Soil and Food Security

By Terry L. Roberts and John Ryan

The food we grow provides the energy, proteins, fats, vitamins, and minerals people need and the crop's ability to produce nutritious foods depends directly on the health of the soil. Food security and healthy, or fertile, productive soils are intrinsically linked. Indeed there is a close link between civilization and the quality of the soil; fertile productive soils supported flourishing societies while poor soils were—and still are—associated with poverty and underdevelopment.

In the past century, innovations in agricultural science and technology have alleviated society's concerns about the capacity of global agriculture to feed and clothe the world's burgeoning population. However, predictions that the world population is likely to increase from its current 7 billion to 9 billion, or more, by mid century have questioned whether mankind can respond to the challenges inherent in such demographic changes. Considering increased affluence in developing countries, especially for the demand for meat, world food production has to be doubled by 2050. The challenge of meeting this goal of enhanced output is all the more acute as it has to be achieved on ever-decreasing per capita availability of arable land, exacerbated by urbanization and soil degradation and greatly increased water and energy use (Lal and Stewart, 2010). Agriculture has to compete with other soil uses. Ensuring mankind's capacity to produce an adequate food supply has never been more daunting (Godfray et al., 2010). While reducing food waste, changing diets, and expanding aquaculture can help in meeting food demand, enhancing crop productivity and closing the yield gap between efficient producers and subsistence ones will be the major goal.


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Terraced soils supporting intensive rice production in Mu Cang Chai, Yen Bai, Vietnam.

Food security is more than food production at farm level; it is influenced by economic, social, political, and administrative factors that affect stability, access and safety of the world's food supply. In its simplest terms, food security implies that all people have sufficient, safe and nutritious food so they can maintain a healthy and active life. Healthy soils sustain plants, animals and humans and function as a living ecosystem maintaining a diverse community of soil organisms that not only improve crop production, but also promote the quality of our air and water environments (FAO, 2008). While healthy soils are primarily associated with good crop yields, more recent attention has been given to the nutritional quality of such yields although the economic benefit of this aspect of crop nutrition is difficult to assess.

The chemical composition of plants reflects that of the soil, where nutrients in the soil are low, concentrations of those nutrients are low or deficient in plant tissue. Conversely, where nutrients or other minerals are in excess in the soil, toxic effects can occur for humans or animals that consume such produce (Brevik and Burgess, 2012). Fertilizer use can improve nutritional quality of crops (Bruulsema et al., 2012). For example, N can increase plant protein depending on the level of application, while P fertilizers increase the P content of crop produce, and trace elements such as Zn and Se can be increased by fertilization. Before the widespread use of P fertilizers, P deficiency was widespread in animals and humans, while Zn deficiency in humans is currently widespread globally.

Because of its close relationship with crop growth, nutrients and their availability have been intensively studied. Soil fertility, or its supply of available plant nutrients, is a critical component of a healthy and productive soil. It integrates physical (i.e., texture and structure, water, and air), biological (microorganisms and organic matter) and chemical (minerals and nutrients) processes in supplying essential nutrients to plants. A productive soil is always a fertile soil, but nutrient status alone does not ensure soil productivity. Soil moisture, temperature, drainage, physical condition, soil acidity, soil salinity, biotic stresses (weeds, insects, disease), and other factors can reduce the productivity of even the most fertile soils.

While physical properties of soils are relatively stable,

Abbreviations and notes: N = nitrogen; P = phosphorus; K = potassium; S = sulfur; Ca = calcium; Mn = manganese; Se = selenium; Zn = zinc.

soil fertility is dynamic or subject to change both in time and space. Nutrients are constantly being removed from the soil in harvested plant products, being lost from the soil through leaching, erosion and other natural processes, or being tied up by soil clays and minerals. Soil organisms immobilize and then release nutrients and nutrients become imbedded in soil organic matter (SOM). Plant nutrients continuously cycle, but the system is not closed; in addition to plant removal some nutrients leak from the system, reducing their efficiency and potentially impacting the environment.

While world soil types vary in their fertility, none have unlimited capacity to sustain crop yields indefinitely. Prior to the modern era of chemical fertilization, which took hold in the middle of the last century, agricultural output and crop productivity was dependent on the native fertility involving plant-available nutrients in the soil. When nutrients are removed from the system through plant and animal products or lost through other processes, they must be replaced to maintain the fertility and productivity of the soil. If nutrient removal continuously exceeds nutrient inputs the soil becomes degraded. Soil organic matter is a vital component of healthy soils (Johnston et al., 2009); where it becomes depleted, soil structure tends to breakdown, making the soil more susceptible to erosion and eventually unable sustain a productive agricultural system. Plant nutrients must be returned to the system through mineral or organic nutrient sources, and other conservation measures must be implemented to allow the organic matter levels to build up until the soil is restored to its health and productive potential.

The advent of the chemical fertilizer age was, along with improvements in medicine, a major factor underpinning the expansion in world population since the beginning of the 20th century. Along with mechanization and improved crop varieties, fertilizers have been a main factor supporting the world's expanded crop yields. Mineral fertilizers have been the major pathway of nutrient additions to soil and have played a decisive role in humankind's access to food.

Notwithstanding the misplaced concerns in modern society—indeed outright antipathy—and reservations of environmentalists about chemical fertilizer use, the overwhelming evidence clearly shows that global food production is largely dependent on chemical fertilizer use. Indeed the late Norman Borlaug, the father of the Green Revolution, a few decades ago, stated that a world without chemical fertilizers would support no more than one sixth of the world population. Based on numerous long-term trials across the world, Stewart et al. (2005) attributed over 50% of crop yields to chemical fertilizer use; these authors suggested that dependence would even further increase with increasing crop yields in the future.

The relationship between fertilizers and food security is most clearly shown in the case of N, the dominant nutrient in terms of global use. Erisman et al. (2008) estimated that N fertilizer, made possible by the Haber-Bosch process, was responsible for feeding 48% of the world's population since 1908. While inherent soil fertility, climatic conditions, cropping systems, plant breeding, genetic modifications, and agronomic management make it difficult to quantify exactly how much of the global population is dependent on fertilizer inputs to produce food, estimates suggest 40 to 60% of the worlds' cereal production is due to fertilizers (Roberts and Tasistro, 2012). Given the disparity in fertilizer use in the developed and developing world, allied to the diversity of crops for human consumption, and the time frame being considered, such a range in response is not unexpected. Some data are pertinent to indicate the agricultural significance of fertilizers.

As N dominates commercial fertilizer use, it is relevant to examine its impact in U.S. cereal production (**Table 1**). Omitting N fertilizer reduced yields of maize, rice, barley and wheat by 16 to 41%. Fertilizer P and K and other secondary and micronutrients are equally important in ensuring crops received a balanced diet of needed elements. Organic nutrients are also important. While the relative importance of organic manures as a production factor in agriculture in developed countries has declined relative to chemical fertilizer use, the disposal of excess supplies of animal manures has posed an environmental pollution threat. However, many subsistence farmers in developing countries rely to a large extent on locally produced manures.

Table 1. Estimated effect of omitting nitrogen fertilizer on cereal yields in the USA (Stewart et al., 2005).

Crop	Estimated crop yield, t/ha Baseline yield	Without N	% reduction from no N
Maize	7.65	4.52	41
Rice	6.16	4.48	27
Barley	2.53	2.04	19
Wheat	2.15	1.81	16

Organic and mineral fertilizers are complementary; often the best yields are only achieved when inorganic and organic nutrients are applied together. Data from a 9-year field trial in India showed that highest yields were obtained when fertilizer was applied in combination with farmyard manure (**Table 2**).

Table 2. Effect of fertilizer and farmyard manure (FYM) on millet yield and yield stability over nine years in Bangalore, India (Roberts and Tasistro, 2012).

Annual treatment	Mean grain yield, t/ha	Number of years in which grain yield (t/ha) was: <2	2 to 3	3 to 4	4 to 5
Control	1.51	9	0	0	0
FYM	2.55	1	6	2	0
NPK	2.94	0	5	4	0
FYM (10 t/ha) + NPK*	3.57	0	1	5	3

*Fertilizer 50-50-25 (kg/ha N-P_2O_5-K_2O)

Together inorganic and inorganic nutrients produced grain yields of at least 3 t/ha in 8 of the 9 years of the study. This is most evident on soils where nutrient mining, or depletion of nutrients over the years (where nutrient off take greatly exceeds inputs) has degraded the soil to the point where response to mineral fertilizer is only possible if applied together with manure or other organic materials. For example, degraded soils in sub-Saharan Africa are best managed when fertilizer is used together with manure. An additional advantage of manures in such situations is that it increases SOM, and improves the physical properties of the soils (i.e., aggregation) which in turn facilitates crop growth through improved microbial status, aeration, and water relations. Rusinamhodzi et al. (2014) re-

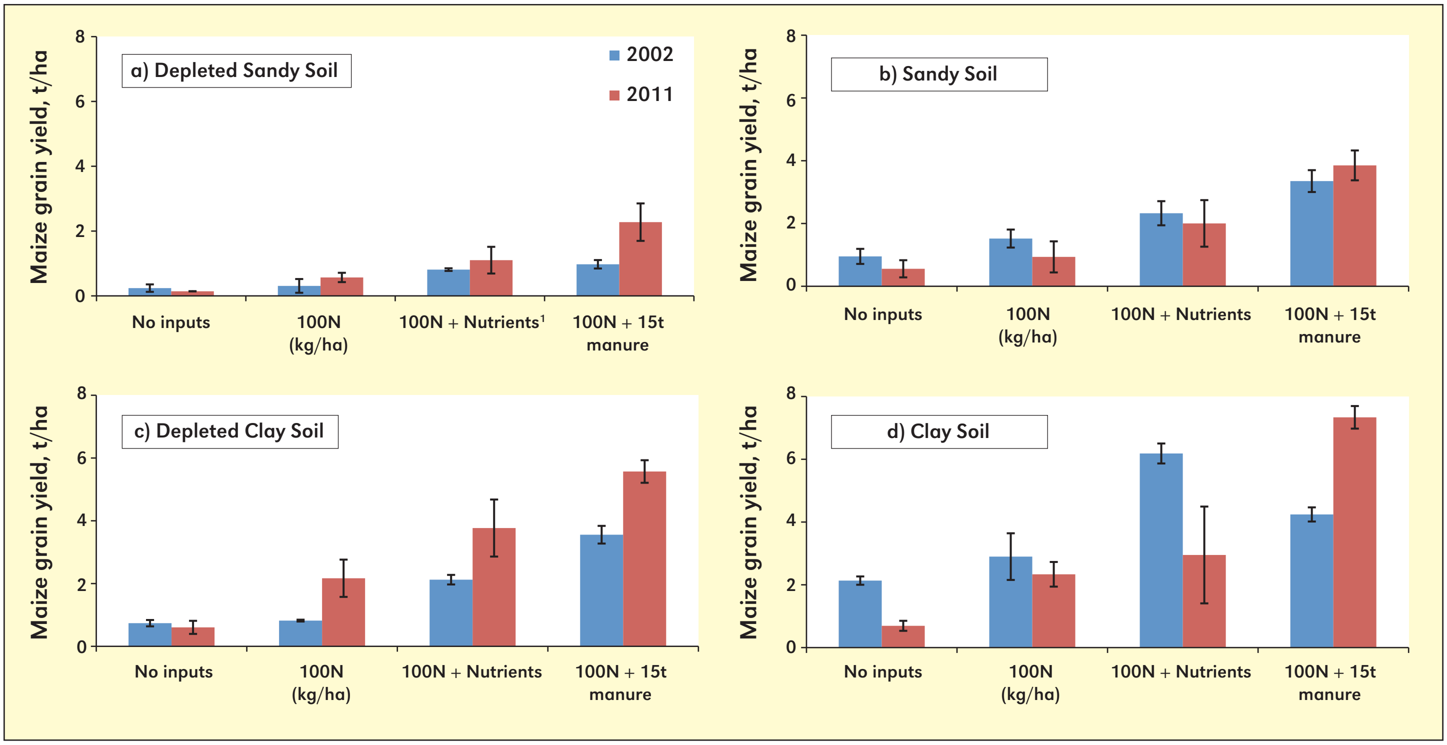

Figure 1. Initial and final maize yields and yield responses to long-term application of manure and mineral fertilizers under variable soil fertility conditions in Zimbabwe. Bars represent standard error of means. [1]Nutrients = application (kg/ha) of 30 P + 25 S + 20 Ca + 5 Mn + 5 Zn (from Rusinamhodzi et al., 2014).

ported on a 9-year study in Zimbabwe that found smallholder maize yields on nutrient-depleted soils were only marginally increased with mineral fertilizers and were decreased when N was used alone, but increased when cattle manure was used with N fertilizer (**Figure 1**). Maize response to fertilizer and manure varied with soil texture and the soil fertility status. This is but one illustration of the need to accommodate fertility management practices to the characteristics of soils that affect growth (e.g., soil depth, sub-soil layers, acidity).

While mineral fertilizer use, especially N, increases crop growth, some would argue its long-term use harms the biology of the soil and reduces the soil's capacity to make native nutrients available to plants. There is no basis for this popular misconception, as refuted by two extensive field studies. A recent meta-analysis of 64 long-term crop fertilization trials from 107 datasets from around the world found that the use of N fertilizer increased microbial biomass by 15% and soil organic carbon by 13% (Geisseler and Scow, 2014). A location-specific multi-year rotation trial that assessed various agronomic factors at a semi-arid site in northern Syria, characterized by relatively low SOM, showed that overall soil carbon levels consistently increased with increasing fertilizer N and P application rates (Ryan et al., 2008). Such studies also show that the particular crops in the rotation and the type of tillage condition influence the effects of N on soil quality components (i.e., conventional or minimum or no-tillage systems).

In summary, modern agriculture is related to soil quality and is dependent to varying extents on the use of chemical fertilizers; they support today's high crop yields and thus ensure food security for the world's burgeoning population. Fertilizers can also contribute to improving the biological and physical quality of soils and thus influence the environment through carbon sequestration resulting from enhanced root growth. A secondary benefit of fertilizer use is an indirect contribution to improved human and animal nutrition through nutrient enrichment in crop produce. The key to maximizing the productive potential of soils and exploiting the direct and indirect beneficial effects of fertilizers, while minimizing potentially harmful environmental effects, is the adoption of scientifically proven best management practices. BC

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