

# Soil Management for Sustainable Intensification: Some Guidelines

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One of the fundamental lessons learned through the past half century of agricultural research is that there are no “one size fits all” best management practices. The interaction of different soils with different cultures in different climates results in the need for unique approaches to sustainable agricultural systems in each situation. The transition to systems that are both sustainable and sufficiently intense to support the increasing density of human population will be faster or slower depending on the resources available. The ease of this transition will also depend on how far down the road to resource degradation and unsustainable intensification a particular system has already gone. Although there are no easy short cuts to this transition, we can avoid the mistakes of the past and build on experiences with successful systems. This paper focuses on certain principles of soil management that have wide, although not universal, applicability and can help guide the transition to sustainability.

Major goals that need to be addressed by soil management approaches include: 1) conservation and efficient use of water resources, 2) prevention of erosion and soil degradation, and 3) enhancement of nutrient cycling. If we examine sustainable approaches to meeting these goals, we will see that there is a common thread involving the management of soil organic matter. During the past half-century agriculturalists allowed the immediate effectiveness of modern agricultural inputs such as fertilizers and pesticides to somewhat divert their attention from the need to manage soil organic matter. More recent experience and research have brought us back to the realization, shared by earlier generations, that soil organic matter management is a key factor in achieving successful long-term sustainability.

## **Renewed recognition of the importance of soil organic matter.**

Contrary to the belief of many, the role of soil organic matter becomes more, not less, important as the environment becomes more harsh and less forgiving. That is, in semi-arid environments, on steep terrain, and in areas where organic matter is inherently in low supply, it becomes ever more critical to properly manage and maximize the small amounts attainable.

I am reminded of the experience of a professor who, in the mid 1980s was preparing for a sabbatical

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Presented to The World Bank Rural Week Program on Sustainable Intensification, Washington D.C., 2 April, 1999;

Published as: Weil, R.R. 2001. Soil management for sustainable intensification: some guidelines., p. 145-154, In W. Payne, et al., eds. Sustainability of Agricultural Systems in Transition. ASA Special Publication No. 64. American Society of Agronomy, Madison, Wisc.

year at a University in southern Africa. He contacted the head of the department in which he was to work as a Visiting Scholar and discussed his plans to study the organic forms of phosphorus in the local soils and the microbial processes by which this P could be made available to crops. The Department Head, an experienced pedologist, laughed at the idea, suggesting that the visiting professor would be wasting his time in such a study, since although the soils were indeed low in phosphorus, they were also so low in organic matter (only 1 or 2 %) that there was not enough organic matter to be of much importance in crop production. The visitor persevered in his study and subsequently showed that mineralization of organic forms of phosphorus was the main mechanism by which phosphorus became available to crop plants in the highly weathered soils of the region.

### **Some General Guidelines for Sustainable Soil Management.**

While the specifics vary from site to site, some general principles apply to sustainable soil management over a wide range of situations. The guidelines outlined here derive from several decades of research and farmer experience in managing soils for sustainable agriculture.

#### **1. Keep the Soil Covered and Minimize Tillage.**

Maintaining soil cover is truly a win-win proposition. Continuous (or as nearly continuous as possible) close-growing living vegetation or a mulch of dead vegetative material on the soil surface achieves the dual goals of reducing off-site negative environmental impacts and enhancing on-site soil quality and productivity. Practices that help maintain a living vegetative cover throughout the year include managed fallows, inter crops, relay crops, crop rotations, perennial vegetation and various agroforestry schemes. The use of mulches whether grown in place or cut-and-carried and careful management of crop residues can enhance and complement live vegetation in keeping the soil covered.

Covering bare soils with either mulch or living plants dramatically increases the amount of rainwater that enters the soil to become available for crop growth and decreases the amount of water that runs off the soil surface causing floods and erosion. Continuous vegetative and residue cover can maintain soil quality and nearly eliminate erosion losses, even from very steep terrain. Of course, maintaining this cover becomes more challenging as the environment becomes more difficult, especially where hot dry conditions limit plant biomass production even as they speed the oxidation of what organic matter that is produced. Fortunately, complete coverage of the soil is not necessary; even a modest amount of soil cover (10 to 30%) will give substantial improvements in water conservation, soil quality and, especially, erosion control.

As it is a major mechanism for destroying soil cover, tillage should generally be kept to a minimum. If the soil must be tilled, then tillage practices chosen should allow upwards of 30% of the soil surface to remain covered by plant residues. Tillage not only destroys surface cover, it also adversely affects the maintenance of soil organic matter because it stimulates the breakdown of soil structure and the oxidation of soil carbon. In addition, tillage is very costly in terms of both time and energy. Maintenance of soil cover and avoidance of the physical disturbance associated with tillage also promotes biological activity in the soil and, hence, the development of a biologically based soil structure. These factors allow natural processes to achieve many of the functional goals for which

tillage was originally designed. Therefore, it is not surprising that in some situations the best long-term results are found when no-tillage systems are used either with or without chemical weed control. However, in certain circumstances, such as preparation of rice paddies and the cultivation of poorly drained soils in cool regions, no-tillage is not advantageous.

Earthworm burrows, old root channels, shrinkage cracks in clay soils, and other macro structure features are promoted and made more functional by the absence of tillage near the soil surface. No-tillage and continuous soil cover does not necessarily require high capitalization and industrial inputs. Examples from the Cerrado of Brazil with soybeans and maize and from central India with wheat show that relatively simple modifications of inexpensive animal drawn or hand operated implements can make no-tillage systems work for smallholder farmers.

## **2. Seek Out and Utilize Indigenous Nutrient Resources.**

The lack of mineral nutrients in sufficient amounts, when and where needed, limits the productivity of both crop and animal agriculture in most settings. Nitrogen limits productivity almost everywhere while deficiencies of phosphorus, potassium, sulfur and micronutrients are significant problems in more limited areas. Although often overlooked or underutilized, the nutrients needed to increase productivity in many cases exist indigenously at the village, landscape, regional or national level. Indigenous nutrient sources may include native plants, hedgerows, waste products, local mineral deposits, nutrient accumulations in deep soil horizons, and opportunities to recycle crop and animal residues. The advantages of using nutrients from sources indigenous to a system include the low transport costs and infrastructure needs, and the possibility for stimulating local economy with jobs capital. Some indigenous nutrient sources also are associated with the benefits of organic materials. The challenge is to be imaginative and observant enough to find the sources that may have been overlooked.

An example of an often underutilized indigenous nutrient source is the ash left behind by Africa=s countless cooking fires. Whether it comes from community woodlots, native trees or agroforestry systems, fuel wood is principle source of energy for cooking and heating in sub-Saharan Africa. The per capita fuel wood use in sub-Saharan Africa is 7,000 mega Joules per year (World Resources Institute, 1997). In some countries (e.g. Tanzania and Malawi) per capita fuel wood consumption is closer to 14,000 MJ per year. Most of this wood is burned in the inefficient open cooking fires typical of African villages. These fires produce food flavored by smoky fragrances, as well as warmth and light to sit around in the evening. They also require countless hours of labor by the women of the village to cut and carry (often for many kilometers) the wood that will be used. By early morning, when the fire has burned out, the women of the village can be seen sweeping the grounds clean, often sweeping the now cool ashes just beyond the living compound. Some ashes may be used in the pit latrine. Only in rare cases will villagers carefully collect the ashes from the cooking fires, store them in a covered urn to protect them from rain, and then later carry them far from the home to the fields that are most lacking in fertility, and finally spread them evenly over those fields where they can do the most good.

How significant a nutrient resource is this ash left by cooking fires? The 7,000 MJ of energy that the

average African releases each year in cooking fires represents approximately 550 kg of dry wood. The amount of cropland available per capita in sub-Saharan Africa is approximately 0.25 hectares. Thus for each hectare of cropland there are approximately four people burning approximately 2,200 kg (4 x 550) of dry wood per year. Depending somewhat on the tree species, this mass wood will produce ashes containing approximately 25 to 30 kg of calcium, 8 kg of magnesium, 8 kg of potassium, 2 kg of phosphorus, and small but significant quantities of sulfur and micronutrients. If collected, protected from rain and spread where most needed, these ashes could supply sufficient nutrients reverse or arrest the acidification process and in replace nutrients removed by crop harvest and leaching on approximately 25% of the cropland each year. The careful use of ash could produce substantial yield gains and preserve soil quality, especially if sources of nitrogen and additional phosphorus can be found. In this example, the nutrients are additions to the particular fields where applied, but they do not represent additions to the landscape. Rather, the use of ash represents a transfer of nutrients to the croplands from woodlots, hedges and areas of native vegetation.

### **3. Recognize and Take Advantage of Variability in Soil Properties.**

It is often said that soils are like people; each soil is different from the other. As with people, the differences between soils occur among different nations, among regions within a nation, or even within the same village. During the past half century, much research has focused on large-scale regional soil variations. The differences between sandy Alfisols of the Sahel region and low activity clay Ultisols and Oxisols of the wetter regions have been well documented. Such large-scale differences have been addressed by developing appropriately different systems of management and fertilization. Much less attention has been paid to soil variation on the local scale, such as within a field or within a village. Farmers themselves are usually very much aware of this local soil variation. In some cases, farmers have named the various types of soils and have developed considerable body of knowledge about how the different types of soil may best be handled.

Nonetheless, it is a very common sight both on large-scale farms and on small village plots to see marked differences in soils ignored in the implementation of the local cropping system. Neat rows of young maize, beans or millet may run across several types of soils on which the crop yield potential differs several-fold within a distance of just a few meters. Such small-scale soil variability is especially common in steeply sloping landscapes or where depth to bedrock is shallow.

The unproductive patches, be they 1 hectare or 0.001 hectare, may produce almost nothing. The labor and other inputs devoted to row crop culture on these soils might be better applied to intensification of crop production on the more productive parts of the farmer=s land. The unproductive patches might be put to other uses such as growing trees for firewood and fruit, or growing forage grasses for goats and cattle. Such low-intensity uses would improve the low-productivity soils while still providing output of some value. Detailed attention to soil variability, and adaptation of farming systems to this variability, should pay large dividends to the individual farmer while increasing the overall productivity of the landscape over time.

Although such small scale spatial variability of soils has been well documented, little research attention has been applied to the question of how to adapt farming systems to best take advantage of

the variable soil conditions. To some extent high tech "precision farming" in large-scale industrialized farms is a response to the same issue of customizing management practices to utilize information on soil variability. For smallholder farmers in developing countries, specific farmer-participatory research will be needed to develop and evaluate low tech, accessible land management options for each case.

#### **4. Utilize Diverse Plants, Especially Legumes in Cropping Systems.**

Plant diversity in cropping systems offers many advantages to the farmer and to the landscape ecosystem. The advantages to the farmer include spreading market risks, increasing income opportunities, improving dietary balance, spreading labor requirements more evenly throughout the year, enhancing soil quality, improving nutrient cycling and decreasing risk from pests and adverse environment factors such as drought. There is also evidence that using a diversity of crops can improve the effectiveness of mycorrhizal (fungal root symbioses) associations in a cropping system.

Biodiversity within the farming system can be achieved through intercrops (growing two or more crop species simultaneously on the same land), crop rotations (growing different crops sequentially on the same land) and relay crops (growing different crops partially overlapping growing seasons). Perennial woody vegetation can add to plant diversity in the agroecosystem in the form of hedgerows along field borders or alleyways within field. Woody perennials can also add diversity to crop rotations by such practices as planting fast-growing trees as off-season cover crops or longer periods of managed fallows.

Plants of the legume family have a special role to play in achieving the advantages of biodiversity. Many legumes, both annual and perennial, are capable of utilizing or "fixing" atmospheric nitrogen for their growth. Legume tissues are, therefore, typically much richer in nitrogen than tissues of non-legume plants. Thus, legumes may enrich the soil with nitrogen to the benefit of subsequent plantings of non-leguminous crops. Since naturally occurring supplies of soil nitrogen are almost universally insufficient for optimal growth most crops, the inclusion of legumes in the farming system can go a long way to overcome fertility limitations to crop production.

If maximum soil fertility benefits are to be obtained by non-legume crops, legumes should occupy farmlands from one third to one half of the time. . However, existing markets for the harvested product of legume crops (such as beans, soybeans, peanuts, pigeon peas, or forages) may not justify putting legumes on such a large share of the total cultivated land. Other ways of increasing the presence of legumes can be sought. Alley cropping and the use of woody species in hedgerows to provide high nitrogen organic soil amendments is one solution for increasing the presence of legumes in the farming system.

Many decades of research in all environments around the world have shown that appropriate cropping systems with legumes can effectively supply nitrogen for high yields of cereal crops. One limitation to the role of legumes in supplying nitrogen is the use by the legumes of stored soil moisture that might be needed by the non-legume crops. Another limitation is the proportion of the land resource that may be needed over time. Conventional economic analysis of the use of legumes

in cropping systems often credits the legume only with the value of the nitrogen fertilizer it can replace. It should be remembered, however, that the value of using legumes to replace inorganic nitrogen fertilizer includes many accessory benefits that are derived from the effects of the organic matter and biological stimulation associated with legumes and crop bio-diversity.

On the other hand, it should be noted that not all legume crops enrich the soil in nitrogen to an extent that will benefit associated non-legume crops. For example, most common bean plants (*Phaseolus vulgaris*) do not fix enough atmospheric nitrogen even for their own needs. Harvest of the protein-rich bean seed may remove more nitrogen from the system than was fixed from the atmosphere, leaving additional nitrogen for succeeding crops. Nonetheless, even these less efficient nitrogen-fixing legumes can be thought of as nitrogen savers (as compared to non-legume species), if not nitrogen builders.

Also, legumes can contribute only nitrogen and not other nutrients. This is true even though some legume plants, especially woody perennials, are capable of recycling sulfur, phosphorus, potassium, calcium and other nutrients from deep in the soil profile. They convert the inorganic nutrients they take up into organic plant tissue, which will re-enter the organic decomposition cycles that can then feed successive crops. Thus, the legumes in a rotation may conserve some other nutrients as well as contribute nitrogen.

The legumes plants themselves have a high demand for certain nutrients and their capacity to fix atmospheric nitrogen is quite dependent on the supply of other mineral nutrients in the soil. This is especially the case with regard to phosphorus, potassium and molybdenum. In areas of volcanic or highly weathered soils, such as the humid parts of Africa and Central America, phosphorus deficiency may be pronounced. In these soils, most legumes will not grow vigorously, nor will they be effective in nitrogen fixation without the addition of available forms of phosphorus. In these areas, additions of available phosphorus can be leveraged to produce additional nitrogen, and can be considered a prerequisite for the establishment of efficient cropping systems. Because of the unique ability of some legumes (e.g. Pigeon pea) to use phosphorus in certain low-solubility forms, it may be most efficient to add phosphorus to the farming system via the legume component, especially where low solubility sources of phosphorus are being considered. The resulting abundance of high-quality, easily decomposable plant residues can provide readily available nutrients to succeeding crops.

## **5. Integrate Livestock Into the Farming System As Far As Possible.**

Integration of livestock into both industrial monocultures and many traditional smallholder-farming systems would improve overall efficiency and sustainability. Livestock integration may include such practices as 1) animal traction for timelier planting and farming operations, 2) collection and conservation of animal manure for use as a soil fertility amendment, 3) use of cattle to economically justify the inclusion of soil-improving grazing land and forage crops in the farming system. Sometimes effective livestock integration is simply a matter of collecting manure, protecting it from the elements and then spreading it on the fields, which are most in need of the nutrients in the manure (rather than on the fields closest to the source of manure). An effective (and in some places, traditional) practice for spreading manure with minimal effort is herding or fencing livestock on

cropland after harvest to graze down the plant residues. These kinds of livestock integration practices do not necessarily require that the owner of the cropland and the owner of the livestock be the same.

Certain land tenure arrangements and livestock herding practices may hamper livestock integration. Opportunities for improvement are particularly great, although also especially challenging, where migrations or other disruptions have caused major changes in traditional agricultural systems. For example, when traditionally nomadic herders have become sedentary livestock and crop farmers, they may not fully recognize the value of manure for croplands. Likewise, where grazing lands are communally utilized, the tendency is to deplete the resource by over-grazing. Structural changes in the rules that govern communal grazing may be needed to encourage improved management of the grazing resource. These difficult issues must be addressed in a community participatory manner.

## **6. Use Fertilizers To Enhance Soil Nutrient Capital and Jump-Start Integrated Farming Systems.**

In many areas indigenous nutrient sources, legume-centered cropping systems, and integration of livestock can greatly increase the productivity of farming systems without the need to import fertility inputs from outside the local landscape. In other areas, however, the availability of one or more nutrients may be so limiting in the ecosystem as to preclude establishment of these measures. In such cases it will be necessary to use outside sources of nutrients, such as manufactured fertilizers, to raise the level of soil fertility to the point where kinds of practices just discuss under points 1-5 can be successfully carried out and make vigorous contributions to the farming systems.

Where the soils are naturally very low in one (or more) nutrient, all components of the eco-system are likely to be low in that nutrient. For instance, in severely phosphorus deficient areas, not only are the soils low in available phosphorus, but so are the plants used as forage by cattle. As a result, cattle health and growth may be limited by phosphorus and the manure emanating from the cattle may be too low in phosphorus to be an inadequate nutrient source for other parts of the cropping system. In such a case, the addition of phosphorus from the outside will increase the productivity and the opportunities for recycling through out the landscape.

Once the necessary nutrient(s) have been applied to raise soil fertility levels to non-limiting values, steps can be taken to tightly recycle these nutrients so that losses are limited primarily to harvested produce sold outside the landscape in which recycling measures can be effective. Therefore, the marketing of agricultural products in distant cities may require continued inputs of fertilizers to offset nutrient losses. However, in many soils, especially those in regions of moderate rainfall, have the capacity to release additional nutrients from the weathering of soil minerals in various horizons. Therefore, only a portion of the exported nutrient stock need be replaced on a continuing basis. In industrialized nations, failure to recognize this fact early on has led to inefficient over-fertilization, excessive nutrient build-up, and subsequent problems of aquatic eutrophication. In other areas, especially on old landscapes in humid regions where the supply of weatherable minerals is very limited, continued nutrient imports will be necessary to balance the off-take of nutrients in harvested crops.

The value of inorganic fertilizers in enhancing crop production has been proven beyond a doubt and is well recognized by farmers throughout the world. Very few areas remain where educational efforts are needed to convince farmers of the effectiveness of fertilizer materials. Rather most farmers desire financial and logistical assistance in obtaining the fertilizers, which they know, can increase their crop yield. The high cost of fertilizer relative to the market price of agricultural products, still hampers appropriate levels of fertilizer use in some areas.

A major lesson gleaned from the experience of the past half-century is that neither purely organic matter management nor purely inorganic fertilizer application will provide long-term high-yield sustainable results on low fertility soils. Rather, building soil fertility requires the combined use of inorganic nutrients where and when needed, and the proper management of all the organic matter resources available in the landscape.

In the drier, semi-arid regions farmers tend to approach fertilizer use with caution. They recognize the risk that fertilizers, especially those containing nitrogen, may stimulate excessive crop growth early in the season leading to rapid depletion of stored soil water and subsequent crop failure. Returns to investment in fertilizer are highly dependent on good soil moisture availability. Without appropriate soil organic matter management, fertilizer use may be especially risky. The careful husbanding of crop residues and other organic amendments has been shown to act synergistically in conjunction with the use of modest fertilizer inputs to produce relatively high yields and low risk of failure.

Getting the proper type of fertilizer to the proper area at the proper time remains a major problem in many developing countries. Many developing countries are still using blanket recommendations for fertilizer on a national basis. Yet most countries have distinct soil regions in which one or another nutrient is likely to be limiting while other nutrients may be found in adequate amounts. In most countries, significant economic response to the phosphorus or potassium is still more the exception than the rule, thus purchase of these nutrients may be a waste of money for many farmers where such mixed fertilizers are being distributed. On the other hand, performance of nitrogen fertilizers in some areas is limited by lack of sulfur, a nutrient only that may not be widely available in fertilizers. Soil testing programs are used in developed countries to ensure greater site-specific accuracy in fertilizer use, but sampling and testing individual smallholder fields in developing countries is uneconomic and therefore rarely practiced. Possible alternative measures include the mapping of nutrient availability at regional and village scales based on surveys of crop and soil nutrient status. Such programs are needed to help farmers and fertilizer distributors know what type of fertilizers is likely to be truly profitable. On-farm experiments and validation trials can be useful to individual farmers, but most farmers will not be able to afford to experiment with different fertilizers to see which gives the best response. Thus these trials, as well as regional surveys, must remain a function of the public sector or become a community responsibility through appropriate NGOs.

Finally, it is important to avoid some of the mistakes that occurred in both developing and industrialized countries as fertilizers became inexpensive and widely used. Fertilizers often produced such a dramatic response in crops, and required so little labor to use, that farmers and

policy makers tended to forget about the more management- and labor-intensive organic matter management practices of the past they had relied upon in the past. In industrial countries rotations, legumes, livestock manure husbandry and other types of nutrient cycling were largely abandoned in the 1960's, 70's and 80's when fertilizer seemed to solve all soil fertility problems.

Similarly, farmers in Africa and other developing regions soon abandoned the traditions of composting, manure collection, rotations and agroforestry because these laborious practices seemed irrelevant where fertilizers were subsidized and widely used. The complaint, often voiced by African farmers, that "urea burns up and ruins my soil" can usually be ascribed to the fact that with the advent of relatively inexpensive fertilizers farmers abandoned the organic matter management practices which had previously been needed to supply nitrogen. The adverse effects on soil quality that fertilizer-using farmers now observe are not due directly to their modest use of urea fertilizer, but rather to the use of fertilizer as a replacement for good organic matter management.

## **7. Build On Indigenous Farmer Knowledge and Sound Ecological Principles to Develop Farming Systems - Don't Expect the Future to Look Like the Past.**

As we work toward developing intensive, yet sustainable agricultural systems for the future, we must avoid the trap of thinking we can transfer systems that seem efficient in the developed industrialized world to various situations in other parts of the world. Many agricultural systems currently in vogue in the industrial world have their own problems regarding sustainability and adverse environmental and social impacts. Little is gained if the developed world exports its serious environmental and sustainability problems to developing countries that are seeking a more sustainable way forward.

Promoting farming systems in the context of indigenous farmer knowledge is important for at least two reasons. First, where communities have a long history of agricultural settlement in an area, the people intimately involved with producing food from the land have gradually built up valuable knowledge about what will work and what will not. Indigenous people know a great deal about variations in climate, the capacities of their soils, and local markets. Traditionally, farmers have also often developed land races of crops that are well adapted to the demands of the local environment.

Second, it is important to fully utilize indigenous knowledge in order to give farmers a stake in changes that need to be made. If people see themselves as having ownership in the new systems, they will work to make them functional. One of the major lessons of twentieth century agricultural development is that the top-down importation of farming system models can only be made to work as long as farmers are bribed or forced to comply with the new system. If farmers do not feel ownership of the system and see both long and short-term benefits in the system, they will abandon it as soon as subsidies or penalties are lifted. Incidentally, this lesson and the resulting farmer-centered, integrated farming systems research, is one of the areas in which agriculturalists in industrialized nations have learned from the work of developing countries. Sustainable intensification of agricultural production will depend on how well we all take such lessons to heart and built upon what we have learned.