supply. Data from the spring wheat experiment is shown in **Table 2**.

Table 2. Effect of increasing K fertilizer doses (kg K_2O/ha) on yield and ^{137}Cs transfer to spring wheat grain under three different contents of exchangeable soil K in Podzoluvisol loamy sand soil of Belarus, Gomel region.

Soil treatment†	Yield of grain, t/ha	Response to control, t/ha	^{137}Cs Tag value, $m^2/kg \times 10^{-3}$	Reduction factor
		3.2 mmol K/kg		
Control	3.24	-	0.028	1.0
$N_{70}P_{60}K_{80}$	4.58	1.34	0.024	1.1
$N_{70}P_{60}K_{160}$	4.79	1.55	0.017	1.6
$N_{70}P_{60}K_{240}$	4.90	1.66	0.014	2.0
		5.3 mmol K/kg		
$N_{70}P_{60}K_{80}$	4.90	1.66	0.014	2.0
$N_{70}P_{60}K_{160}$	4.90	1.66	0.010	2.7
$N_{70}P_{60}K_{240}$	5.00	1.76	0.009	2.8
		7.4 mmol K/kg		
$N_{70}P_{60}K_{80}$	5.00	1.76	0.010	2.7
$N_{70}P_{60}K_{160}$	5.13	1.89	0.010	2.8
$N_{70}P_{60}K_{240}$	5.21	1.97	0.009	2.9
LSD_{05}		0.22	0.0037	

†Note values indicated for P and K application are actually P_2O_5 and K_2O.

It was found that improvement of soil K supply level (exchangeable K) of a Podzoluvisol loamy sand soil from 3.2 to 5.3 mmol/kg significantly increased yields and reduced ^{137}Cs transfer from soil to grain by a factor of 1.7 to 1.6. High K fertilizer rates up to 160 to 240 kg K_2O/ha are effective for crop cultivation on loamy sand soils with low K content. Only moderate K fertilizer rates are needed for soils with medium to high K supply (5.3 to 7.4 mmol/kg) to replace crop K removal.

Our investigation provided experimental background for K fertilizer application efficiency as affected by radionuclide deposition, soil agrochemical status, and genotypic differences of crops. For example, a close reverse correlation was observed between ^{137}Cs accumulation in clover (*Trifolium pratense*) biomass and available K content in soil (**Figure 2**).

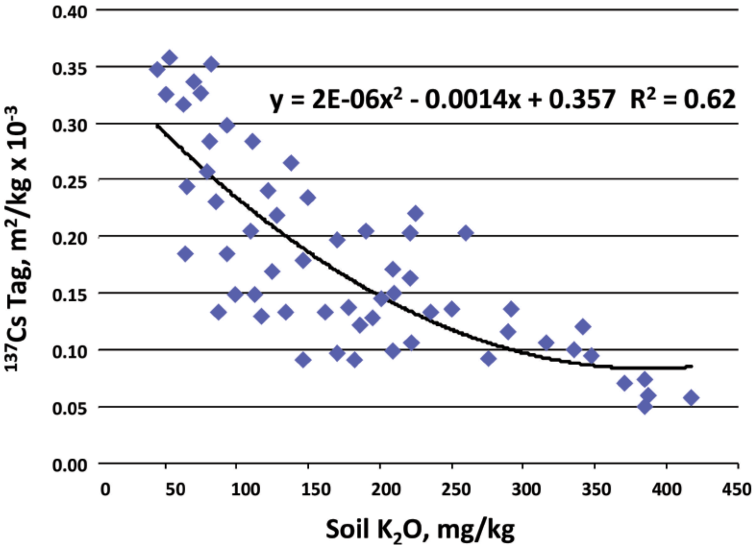

Figure 2. ^{137}Cs transfer (Tag value, $m^2/kg \times 10^{-3}$) to clover biomass depending on K supply of Luvisol loamy sand soil.

The relationship between ^{137}Cs transfer to clover plants and soil supply K level is well described by a negative power function that explains 62% of the variability of the data. A significant decrease of ^{137}Cs accumulation took place within the available K content range of 50 to 250 mg/kg, or 1.1 to 5.3 mmol/kg. Data indicates the optimal K content threshold in sod-podzolic loamy sand soil is about 5.3 mmol/kg for most field crops. Further increase in exchangeable soil K did not provide a significant reduction in radionuclide accumulation in plants, but strongly increased the cost of treatment. The efficiency of K fertilization was found to be higher after liming if soil acidity was significantly reduced. This result is in agreement with those obtained by Nisbet (1995) who concluded that K fertilizer could be beneficial in ameliorating the effects of ^{137}Cs contamination in both organic and mineral soils of low fertility in which exchangeable K is less than 5 mmol/kg. Therefore our experimental data provided the quantified base for prediction of efficient use of K fertilizer in relation to K soil tests.

However, different soil properties can strongly influence the concentrations of ^{137}Cs and ^{90}Sr (and their competitor ions) in the soil water, and observed uptake to plants can vary within a wide range of values (Sheppard and Evenden, 1997). We studied the inhibitory effect of increasing doses of K, balanced with NP fertilizers, on ^{137}Cs and ^{90}Sr transfer to wheat grain in relation to three levels of FYM application within a long-term field experiment started in 1999. The levels of FYM (0, 8, and 16 t/ha) resulted in different levels of soil organic matter content in the topsoil layer, corresponding to 1.56, 1.94, and 2.40%. Application of 16 t/ha of FYM had a prolonged effect on crop rotation yield and it resulted in a spring wheat (*Triticum aestivum*) grain response of 0.96 to 1.14 t/ha. The accumulation of ^{137}Cs in the grain decreased by 1.3 to 1.4 times due to FYM application, while ^{90}Sr accumulation in grain was reduced by 2.0 to 2.6 times (**Figure 3**).

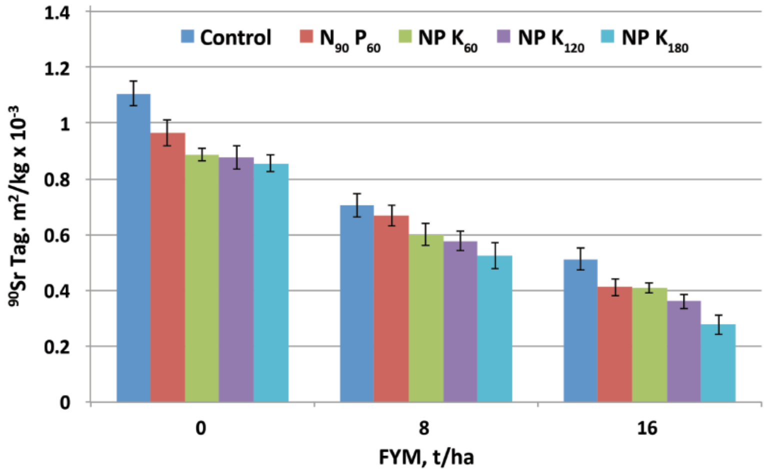

Figure 3. Transfer of ^{90}Sr (Tag value, m²/kg x 10^{-3}) from soil to spring wheat grain in relation to farmyard manure (FYM) and K fertilizer rates on Podzoluvisol loamy sand soil.

The major factor in the behavior of Sr in soils is the formation of organic complexes with humic substances (Arapis et al., 1997). Therefore additions of organic matter to coarse-textured soils can decrease ^{90}Sr plant uptake by increasing the holding capacity of soils for trace levels of radionuclides. The combined effect of higher rates of FYM and optimal fertilizer treatment ($N_{90}P_{60}K_{180}$) allowed for a 4 times reduction in ^{90}Sr transfer to wheat grain (Tag value) from 1.11 to 0.28.

Phosphorus Fertilizer

It is known that heavy dressings of P fertilizer can prevent or reduce plant uptake of toxic concentrations of trace elements (Bergmann, 1992) as well as of ^{137}Cs and ^{90}Sr radionuclides (Nisbet et al., 1993; Prister et al., 1993). The reduction of

^{90}Sr transfer from soil to crop production was admitted to be due to formation of insoluble strontium phosphates. However application of unbalanced high doses of NP fertilizers on fertile soils has resulted in the enhancement of ^{137}Cs accumulation in plants (Sanzharova et al., 1996). Usually the agrochemical properties have close intercorrelations. In our experiment we had opportunity to measure the effect of different concentrations of available P in soil while keeping the level of other input factors equal (**Figure 4**).

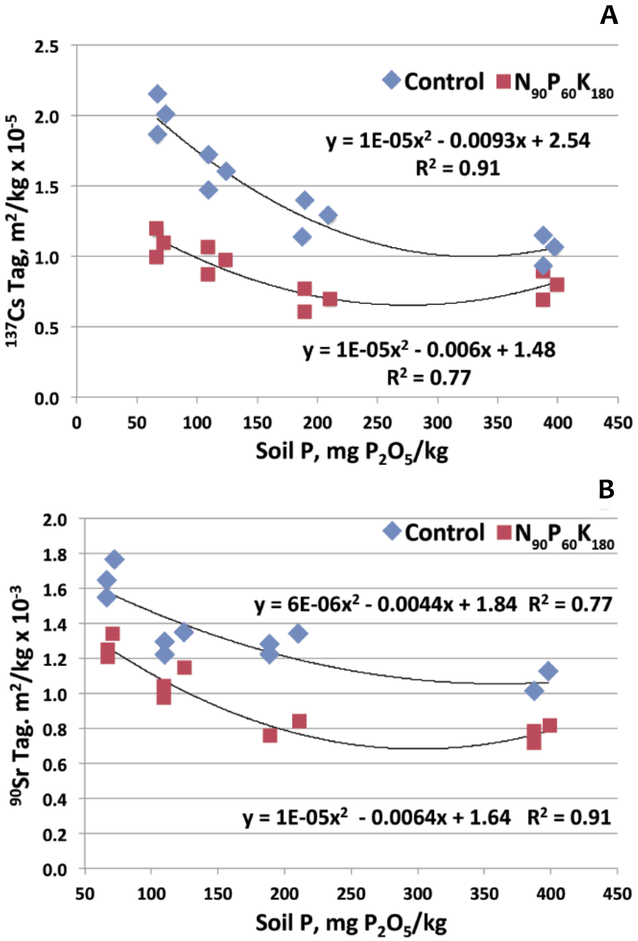

Figure 4. Tag values ($m^2/kg \times 10^{-5}$ for ^{137}Cs and $m^2/kg \times 10^{-3}$ for ^{90}Sr) indicating flux into grain of spring wheat (means for 2005, 2006, and 2007 under the Control and $N_{110}P_{60}K_{180}$ treatments) in relation to different levels of available P content for a Luvisol loamy sand soil.

Four blocks with different content of available P in soil (mg P_2O_5/kg) were prepared: I (67 to 72); II (110 to 124); III (189 to 211), and IV (388 to 398). Increasing available soil P content within the wide limits of 67 to ~400 mg P_2O_5/kg has been accompanied with an increase in grain yield on fertilized plots from 3.8 to 6.9 t/ha, as well as a decrease in accumulation of ^{137}Cs by a factor of 1.4 to 1.9, and by a factor of 1.5 to 1.6 for ^{90}Sr. Close relation of Tag transfer values of ^{137}Cs and ^{90}Sr to wheat grain (y) with increasing available P content in soil (x) was found to fit well with quadratic curves (R^2 = 0.91 and 0.77, $P<0.01$). The minimum accumulation of radionuclides in wheat grain is expected at an available P content of 300 to 320 mg P_2O_5/kg for loamy sand soil (Bogdevitch and Mikulich, 2008).

We also studied the inhibitory effect of increasing doses of K, balanced with NP fertilizers, on ^{137}Cs transfer to wheat grain in relation to different levels of soil P supply (**Figure 5**).

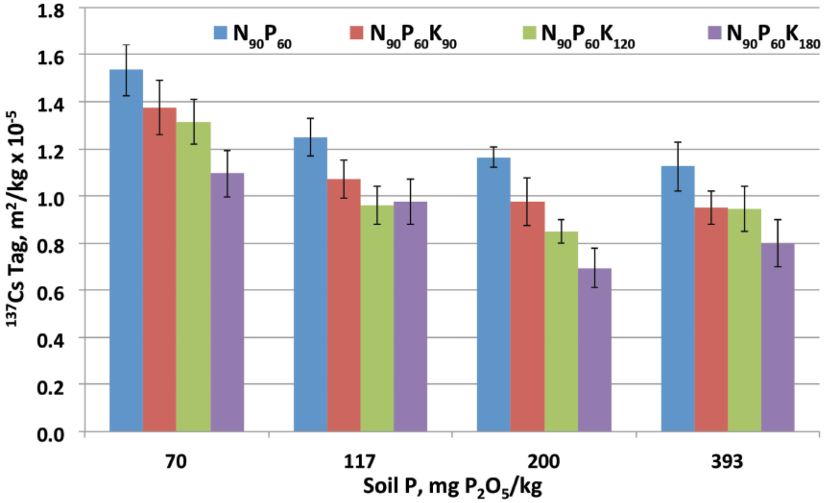

Figure 5. Transfer Tag values ($m^2/kg \times 10^{-5}$ for ^{137}Cs) indicating flux into grain of spring wheat (mean ± SD 2005 to 2007) in relation to increasing rates of K fertilizer at different levels of available P content for a Luvisol loamy sand soil.

The K status of our experimental field was close to optimal for cereal crops on loamy sand soil (4.7 mmol/kg of exchangeable K). The application of increasing rates of K fertilizer resulted in sufficient reduction of ^{137}Cs transfer from soil to wheat grain. Compared to the background application (kg/ha) of $N_{90}P_{60}$, addition of K_{90} reduced ^{137}Cs transfer by 10 to 16%, K_{120} by 14 to 27%, and K_{180} by 22 to 40%. The range of reduced ^{90}Sr transfer to grain under the influence of K fertilizer rates has been comparatively lower at 3 to 28%. The relative inhibitor effects of K fertilizer on radionuclide transfer from soil to wheat grain were similar for all studied levels of soil P supply. However the values of the transfer coefficients of ^{137}Cs had a clear tendency to decrease as the available P content in soil increased.

The Tag values for ^{137}Cs were low; therefore the grain activities varied for the treatments and P levels between 1.9 to 9.1 Bq/kg, which is much lower than the permitted level (PL) for food-grade grain (90 Bq/kg). The transfer of ^{90}Sr from soil to wheat grain was almost two orders of magnitude higher and the grain activities varied between 19.5 to 42.7 Bq/kg. The PLs for ^{90}Sr currently in force in Belarus are particularly low at 11 Bq/kg for food-grade grain and 3.7 Bq/kg for bread. For this reason the increase of the available soil P content up to an optimal level is very important because it permits the production of food-grade wheat in cases of ^{90}Sr deposition up to 16 kBq/m^2. On soil with poor soil P status, food-grade wheat can only be permitted in cases of ^{90}Sr deposition below 11 kBq/m^2. About 80,000 ha of arable land in Belarus are contaminated with ^{90}Sr higher than 11 kBq/m^2.

For farmers in contaminated areas, it is important to be able to grow food-grade grain (instead of fodder) under the relevant PL values to maximize their income. The most economically efficient treatment was 110-60-120 kg N-P_2O_5-K_2O/ha. The profitability of fertilization has been increasing along with enhanced soil P supply, resulting in net returns of 99 and 252 €/ha, respectively, for food-grade grain produced at the 1st and 4th level of P input. Grain contaminated by ^{90}Sr above the PL and sold as fodder gave a lower net return, correspondingly, 28 and 105 €/ha. No stimulation effect on radionuclides ^{137}Cs and ^{90}Sr accumulation in wheat grain was observed due to increasing rates of N fertilizer because moderate rates (60, 90, and 110 kg/ha) were used. Moreover, the well-known biological "dilution" effect of radionuclide concentration was observed due to high wheat grain yield response to applied rates of N fertilizer.

Biofertilizer

Diazotrophic bacteria belonging to the genera *Azospirillum* has attracted much interest among agronomists and microbiologists. They were successfully used for inoculation of plants to achieve higher yields and production quality (Boddey and Dobereiner, 1995; Okon and Kapulnik, 1986; Kennedy et al., 2004).

The biofertilizer Azobacterin, containing a local strain of *Azospirillum brasilense* B-4485, was developed at the Belarusian Research Institute for Soil Science and Agrochemistry. The strain was found to possess high N_2-fixing activity, significant hormonal effect, and P solubilization activity as well. Azobacterin proved to be effective inoculant for barley, flax, and perennial grasses (Mikhailouskaya, 2006; Mikhailouskaya and Bogdevitch, 2009).

A series of experiments with the application of Azobacterin for perennial grasses inoculation were performed on Podzoluvisol loamy sand soil contaminated with radionuclides as a result of the Chernobyl accident. Our 6-year field experiments have revealed a significant yield increase of 11 to 17% as well as a reduction in radionuclide accumulation in perennial grasses (**Table 3**).

Table 3. Perennial grass yield responses to *Azospirillum brasilense* inoculation and radionuclides transfer from soil to grass (Tag value, m^2/kg x 10^{-3}).

Indices	*Bromus inermus*	*Dactylis glomerata*	*Phleum pratense*	*Festuca pratensis*
Dry matter yield (Control), t/ha	5.2	4.7	4.1	3.5
Yield response to inoculation, t/ha	0.9*	0.7*	0.7**	0.4*
LSD $_{05}$	0.39	0.43	0.4	0.35
^{137}Cs Tag (Control)	0.35	0.27	0.30	0.21
^{137}Cs Tag (Inoculated plants)	0.22	0.19	0.22	0.17
Reduction factor	1.6**	1.4**	1.3**	1.2*
^{90}Sr Tag (Control)	2.33	3.08	1.67	1.33
^{90}Sr Tag (Inoculated plants)	1.25	1.67	0.75	0.75
Reduction factor	1.9**	1.8**	2.2**	1.8**

*Responses are significant at *P < 0.05 and **P < 0.01.*

Cheap and environment-friendly biofertilizers may be accepted as an effective remediation measure. The beneficial effect of bacteria on reduction of ^{137}Cs and ^{90}Sr accumulation by a factor of 1.2 to 1.6 and 1.8 to 2.2, respectively, could be explained by a combination of the "dilution" effect due to increased yield, and also the effect of biosorption. This is supported by Russian scientists who report that bacteria of the genus *Azospirillum* are best for immobilization of ^{137}Cs and ^{90}Sr with biomass-medium distribution coefficients of 560 and 6,400, respectively (Belimov et al., 1996).

Table 4. Recommended annual doses of K fertilizer on Podzoluvisol soils contaminated with radionuclides ^{137}Cs and ^{90}Sr in Belarus.

Land	Available K_2O, mg/kg	Initial doses of K_2O, kg/ha	Additional doses of K_2O (kg/ha) according to deposition, kBq/m^2		
			^{137}Cs 37-184 ^{90}Sr 6-10	^{137}Cs 185-554 ^{90}Sr 11-73	^{137}Cs 555-1,480 ^{90}Sr 74-111
Arable land	< 80	100	50	100	150
	81-140	90	30	60	90
	141-200	80	20	40	60
	201-300	55	15	30	45
	> 300	25	-	-	-
Meadows/ pastures	< 80	80	40	80	120
	81-140	70	30	60	90
	141-200	60	20	40	60
	201-300	45	15	30	45
	> 300	20	-	-	-

Table 5. Recommended annual doses of P fertilizer on Podzoluvisol soils contaminated with radionuclides ^{137}Cs and ^{90}Sr in Belarus.

Land	Available P_2O_5, mg/kg	Initial doses of P_2O_5, kg/ha	Additional doses of P_2O_5 (kg/ha) according to deposition, kBq/m²		
			^{137}Cs 37-184 ^{90}Sr 6-10	^{137}Cs 185-554 ^{90}Sr 11-73	^{137}Cs 555-1,480 ^{90}Sr 74-111
Arable land	< 60	45	15	30	45
	61-100	40	10	20	30
	101-150	35	5	10	15
	151-250	20	-	5	10
	251-400	10	-	-	-
Meadows/ pastures	< 60	35	15	30	45
	61-100	30	10	20	30
	101-150	25	5	10	15
	151-250	10	-	5	10
	251-400	-	-	-	10

Recommendations

The K fertilizer application system in combination with NP fertilizers, manure, and liming has been elaborated on soils contaminated after the Chernobyl accident in 1992 and then improved in 2003 (BRISSA, 2003). The economically acceptable rates of potash were found to ensure the stable level of soil fertility and minimization of the radionuclide uptake in crops and pastures. The recommended fertilizer doses were differentiated for soil types, levels of soil K content, and deposition density of ^{137}Cs and ^{90}Sr. The annual K doses for typical crop rotation on Podzoluvisol soils is shown in **Table 4**. The doses of P fertilizer have been differentiated in a similar manner according to available P soil test values and deposition of radionuclides (**Table 5**).

The recommended doses of NPK fertilizers have been widely implemented on all contaminated soils because the cost of PK fertilizers for farmers are totally subsidized by the State Programme for Overcoming the Consequences of Chernobyl Catastrophe. The costs of N fertilizer for farmers are also subsidized 30 to 60% by the Ministry of Agriculture and Food and by local budgets. The soil fertility in Belarus is commonly evaluated in terms of the properties monitored every 4 years (pH value, P_2O_5, K_2O, Ca, Mg, and organic matter contents as standard practice, and also B, Cu, and Zn contents as required). The monitoring of soil fertility and recommendations for the efficient use of fertilizers are the responsibility of the Agrochemical Service under the methodical management of the Research Institute for Soil Science and Agrochemistry.

The high efficiency of countermeasures applied in Belarus is evident. The flow of ^{137}Cs to the food chain decreased by more than 12 times, ^{90}Sr up to 3 times during the post-accident period. All agriculture foodstuff that is produced in large cooperative farms satisfied the requirements of National permissible levels PL-99 for radionuclide content. On the majority of agricultural land the optimal level of soil reaction and K status is achieved and maintained.

Experimental findings were implemented in cooperative farms as well as on private farmer's fields in the course of the EC project ETHOS (1996 to 2001). This pilot project was initiated in 1996 by a team of scientists from France with the objective of directly involving the population in the management of the radiological situation (Jullien, 2005; Lochard, 2007). The inhabitants of six villages of Stolin and Slavgorod districts during 2000 to 2007 years tested developed technology for growing potatoes that included seed selection of new potato varieties, application of fertilizers and plant protection means. As a result, average potato yields increased 1.6 times from an initial 15 to 20 t/ha and radionuclide concentration declined by 20 to 30% in comparison with control plots. Every 1 € invested in the potato project provided 1.5 to 2.0 € of net return. The ETHOS approach had been highly appreciated by local farmers and authorities on the State and Local levels.

Conclusions

Soil fertility improvements through liming, manure, and NPK application are the basic remediation measures in the long-term period after the Chernobyl accident. Balanced NP fertilizers with K fertilizer rates up to 180 kg K_2O/ha are profitable for crop cultivation on soils with low and medium K content. Increasing soil K supply in Podzoluvisol loamy sand soil from 2-3 to 5-6 mmol/kg allowed a yield improvement and a reduction in radionuclide ^{137}Cs transfer from soil to crops by a factor of 1.8 to 2. Only moderate K fertilizer rates are needed for high K soils to replace the crop K removal.

The rise of available P content of soil within the wide limits of 67 to ~400 mg P_2O_5/kg has been accompanied with an increase of the spring wheat grain yield from 3.8 to 6.9 t/ha as well as decreased radionuclide accumulation for ^{137}Cs (by a factor of 1.4 to 1.9) and for ^{90}Sr (by a factor of 1.5 to 1.6). The values of ^{137}Cs and ^{90}Sr transfer from soil to spring wheat grain were in close relation with available soil P content and were well described by downward concave quadratic curves. The minimum accumulation of radionuclides in wheat grain was calculated at available P_2O_5 contents of 300 to 320 mg/kg in Podzoluvisol loamy sand soil.

Azobacterin containing N_2-fixing bacteria *Azospirillum brasilense* B-4485 may be used as an additional countermeasure. The inoculation of perennial grasses resulted in yield increase of 11 to 17% and the reduction of ^{137}Cs and ^{90}Sr accumulation in forage by factor 1.2 to 1.6 and 1.8 to 2.2, respectively.

The implementation of potato growing on private plots with modern technology as demonstrated in the ETHOS Project has a high social significance. The involvement of rural inhabitants in processes of self-rehabilitation and self-development is a way to improve people's life quality on radioactive contaminated territories as an example of common heritage. FCHH

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