MANAGEMENT OPTIONS TO INCREASE SOIL ORGANIC MATTER AND NITROGEN AVAILABILITY IN CULTIVATED DRYLANDS

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Abstract

Cropping of dryland soils in marginal regions with an emphasis on economic rather than ecological sustainability has generally led to decline in soil organic matter reserves and hence nutrient availability. Outputs commonly exceed inputs, with degradation of soil structure, reduction in infiltration and increase in runoff. Biological productivity is severely affected, leading to a vicious cycle of events usually culminating in decreased N release, excessive soil loss and ultimately desertification. Reducing the incidence of bare fallow, increasing crop-residue retention, strategic N-fertilizer application and shifting to cereal-legume rotations (as opposed to monocultures) and intercropping can slow the spiral. Simulation models such as DSSAT and SOCRATES provide suitable and easy-to-use platforms to evaluate these management strategies in terms of soil organic matter accumulation and yield performance. Through the linkage of these models to global information systems and the use of spatial-characterization software to identify zones of similarity, it is now possible to examine the transportability and risk of a particular management strategy under a wide range of climatic and soil conditions.

1. INTRODUCTION

The abundance and formation of soil organic matter in dryland agro-ecosystems has, within the last decade, assumed increasing importance within the context of crop production and resource sustainability, and the impact thereupon of global climate change and shifting rainfall patterns. Enhancing native soil fertility in the cropping systems of the major semi-arid regions of the developing world, such as sub-Saharan Africa, have come under the closest scrutiny, as population and production costs (particularly fertilizers) increase. The area of rainfed croplands has been estimated as 457 M ha, which is approximately 10% of the world's total dryland area as classified by UNEP in 1992. Of this area, nearly half is listed as degraded to some extent, with an additional 4 M ha being lost each year, the result either of erosion or urbanization.

There are essentially two approaches to managing soil fertility: by application of fertilizers and by manipulating biological processes to optimize nutrient availability [1]. The latter minimizes the use of external purchased inputs while maximizing organic inputs; it is the more complex approach, but can lead to a more readily sustainable, self-perpetuating system because it relies on the gradual transformation of organics to inorganics, as opposed to the immediate availability of chemical-based nutrients. The chemical fertilizer approach has the greater potential for inefficiency and loss of inorganic N from the system, critical factors in low-input cropping systems of the semi-arid regions.

Abiotic influences on soil organic matter dynamics, such as moisture, temperature, aeration and composition of plant residues are reasonably well understood [2]. However, in rainfed arid and semi-arid environments, superimposed on these properties and processes is the fact that most soils are deficient in both N and P, as a direct result of inputs not meeting outputs, reduced ground cover and increased losses of nutrients by erosion. This cycle of events is difficult to reverse without a dynamic and informed management approach (as opposed to decisions made haphazardly or for historical reasons).

Further complicating these issues is the fact that farm holdings in the developing regions are small and rely on family resources. Although many resource-management options are potentially available, few are actually accessible to farmers. Human labour and some animal traction are used to prepare lands, incomes are low, with production barely subsistent at the best of times, hence little or no money is available for external inputs such as fertilizers, and chemicals for weed and disease management. Blanket recommendations are also usually made that ignore climatic variation in the areas farmed by small-holders. For example, of 32% of farmers in Zimbabwe who followed fertilizer recommendations for the 1990-91 maize crop, nearly half failed to recover the outlay costs [3].

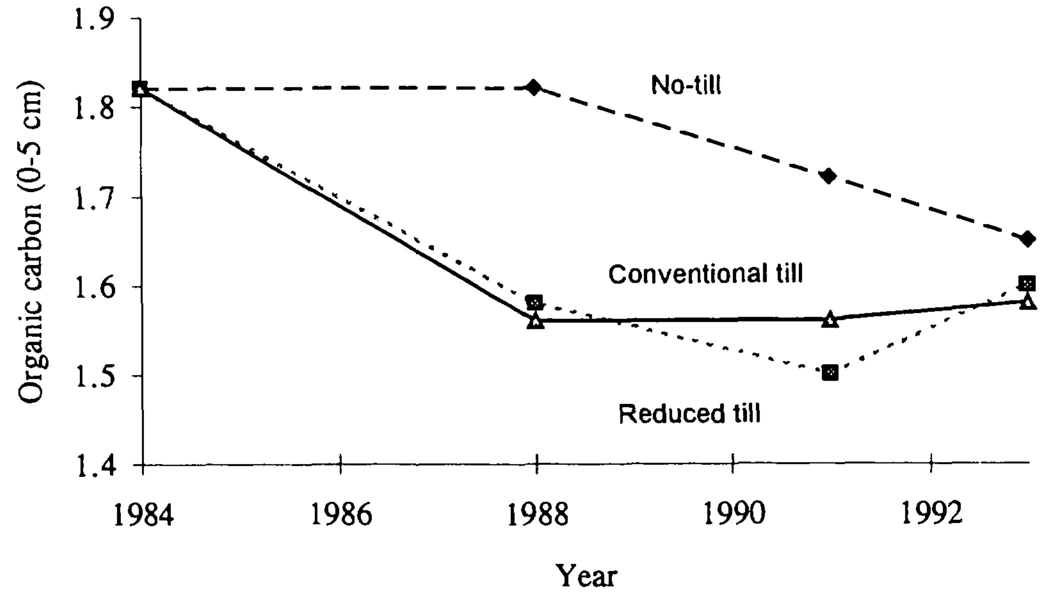

FIG. 1. Soil organic C (0-5 cm) in a wheat-lupin rotation on a sandy loam at Kapunda, south Australia.

Also, many of the solutions for increasing production, which have been generated in countries where mechanization is widely available and farms are much larger with suitable monetary return (e.g. USA and Australia), may not be directly applicable in the non-commercial holdings of semi-arid Africa, Asia, and South and Central America. However, the lessons learned from the impact of some technologies, particularly reduced and no-tillage, residue retention, rotation management, strategic N applications and intercropping, in combination with simulation techniques, can be valuable in providing site-specific management options.

2. MANAGEMENT OPTIONS

2.1. Tillage and residue retention

Reduced-tillage and no-till management practices tend to concentrate crop residues and associated micro-organisms in the surface layer [4], resulting in distinct profile stratification that may greatly improve surface-soil aggregation, increasing infiltration rates and water-use efficiency, critical factors in dryland cropping. Reduced and no-tillage systems also tend to have slower rates of organic-matter degradation compared to conventionally tilled systems [5,6,7]; however, this is not always the case in drylands, where increases in soil organic C in no-till systems may be transient [8] (Fig. 1). There was no conclusive evidence of yield benefit in no-till systems in a detailed survey of twenty-eight long-term cropping trials in the semi-arid regions of Australia [9]. This would suggest that the improvement in aggregate stability and infiltration associated with no tillage after a number of years produces a more favourable environment for microbiological activity in the longer term, causing increases in the rate of decomposition of organic matter and release of simple C substrates that have been linked to increased incidence of root pathogens.

Because crop-residue amounts from semi-arid monocultures are typically low (0.5-5 t ha^{-1}), there is little opportunity for long-term increases in soil organic matter (and subsequent benefits in fertility and water storage). As livestock plays an integral role in many African cropping systems, most crop residues are used as feed. The traditional practice of fallowing (i.e. set asides with volunteer growth) used in semi-arid east Africa to replenish soil fertility is rapidly decreasing due to limited availability of land [10]. Also, in many cases, this practice, which resembles bare fallowing, reduces the risk of crop failure through water stress and increases yield-residue production to meet both livestock and management needs, and the increase in water availability significantly hastens organic-matter degradation. However, the advantages are short term, and it is ultimately self-destructive in terms of sustainable crop production.

The quality as well as the quantity of the residual material has a significant affect on the potential for soils to accumulate organic matter. Improved short fallowing, with the use of annual legumes such as *Sesbania sesban* as organic manure, has been found to increase maize yields three-fold in Zambia [11]. Synchronizing the release of nutrients (e.g. through the use of slow-release organic manures) can also increase N-cycling efficiency [12]. Green manures were heavily researched in Zimbabwe in the 1920s [13], and, until fertilizer prices fell in the 1950s, green manuring was widely practiced by commercial farmers. The rising cost of fertilizers and concern over the sustainability of current cropping systems in east Africa have resulted in a resurgence in the use of this option on small-holdings. The attractiveness of green manures in terms of N-use efficiency is clearly demonstrated in a Tanzanian study where a sunnhemp (*Crotalaria*) green manure was found to be four times more effective than inorganic fertilizers [14].

Evaluation studies of velvet bean (*Mucuna*), sunnhemp and fish bean (*Tephrosia*) productivity in Zimbabwe and Malawi [15] indicate that biomass accumulation is highly dependent on initial soil fertility. Velvet bean appeared to be the most promising candidate as a green manure in these semi-arid regions, provided additional P was applied to the poorer soils. Farmers in central America have successfully used velvet bean for decades [16], and promising results in east Africa are similar to those being found in the high rainfall tropics of Veracruz in Mexico [17]. Little information is available, however, on N cycling and water availability in these systems; for example, is removal of soil water during the green-manure phase sufficiently offset by N credits to the following maize? Such questions can be addressed through the use of nuclear techniques.

2.2. Rotation management

Crop selection in the rotation sequence has a direct impact on residue production and organic matter storage in subsequent years, particularly the N benefit of including grain legumes or the impact of "break" crops such as *Brassica* spp. to control cereal-root diseases [18]. In semi-arid areas of Australia, legume-dominant pastures (*Medicago* spp.) still play a significant role in crop production. Increases in soil organic C were reported for wheat rotations that included 2-4 years of annual sown pasture [19] with associated increases in improvements in soil structure [20,21] and water-holding capacity.

Annual pastures also contribute a large amount of C in root production. As a proportion of C in above-ground production, input below ground may range from 0.40 to 0.97 [22], with subsequent rapid increases in native soil organic matter levels. The residual N made available may boost dry-matter production of subsequent crops. In contrast, immobilization of mineral N accompanying the decomposition of grass-dominant pastures may lead to a reduction in crop production. Grass-dominant pastures also tend to provide suitable hosts for pathogens, e.g. *Gaeumannomyces graminis* pv. *tritici*, that may affect the roots of subsequent crops [23].

Because of the necessity for small-scale food production, annual pastures are not really a viable option in semi-arid regions of the developing world. On large holdings, the potential exists for taking some fields out of food production for periods of 1-2 years, but such luxury is absent in communal farming. Most small-holders in east Africa do practise some form of crop rotation, whether it be maize-groundnut-cotton-soybean or maize-groundnut-sunflower-soybean [24]. The amount of N returned depends on whether the legume is harvested for seed, used for forage, or incorporated as a green manure. Soybean generally sequesters more N in its seed than it contributes to the cropping rotation, even when all stover is incorporated [25]. This may not be the case, though, with locally adapted varieties that are usually leafier and have a lower N-harvest index compared to more highly bred genotypes. In Malawi, N credits of up to 110 kg ha^{-1} from pigeon pea with a 2.8 t ha^{-1} yield advantage in the following maize crop have been reported [26]. Nitrogen-15 natural-abundance techniques can be used to gain a better understanding of the site-specific cycling of N in these rotations, and the potential for wider adoption.

2.3. Fertilizer application

Water use in nutrient-deficient plants is similar to that of nutritionally balanced plants [27], however the precursor to this is sufficient moisture to actually produce a healthy plant. The majority of semi-arid cropping systems are characterized by erratic rainfall, in terms of both intensity and amount. Soils are usually poorly developed due to inherently low organic-matter levels, and subject to degradation and structural decline. In many cases there is either too little or too much rain for the soils to efficiently deal with. Thus, fertilizer-use efficiency in crops of these regions is usually less than 25% and highly inconsistent. Small-holders in Malawi and Zambia using current recommendations can expect 9.5-16 kg of maize per kg of nutrient for local varieties with 17-19 kg for hybrids [28], which is essentially half the fertilizer-use efficiency of crops in tropical west Africa [29]. Such poor return, combined with the fact that fertilizer costs are prohibitive, make inorganic fertilizers an extremely risky option for both yield and biomass production.

Strategic application of fertilizers may improve use efficiency of the supplement with significant gains in both yield and biomass production possible, however, losses of inorganics from the rooting zone may be high at any time. Consistent rains immediately after a dry spell can lead to a flush of inorganic N from the native organic pool, which may be then lost as a result of denitrification if transient waterlogging occurs (provided labile forms of C are available in the profile). Significant losses of nitrate through leaching are possible also in coarse sands and cracking clays. These losses and the dynamics of the soil organic mater pool can be accurately quantified through the use of ^{15}N-labelled fertilizers [30] and the effectiveness of split applications assessed. These data form some of the crucial process information to validate simulation models for a wide range of management options. Versions of the internationally recognized CERES-Maize model have been modified to accommodate isotopes to facilitate the calibration of N and C transfers through the soil-plant-water system [31,32].

There is growing evidence, however, that the best option to improve inorganic fertilizer efficiency in small-holder systems is by adding high-quality organic matter [33,34]. Where high-quality organic manures are employed, fertility is usually at a higher level than the additive benefits of the individual components [35]. Yield increases ranging from 19-60% have been reported [36]. The relative success of green manures in terms of nutrient carryover in the semi-arid environment allows the most limiting requirement of high-quality inputs (i.e. high N concentration) to be met. The application of high-quality organic residues also tends to increase the labile and slowly decomposable organic matter fractions, easily identified as particulate organic matter (POM), a handy indicator of the sustainability of a particular cropping system. Unfortunately, when a green manure is being grown it also means the field is not producing an edible product during that time. Application of animal dung can overcome the need for green manuring, but it tends to be of lower quality with less potential to maintain soil fertility and yield, even though it may release nutrients for sustained periods of time.

2.4. Intercropping

Intercropping of cereals and pulses is a traditional practice in developing countries. In Africa and Latin America it forms a major part of small-holder agriculture. The practice tends to have a stabilizing effect on food security and enhances the efficiency of land use [36]. Its impact is most significant in low-fertility, N-depleted soils [37], such as those found in many rainfed semi-arid zones. Growth characteristics and planting densities contribute to success or failure. The yield advantages with intercropping are usually less than for grain-legume/cereal rotations [38]. However, this is not always the case: cowpea-maize intercrops in the wetter regions of Zimbabwe yielded better than their sole crops on a land-equivalent basis [39].

The amounts of N transferred from the legume to the cereal vary greatly and are difficult to decipher and compare due to the variety of methodologies used for quantification. The standard N-difference method indicated greater amounts when compared to isotope-dilution data [37]; in the case of the latter, the majority of experiments have failed to demonstrate an agronomically significant transfer of N. Intercrop biomass is usually less than that of a solecropped cereal, however, the material applied to the soil from the former is of higher quality, thus enhancing the supply of readily available nutrients. The mixture of high- (legume) and low-quality (cereal) residues can provide a continuous N supply and improve nutrient-release synchrony [40]. Little information is available on this interaction, however, intercropping provides the small-holder with food and a better overall quality of organic matter for sustained cropping, provided that sufficient water is available or the planting strategies are carefully adjusted for the climatic conditions of that year. The complex interactions between water and N in the intercropping system are difficult to unravel, but nuclear techniques offer valuable approaches. Fortunately, some empirical simulation models do exist to investigate intercropping [41], allowing various planting strategies to be tested against a range of climatic conditions.

3. SIMULATION MODELS

Whilst the majority of studies would indicate the success of reduced tillage and rotations in improving a soil's ability to accumulate organic matter and be more productive, the exceptions rather than the norm may tell us more about the long-term consequences of such management practices. Strategies to improve soil fertility and ecological sustainability are definitely soil- and environment-dependent. Single indicators of soil quality or health are of questionable value, considering the complexity of the soil-plant system. The full potential of the effects of management on nutrient cycling in agro-ecosystems can be accurately assessed only in the context of whole-system simulation models. These allow the integration of the many basic empiricisms describing the processes and properties in organic-matter decomposition and nutrient availability, and allow feedbacks of crop production, disease and climate to be fully coupled.

A vast array of models exist that deal with crop production at various levels of complexity. Few deal with short- and long-term concepts of sustainability in terms of both crop production and the soil resource, and few operate at a level whereby data requirements are not excessive and also provide accuracy. These characteristics are important when trying to develop useful long-term management strategies for a wide range of environments under a common framework. It also does not isolate the experimentalist from the model user, an important interaction in developing suitable, but also very practical, management strategies. This is particularly important in the semi-arid regions where climatic variability makes essential a flexible approach to sustainable production.

SOCRATES and CENTURY are models that specifically deal with soil organic matter dynamics, fertility and yield performance, offering great flexibility in terms of management options and the impact of climate. CENTURY [42] has been widely used, but has slowly increased in complexity and experience is now needed to make full use of it. On the other hand, SOCRATES [43], although based on a similar conceptual structure, is extremely simple to use. Its strength lies in being easily modified for any environment, and it can be used by researchers and extension personnel. It was recently selected by researchers in Canada, after comparisons with CENTURY and other models, as the best option to look at long-term changes in soil C and to develop sustainable rotations in their farming systems.

SOCRATES, Soil Organic Carbon Reserves And Transformations in agro-EcoSystems, is a robust simulation model encapsulating our current knowledge for promoting soil organic matter storage and reducing degradation in semi-arid agro-ecosystems. To make the model applicable to the decision-makers from the farm to regional levels, it emphasizes the use of easily accessible input data. Users also have access to a simple utility that changes some key parameters, thus allowing re-calibration of the model to a particular environment. SOCRATES was designed specifically to estimate changes in surface soil organic C as influenced by crop, pasture and legume rotations, N fertilizer addition, disease, grazing intensity and climate. It runs on a monthly timestep, and simulations can range from 5-100 years.

SOCRATES contains a simplistic plant-growth model that is essentially a means of producing either leguminous or non-leguminous dry matter. This calculation is based on the relationship between growing-season rainfall (including an estimate of stored water) and productivity, after adjustments are made for water-use efficiency in the system [44]. A linear regression is specified for each crop or pasture for the potential yield in a certain environment, and the yield is then adjusted for crop/soil water-use efficiency (a function of run-off and evaporation). As a strong relationship exists between C accumulation, aggregate stability and infiltration [21], the water-use efficiency in the model also changes in response to annual fluctuations in C reserves. Nitrogen-fertilizer-use efficiency in SOCRATES varies as a function of annual rainfall. The individual crops considered (but not restricted to) in the model are canola, barley, wheat, oats, maize and grain legume, with the model also capable of estimating annual pasture productivity and simulating green manures. SOCRATES, like CENTURY, has been tested across a wide range of environments, including east Africa.

The major drawback of models such as SOCRATES and CENTURY is that the monthly timestep for climate can mask major changes in yield performance in the highly variable rainfed systems common in semi-arid regions. To gain a more accurate assessment of yield variation due to strategic fertilizer amendments and in intercropping systems, we need to use a daily timestep model to capture the transient changes in water availability that are the primary limiting factor in drylands. For this reason, the DSSAT model, Decision Support System for Agrotechnology Transfer [45], is considered the best equipped and most easily usable platform for analyzing the impact of more detailed management decisions (e.g. sowing dates, N-fertilizer rates, residue management, rotation selection) on yield and grain quality in response to the physical and climatic characteristics of the environment. Simulations can be made for many consecutive years.

DSSAT is actually a set of validated crop models for simulating the growth and development of specific cultivars in response to soil water and N. The cornerstone of the package are the CERES cereal [46] and CROPGRO grain-legume [47] models, which have been validated and used extensively around the world. DSSAT also contains a database-management scheme to store and retrieve the minimum data set required for running the models. This database also contains generic soil profiles and a weather-generating option to facilitate problem solving. Its decision-support strength is its applications program for analyzing "what if" scenarios or management questions frequently asked by farmers and advisors concerned with sustaining economically sound and environmentally productive agriculture. This includes risk and gross-margin analysis for a single season or for long-term rotations. The model requires daily inputs of air maximum and minimum temperature, rainfall and solar radiation, or a weather generator option can be employed to give a wide variety of scenarios. Simulations require initial values of organic C, soil water and nitrate, but these can be estimated. Soil physical characteristics are available in the database supplied with the model.

4. THE POTENTIAL ROLE OF CIMMYT

Up to recent times, the Centro Internacional de Mejoramiento de Maiz y Trigo (CIMMYT) was recognized as chiefly a "plant breeding" institute dealing with germplasm improvement for increased production of wheat and maize predominately in third-world countries. More than 70% of the developing world's wheat lands have been sown to CIMMYT-derived varieties. Just over 50% of the maize area in developing countries is planted to CIMMYT cultivars [48]. It has become abundantly clear over the past decade that improved germplasm does not in itself produce the yield increases required to feed the rapidly expanding global population. The organization has always been at the international forefront in combining the physiological, agronomic and economic aspects of agriculture in the quest for sustainable productivity increases in wheat and maize production. However, at current population densities and production levels, the degradation of both soil and water resources in agricultural lands of both the developed and undeveloped countries is becoming critical.

Within this context of agro-ecosystem management, CIMMYT has recently formed the Natural Resources Group (NRG) to aid in the development of robust cropping strategies to sustain production of wheat and maize systems whilst maintaining the natural resource-base on small farm holdings. The NRG's holistic approach to agro-ecosystem sustainability as a means of enhancing crop production is underpinned with specific expertise in the use of isotopes in the soil and plant sciences, farming-systems research, simulation models and geographic information systems (GIS).

With the effectiveness of natural-resource management often hindered by the inability to "scale up," the NRG is also using advanced methodologies for geographical extrapolation of possible strategies. Both DSSAT and SOCRATES are process models dealing with information from one point in space over a specified time-period - historically or predicted. What happens when we require its application at a local, regional, national or world-wide scale? To develop these models, and others of similar nature, as powerful tools for planning and management purposes of areas rather than individual points, requires the integration of appropriately geographically referenced data sets with the model. Such data sets in this instance are rainfall, temperature, soil type, land zone and chemical-analysis data (e.g. cation exchange capacity and initial soil organic C values). In most instances, these data sets exist only as point-in-space information, and interpolation methodologies must be employed to convert them into a "spatial data set" to make the models usable over the landscape. Spatial variability within the data sets is a critical issue,and, in our on-going work to convert DSSAT and SOCRATES from strictly process models into those that have a strategic spatial approach, we are employing a variety of techniques to produce accurate spatial data sets from the original point data.

One of the means by which management strategies can be evaluated across a wide range of climate zones is through the use of the Spatial Characterization Tool (SCT), which is a GIS application that accesses gridded environmental data, point data and vector-based information (polygons) [49]. The tool provides a suite of querying capabilities that allow the characterization of agricultural and agroecological environments. The tool enables the rapid construction of simple empirical models of conditions at a site or a zone for the purpose of supplying decision-makers with broad-scale environmental information (climate, available water-holding capacity of soil and topographic characteristics). Databases currently exist for Africa and Latin America, with a global dataset being released shortly. As an example of its use, zones of similarity can be identified where the growing season is defined by the five consecutive months that maximize the precipitation to potential evapotranspiration ratio. Probability distributions of rainfall and other climate variables can be made. This information identifies target domains for management strategies developed at one particular site with a defined climate. Simulation models can then be used for risk assessment by evaluating the spatial variation in crop production as a function of soil type and climatic variation.

CIMMYT is involved also in a collaborative effort to combine vertical dimension water-flow simulations from a crop model with a terrain analysis. Having a water balance on a landscape scale should permit more realistic assessment of the effects of tillage practices and other factors on crop-production sustainability. The same analyses should have direct application to precision agriculture and crop improvement under variable edaphic conditions.

5. CONCLUSIONS

Specific experiments should involve the use of ^{15}N-labelled fertilizers and organic materials to examine N-use efficiency in defined treatments as well as prospects for sustained release of N from soil organic matter. As soil-water availability plays the dominant role in semi-arid farming systems, it is important that a complementary assessment of water-use efficiency be made in these treatments to evaluate possible tradeoffs between water and N. These data then allow the refinement of simulation models. Even without this information immediately available, a large-scale simulation modelling exercise should be undertaken using the DSSAT model linked to a GIS to identify site-specific management strategies to maximize yield and reduce resource-degradation.

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