Land use and soil organic matter in South Africa 2: A review on the influence of arable crop production

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The decline of soil organic matter as a result of agricultural land use was identified for a review with the ultimate aim of developing a soil protection strategy and policy for South Africa. Such a policy is important because organic matter, especially the humus fraction, influences the characteristics of soil disproportionately to the quantities thereof present. Part 1 of this review dealt with the spatial variability of soil organic matter and the impact of grazing and burning under rangeland stock production. In this second part of the review, the impact of arable crop production on soil organic matter is addressed. A greater number of studies have addressed the degradation of soil organic matter that is associated with arable crop production than the restoration. However, cropping under dryland has been found to result in significant losses of soil organic matter, which is not always the case with cropping under irrigation. Restoration of soil organic matter has been very slow upon the introduction of conservational practices like zero tillage, minimal tillage, or mulch tillage. Reversion of cropland to perennial pasture has also been found to result in discouragingly slow soil organic matter restoration. Although increases or decreases in soil organic matter levels have occurred in the upper 300 mm, in most instances this took place only in the upper 50 mm. The extent of these changes was dependent *inter alia* on land use, soil form and environmental conditions. Loss of soil organic matter has resulted in lower nitrogen and sulphur reserves, but not necessarily lower phosphorus reserves. Depletion of soil organic matter coincided with changes in the composition of amino sugars, amino acids and lignin. It also resulted in a decline of water stable aggregates which are essential in the prevention of soil erosion. Although much is known about how arable crop production affects changes in soil organic matter, there are still uncertainties about the best management practices to maintain and even restore organic matter in degraded cropland. Coordinated long-term trials on carefully selected ecotopes across the country are therefore recommended to investigate cultivation practices suitable for this purpose.

Introduction

The decline of soil organic matter as a result of agricultural land use was identified for review, with the ultimate aim of developing a soil protection strategy and policy for South Africa. Organic matter is of great importance in soil, because it impacts on the physical, chemical and biological properties of soils. Physically, it promotes aggregate stability and therefore water infiltration, percolation and retention. It impacts on soil chemistry by increasing cation exchange capacity, soil buffer capacity and nutrient supply. Biologically, it stimulates the activity and diversity of organisms in soil.[1]

The organic matter content of soils is determined mainly by climate (rainfall and temperature), vegetation cover and, to a lesser extent, by topography, parent material and time. Changes in land use, however, can significantly impact on the organic matter content of soils. This impact usually results in the reduction of the organic matter content in soils. The largest of these impacts results from the conversion of natural veld to crop production under dryland or irrigated conditions. These impacts form the focus for the discussion in Part 2 of this review. Part 1 of this review[2] dealt with the geographic distribution of organic matter in South Africa as well as the impact of grazing and burning under rangeland stock production on the organic matter content in soils.

Crop production under dryland

The majority of studies related to this section of the review focused on the Free State and KwaZulu-Natal provinces. Studies in the Western Cape, Eastern Cape, Gauteng, Mpumalanga and North West provinces are very limited, with none having been found for the Limpopo province. The discussion is therefore structured for each province, except that the North West province is accommodated for convenience under either the Free State or Mpumalanga provinces.

Free State

Several studies on dryland cropping and changes in organic matter content of soil in the Free State have been carried out by postgraduate students over the past 20 years.[3,4,5,6,7,8,9,10] Their results and results from other related studies are dealt with in varying degrees of detail here.

Prinsloo[3] pioneered these studies with an investigation into the effects of present or past cultivation on nitrogen fertility in some Free State soils by comparing paired samples of cultivated or reverted soils with uncultivated soils. Cultivation caused on average total nitrogen losses of 55% in the 0 mm – 150 mm layer, 17% in the 150 mm – 500 mm layer and 6% in the 500 mm – 1000 mm layer. Reversion of cropland to perennial pasture appeared to restore nitrogen fertility in the topsoil where leguminous trees were present, but not in their absence, because the total nitrogen was on average only 13% less in the reverted than uncultivated soils.[11]

These findings led Du Toit[4] to study the trend of soil organic matter depletion to a depth of 200 mm for cultivation periods ranging from 0 – 85 years. For this purpose she selected 50 sites, of which 27 sites represented five ecotopes, at Vryburg, Kroonstad, Koppies, Tweespruit and Harrismith. The ecotope at Vryburg was in the North West province. An ecotope is defined as a region where the three environmental factors that affect yield – climate, slope and soil – are for practical purposes homogenous.[12] The aridity indices (precipitation to potential evaporation ratio) of the ecotopes at Vryburg, Kroonstad, Koppies, Tweespruit and Harrismith were 0.20, 0.24, 0.29, 0.33 and 0.36, respectively. All five ecotopes had slopes of less than 1%. The dominant soil forms were fine sand Hutton soil form at Vryburg, fine loamy sand Avalon soil form at Kroonstad, clayey Arcadia soil form at Koppies, fine sandy loam Westleigh soil form at Tweespruit and fine sandy loam Avalon soil form at Harrismith.

Cultivation, irrespective of the period, caused a significant decrease in organic matter at all sites. This decrease amounted to 10% – 75% in the case of organic carbon and 5% – 73% in the case of total nitrogen. Losses of organic carbon were consistently larger than total nitrogen, with the result that cultivated soils had slightly lower carbon to nitrogen ratios than virgin soils.[13]

A general depletion pattern for organic matter as a consequence of cultivation was established for the area under investigation by correlating the cultivation index (organic carbon or total nitrogen of cultivated soil to organic carbon or total nitrogen of uncultivated soil ratio) of each of the 50 sites with its respective cultivation period. This pattern showed three distinct phases: phase 1 – the rate of organic matter loss was rapid (during the first five years of cultivation); phase 2 – the rate decreased until equilibrium was reached (after about 35 years of cultivation) and phase 3 – very little or no further loss occurred.[13]

Similar depletion patterns for organic matter as a result of cultivation were established for every ecotope using absolute values of either organic carbon or total nitrogen. In the ecotopes from the warmer and drier regions, equilibrium was approached before 20 years of cultivation, and in ecotopes from the cooler and wetter regions, equilibrium was approached after 40 years of cultivation. However, the percentage of organic matter loss was larger in the cooler and wetter ecotopes (60%) than in the warmer and drier ecotopes (40%). As expected, in each ecotope, the pattern of loss for mineralisable nitrogen was very similar to that for total nitrogen, because total nitrogen serves as a reservoir for mineralisable nitrogen.[13,14,15]

Du Toit[5] investigated the effect of cultivation on sulphur fractions on the same set of soil samples. He found a decline in total sulphur of between 4% and 70% as a result of cultivation, with the uncultivated soils serving as a reference. On average, there was 40% more inorganic sulphur in cultivated soils than in uncultivated soils. Therefore, the decline in total sulphur resulted from accelerated mineralisation of organic sulphur as a result of cultivation. On average, there was 30% more sulphur mineralised in the cultivated soils than in the uncultivated soils. Thus, the cultivated soils contained more plant-available sulphur than the uncultivated soils. The ratios of carbon to sulphur and nitrogen to sulphur declined with cultivation, indicating that sulphur-containing organic compounds were relatively more resistant to mineralisation than organic compounds not containing sulphur. Depletion patterns of total sulphur were almost mirror images of total nitrogen.[16,17]

Van Zyl[6] also used this set of soil samples to study the effect of cultivation on the total (P_t), inorganic (P_i) and organic (P_o) phosphorus fractions. He used a sequential extraction procedure to fractionate P_i ($NaHCO_3$-P_i, NaOH-P_i, HCl-P_i, and residual-P_i) and P_o (NaHCO-P_o, NaOH-P_o, and residual-P_o) whereafter P_t, P_i and P_o were calculated by summation of the relevant fractions.

In virgin soils, the contribution of the P_i-fractions to P_i and those of the P_o-fractions to P_o increased almost without exception in the following order: $NaHCO_3$-P_i < HCl-P_i < NaOH-P_i < residual-P_i and $NaHCO_3$-P_o < residual-P_o < NaOH-P_o. This increase resulted in greater P_o than P_i contents. An increase in P_t of 6% – 184% was established in 76% of the cases as a result of cultivation. This increase in P_t was ascribed to the larger increase in P_i (11% – 297% in 94% of the cases), as a result of fertilisation, in comparison with the decrease in P_o (5% – 46% in 42% of the cases), as a result of mineralisation. The fertiliser phosphorus, not utilised by the crops, accumulated in the P_i fractions in the same sequence as the observed decline in plant availability: $NaHCO_3$-P_i > NaOH-P_i > HCl-P_i > residual-P_i. Easily mineralisable $NaHCO_3$-P_o declined in 62% of cases, ranging between 8% and 84% on account of cultivation. Cultivation had little effect on NaOH-P_o and residual-P_o. Hence fertiliser phosphorus largely counteracted the mineralisation of P_o.[18,19]

The results of the previous studies motivated Lobe[8] to investigate the fate of organic matter in the topsoil (0 mm – 200 mm) of ecotopes at Harrismith, Kroonstad and Tweespruit, which are dominated by plinthic soils like the Avalon and Westleigh soil forms. His aim was to elucidate the rates and mechanisms of organic matter loss in these plinthic soils as a result of 0 – 98 years of cultivation, using a larger sample set, comprising that of Du Toit's[4] and additional samples that Lobe collected.

The carbon and nitrogen concentrations of these plinthic soils declined rapidly with increasing time of cultivation and approached equilibrium after about 30 years. At this stage, the concentrations of carbon and nitrogen were reduced, by 65% and 55%, respectively, in comparison to those of grassland soils. These losses occurred from all particle size fractions from all three ecotopes. Decreasing decline rates of carbon and nitrogen upon cultivation with decreasing particle size, however, showed that the organic matter associated with clay was more resistant than that in the sand fractions. The concentrations of organic carbon for example reached equilibrium after 14 years for coarse sand (0.25 mm – 2 mm), 46 years for fine sand (0.02 mm – 0.25 mm) and 55 years for clay (< 0.002 mm). Nevertheless, organic matter attached to silt (0.002 mm – 0.02 mm) continued to be lost as cropping continued, probably as a result of wind erosion.[20]

Prolonged cropping of plinthic soils resulted in a rapid exponential decline of macro-aggregates (> 2 mm) but an increase in meso-aggregates (0.25 mm – 2 mm) and micro-aggregates (< 0.25 mm). Both carbon and nitrogen concentrations decreased in these water-stable aggregates; the decline being the fastest in the large macro-aggregates (> 2.8 mm). Most of the carbon lost (about 60%) was from the meso-aggregate fraction. The large macro-aggregate fraction stored 47% of total carbon in grassland, but less than 10% after 90 years of cropping. Some of this carbon was recovered in the smaller aggregate fractions. The carbon stored in the meso-aggregates increased the total stored carbon from 27% to 61%. On average, at least 5% of the organic matter was physically protected in aggregates smaller than 2 mm. Even in these sandy soils (10% – 19% clay), physical protection of organic matter by occlusion in finer pores played a significant role in its maintenance.[8]

The fate of lignin, which is a marker of plant residues, was studied to elucidate some of the mechanisms controlling organic matter loss in these plinthic soils.[21] Prolonged cultivation resulted in a decline of lignin-derived phenols to 36% of that in the grassland. The contribution of lignin-derived phenols to total carbon did not change in the bulk soil as a result of cultivation, which suggests that there was no relative enrichment of lignin functional groups as total carbon was lost during cultivation. Increased ratios of phenolic acids to aldehydes suggests that side chains were increasingly oxidised during cultivation. As cultivation continued, the ratios of syringyl to vanillyl structural units increased, especially in the clay. This increase indicates that the lignin in the soil from the grass was replaced by lignin from the arable crops.[21]

These findings were supported by lignin-specific ^{13}C analyses. After 98 years of cultivation, ^{13}C values of organic matter in the bulk soil indicated that 40% of grassland-derived carbon was replaced by wheat-derived carbon, which dominated over maize-derived carbon. In contrast, 80% of the carbon in lignin was crop-derived, suggesting that the majority of the remaining grassland carbon was recycled through microbial biomass. No significant changes in the ^{15}N signature in the bulk soil were observed on account of cropping, whereas in the coarse sand fraction, decreasing ^{15}N values reflected increased fertiliser input. The sequestration of fertiliser nitrogen into stable carbon pools of the particle size fractions could not be detected. Hence conventional cropping practices on these plinthic soils contributed neither to the preservation of old grassland carbon and nitrogen, nor to effective humus reformation by crops.[22]

As mentioned earlier, these plinthic soils lost 55% of their nitrogen after 30 years of cultivation, despite continued nitrogen fertilisation as recommended. At this stage, loss of amino sugar nitrogen was even higher at 60%. Loss of amino sugar nitrogen could be interpreted as a sign of a deficiency of other nitrogenous substrates for microbial growth. Hence bacterial amino sugars were lost in preference to fungal ones. This effect was evident in both the silt-sized and clay-sized separates. This shift from fungal to bacterial residues was most pronounced within the first 20 years after converting grassland to cropland, but continued thereafter.[23]

In these plinthic soils, most of the organic sulphur loss during the first 20 years of arable cropping occurred from labile-bonded sulphur pools, suggesting that sulphur dynamics in the short term were controlled mainly by biological mineralisation. The long-term loss, that is after 20 years of arable cropping, occurred from the ester SO_4-S pool, probably as a result of biochemical oxidation.[24]

Organic sulphur in the strongly oxidised state was the dominant form of sulphur, followed by sulphur in the intermediate and strongly reduced oxidation states in the humic substances extracted from these grassland soils.[24] Long-term arable cropping of these grassland soils led to a shift in oxidation states from the strongly reduced and intermediate states to the strongly oxidised state and, thereby a change in the relative proportion of the organic sulphur functional groups associated with each oxidation state. Thus land use changes not only brought about quantitative changes but also altered the composition of organic sulphur functional groups in the humic substances extracted from these soils.[24]

Amino acids contributed 34% of the total nitrogen in the grassland soils. After 30 years of cropping, 70% of these amino acids were irretrievably lost. This loss occurred in preference to other nitrogen structures. The amino acid enantiomers responded differently to prolonged cropping, for example the proportions of D-alanine and D-glutamic acids increased relative to the respective L-enantiomers. This increase was attributed to an accumulation of nitrogen in residues of bacterial cells. In contrast, the D to L ratios of leucine and aspartic acids declined, probably reflecting losses of old amino acid nitrogen reserves in the most degraded arable land.[25]

Residues of arbuscular mycorrhizal fungi have the ability to promote soil aggregation.[26] Hence, the fate of arbuscular mycorrhizal fungi residues were assessed in the plinthic soils, assuming that glomalin-related soil protein consists of material of arbuscular mycorrhizal fungi origin. The grassland sites exhibited generally low glomalin-related soil protein contents. Prolonged arable land use reduced the contents of glomalin-related soil protein further. In contrast to carbon, nitrogen and microbial residue dynamics, glomalin-related soil protein contents were not reduced below a certain steady-state level, despite potentially negative management effects on arbuscular mycorrhizal fungi, such as tillage, fallow and phosphorus fertilisation. The steady-state glomalin-related soil protein contents coincided with the low but steady crop yields in these soils.[26]

In the Harrismith, Kroonstad and Tweespruit ecotopes, some lands, which had been cultivated continuously for more than 20 years, were converted to perennial pasture of different ages. The restoration of organic matter on these lands was studied by Birru[7]. He sampled pasture lands that were 25 years old or younger, so conclusions drawn from the study are limited to this restoration period. Integrating the results from all three ecotopes showed that, after this period under perennial pasture, on average only 25% organic carbon and 20% total nitrogen that had been lost during the 20 and more years of cultivation had been restored. Most of this was stored in the 0 mm – 50 mm layer, a little in the 50 mm – 100 mm layer and very little in the 100 mm – 200 mm layer. Results showed a wide variation in the rate of organic matter restoration between sites in each of the ecotopes, mainly as a result of differences in natural resource factors and management techniques. Positive factors and techniques were: a favourable soil water regime, promoted by an adequate rooting depth of at least 500 mm; a clay content above 12%; gentle slopes; an aridity index above about 0.35; plant-available nitrogen levels above 15 mg/kg; and the presence of a legume in the pasture. Pasture burning was shown to be a negative factor.

The effects of land use on the extractable, humic and fulvic-acid associated carbon and nitrogen contents of the plinthic soils in the Harrismith, Kroonstad and Tweespruit ecotopes were studied by Akhosi[10]. Contributions of extractable, humic and fulvic carbon to total carbon in the three ecotopes were 49.6%, 26.7% and 22.9%, respectively, for soils never cultivated, 49.2%, 36.9% and 12.9%, respectively, for soils cultivated for longer than 20 years, and 50.9%, 28.6% and 20.0%, respectively, for cultivated soils reverted to perennial pasture for longer than 20 years. Extractable carbon therefore changed in proportion to total carbon, which was not the case with humic and fulvic carbon. Nitrogen displayed similar trends.

Some of the residue management practices proposed to maintain and, if possible, increase organic matter have been tested since 1979 in a long-term wheat trial near Bethlehem on an Avalon soil. The effects of these practices were studied 10 years[27] and 21 years[28] after implementation. Results of both studies indicated that the effects, especially of straw burning, and to a lesser extent of weeding, were small compared to tillage practice. On a relative basis, the mulched and no-tilled plots respectively contained 10% and 22% more organic carbon than the ploughed plots in the 0 mm – 50 mm layer after 10 years, and 20% and 39% more after 21 years. However, in the 50 mm – 250 mm layer, the mulched and no-tilled plots contained on a relative basis 1.5% and 4.9% more organic carbon than the ploughed plots after 10 years, and 2.2% and 4.4% after 21 years. Total nitrogen, although not as large as organic carbon, showed similar increases in the mulched and no-tilled plots compared to the ploughed plots for these two layers. No tillage combined with chemical weeding is recommended to maintain and even increase the organic matter content of this Avalon soil when cropped annually with wheat.[27,28]

KwaZulu-Natal

Very little attention was given to the effects of sugarcane mono-cropping on organic matter[29] despite its being an important indicator of soil quality.[30] However, several studies were conducted over the past 10 years in KwaZulu-Natal to quantify the effects of long-term sugarcane mono-cropping on this indicator. The results that emanated from these studies, as well as those from other studies, are reviewed in variable detail in the following paragraphs.

The organic matter content of virgin and adjoining cultivated fields at 29 sites in KwaZulu-Natal (15 sites originating from dryland and 14 sites from irrigated sugarcane areas) were compared by van Antwerpen and Meyer[31]. These 29 sites represented 16 soil forms: Bonheim, Fernwood, Glenrosa, Hutton, Inanda, Katspruit, Kroonstad, Mayo, Milkwood, Mispah, Nomanci, Oakleaf, Shortlands, Swartland, Westleigh and Willowbrook soil forms. The virgin fields included native bush and grass, while the cultivated fields were under sugarcane production for 2 to more than 50 years. Organic carbon in dryland sugarcane decreased on average from 3.87% to 3.31% in the 0 mm – 150 mm layer ($p < 0.05$), 3.33% to 3.19% in the 150 mm – 300 mm layer ($p > 0.05$) and 3.16% to 3.04% in the 300 mm – 450 mm layer ($p > 0.05$). The average depletion of organic matter under irrigated sugarcane was from 2.40% to 1.88% in the 0 mm – 150 mm layer ($p < 0.05$), 2.08% to 1.69% in the 150 mm – 300 mm layer ($p < 0.05$) and 1.46% to 1.39% in the 300 mm – 450 mm layer ($p > 0.05$). On a relative basis, depletion of soil organic matter was higher in the irrigated than dryland areas. In both the dryland and irrigated areas, the depletion of soil organic matter decreased with depth.

The effects on organic matter of increasing periods under sugarcane monoculture in a Glenrosa soil form on the South Coast and in a Hutton soil form in the Midlands were investigated by Dominy et al.[32,33] Organic carbon content in the upper 100 mm soil layer at both sites under undisturbed vegetation was 4.6%. This content declined exponentially with increasing years under sugarcane and reached a new equilibrium level of about 3.4% for the Hutton soil and 1.3% for the Glenrosa soil after 30 – 50 years. The higher organic matter content maintained at the Hutton soil form was attributed to clay protection of organic matter, as the clay content of the Hutton soil was 62% compared with 18% for the Glenrosa soil. The loss of soil organic matter resulted in a concomitant decline in soil microbial biomass carbon, basal respiration and aggregate stability. After 50 and more years of sugarcane production, only 39% of the organic carbon in the upper 100 mm of the Glenrosa soil was still forest-derived, with ^{13}C studies showing that 61% was sugarcane-derived.

The influence of dryland sugarcane cropping on soil organic matter was studied by Qongqo and Van Antwerpen[34] on the South Coast (with a mean annual precipitation [MAP] of 1025 mm) and in the Midlands (with a MAP of 918 mm). On the sandy loam granite-derived Glenrosa soils of the South Coast, organic matter declined over 50 years from 4.7% to 2.4% at a rate of loss equivalent to 0.04% per year. The organic matter of the clayey dolerite-derived Hutton soils of the Midlands declined over 30 years from 6.1% to 5.7% at a rate of loss equivalent to 0.01% per year. It was concluded that clay protection caused the difference in loss rates between the Hutton and Glenrosa soils.

Changes in the soil organic matter status of Hutton soils at two sites under various cropping histories in the Midlands were compared.[32,35] Both sites contained fields with continuous cropping histories of more than 20 years. At the one site, soil organic carbon to a depth of 300 mm followed the order: permanent kikuyu pasture > annual ryegrass pasture > native grassland > sugarcane > conventional tilled maize. The order at the other site was: permanent kikuyu pasture > native grassland > annual grassland pasture > zero-tilled maize > conventional-tilled maize. Organic carbon, microbial biomass carbon and aggregate stability were substantially greater in the surface 0 mm – 50 mm layer under zero-tilled than under conventional-tilled maize but this trend tended to be reversed in the 100 mm – 300 mm layer. Although soil organic carbon content was similar under conventional-tilled maize and sugarcane, values for microbial biomass and aggregate stability were lower under sugarcane. These lower values were attributed to the fallow nature of the sugarcane inter-row soil. Therefore, long-term sugarcane production caused a marked decline in soil organic matter content. Practices such as retention of crop residues, zero tillage and the use of green manure crops in rotation should be considered as possible methods of arresting the soil organic matter decline under this cropping system.

The changes in organic matter content of an Arcadia soil induced by 59 years of burning or green cane harvesting, with or without annual fertiliser applications, were investigated by Graham et al.[36,37] at Mount Edgecombe. Crop residues were either burnt prior to harvest with the harvest residues raked off (R1), burnt prior to harvest with the harvest residues left on the soil surface (R2), or left unburnt with all the trash left on the soil surface (R3). Concentrations of organic carbon in the 0 mm – 100 mm layer of soil increased as the amount of crop residue returned increased, that is in the order R1 < R2 < R3. The accumulation of organic carbon was most marked in the 0 mm – 25 mm and 25 mm – 50 mm layers, which was not the case with labile carbon fractions. Labile carbon fractions were increased markedly by trash retention to a depth of 300 mm, reflecting downward leaching of soluble carbon and/or deposition of particulate carbon at depths below the trash blanket. Hence, microbial biomass carbon to a depth of 300 mm was greater under green cane harvesting than under burning.[38] Below 100 mm, there were no significant treatment effects on organic carbon. Fertiliser applications also caused accumulation of organic carbon, and the effect was evident to a depth of 100 mm. Compared with the grass plots in this long-term trial, there was a net loss of organic carbon from the Arcadia soil under sugarcane in all treatments. This loss was more pronounced on the unfertilised plots.[39]

An investigation was done by Haynes et al.[40] to determine the effects of the main agricultural land uses in the Midlands on soil organic matter and microbial biomass carbon. In comparison with undisturbed native grassland, permanent kikuyu pasture resulted in an increase in organic carbon and microbial biomass carbon. Maize and sugarcane production under conventional tillage resulted in a decrease of these two indicators. Under gum and pine forests, the organic carbon content was similar to that of native grassland but the microbial biomass carbon tended to be higher.

Depletion of soil organic matter in sugarcane fields of KwaZulu-Natal was noted by early researchers. Hence the production of green manures as cover or break crops was introduced to reduce the loss of soil organic matter and even rejuvenate it. The advent of inexpensive commercial fertilisers and improved varieties has shifted the economics of sugarcane production away from fallow periods and green manuring since 1930. However, several studies with green manure crops have been initiated to develop strategies for improving *inter alia* soil organic matter in sugarcane fields.[41]

The use of filter cake as an organic amendment for sugarcane soils is actively promoted nowadays. Additions of this waste product from sugar mills increased the organic matter and microbial activity in soils.[42]

After 8 years of direct-drill maize production at Cedara on a clay loam Hutton soil, it was found that organic carbon levels in the top 0 mm – 20 mm layer were higher than in conventionally tilled plots.[43] After a further 4 years, the plots were again the subject of a detailed investigation and it was found that surface organic carbon levels had increased in the interim from 3.8% to 4.7% in the direct-drill plots but remained unchanged at about 3.3% in the conventionally tilled plots. Below a depth of 50 mm, organic carbon did not differ between the conventionally tilled and direct-drill plots.

Western Cape

The change in organic matter content as a result of cropping systems and tillage practices on a Swartland soil near Malmesbury was examined by Smit[44]. She reported that, after 11 years, cropping systems had little influence on either organic carbon or total nitrogen in the 0 mm – 50 mm layer, but in the 50 mm – 100 mm layer, higher contents of both indicators were measured in the wheat monoculture plots than in the wheat-lupine-wheat-canola rotation plots. However, deeper than 100 mm, total nitrogen, and to a lesser extent organic carbon, were higher in the rotation than in monoculture plots.

Tillage practices, in contrast to the cropping systems, had a large influence on both organic carbon and total nitrogen in the 0 mm – 50 mm layer. In this layer, and to a lesser extent in the 50 mm – 100 mm layer, organic carbon and total nitrogen increased as the intensity of tillage decreased from conventional clean tillage to no tillage. However, between 100 mm – 200 mm, the conventional clean tillage plots had higher contents of organic carbon and total nitrogen than the conventional mulch tillage, minimum tillage and no tillage plots. The minimum tillage intervals influenced soil organic matter only in the 0 mm – 50 mm layer. In general, both organic carbon and total nitrogen increased as the intervals between minimum tillage increased from every year to every fourth year.

The effect of four different tillage treatments ranging in tillage intensity from the intensive, conventional mould-board-plus-disc tillage to direct-drilling with a no-till drill were tested on an Estcourt soil in the southern Cape wheat producing area where the annual precipitation is evenly spread throughout the year.[45] Organic carbon and total nitrogen increased in the upper 100 mm soil as a result of less intensive tillage. After three years, organic carbon and total nitrogen were 3.33% and 0.162%, respectively, in the direct-drilling treatment, compared to 2.03% and 0.116% in the conventional tillage treatments.

Eastern Cape

Soil organic matter was studied by Milne[46] on four commercial dairy farms in the Tsitsikamma, situated on sites which represented the three main soil forms in the region: a loamy sand Groenkop form in the low rainfall (MAP = 710 mm) eastern part, a sandy loam Cartref form in the moderate rainfall (MAP = 951 mm) central part and a loam Kroonstad form in the high rainfall (MAP = 1125 mm) western part. In comparison with undisturbed native vegetation, the Groenkop soils under both annually cultivated and permanent pasture had gained soil organic matter. By contrast, in the Kroonstad soils, where the native vegetation consisted of coastal forest, there was a loss of soil organic matter under both types of pasture. In spite of this, soil organic carbon content was lower under annual ryegrass than permanent kikuyu pasture at all the sites, reflecting the degrading effect of annual cultivation on soil organic matter. As a consequence, labile, extractable and microbial biomass carbon were all lower under annual ryegrass than under permanent kikuyu pastures at all sites.

Mandiringana et al.[47] investigated the fertility status of cultivated field and garden soils in the former Ciskei and Transkei regions of the Eastern Cape. Their results showed that a large proportion of the soils (62% – 100%, depending on location) had low organic carbon levels (< 1.0%) but levels were higher in garden than cultivated soils. The organic carbon ranges for garden and field soils were 0.92% – 3.28% and 0.03% to 1.26%, respectively, in the former Ciskei. In the former Transkei, the ranges were 0.3% – 5.8% and 0.1% – 6.8% for garden and field soils, respectively. The differences were attributed to the fact that gardens are generally more intensively managed because they are located next to homesteads, along with livestock pens, and they tend to be small in size. Because of easy accessibility, kraal manure is liberally applied to the gardens; and household refuse also invariably gets thrown into the gardens, contributing to a greater build-up of organic matter. Fields, on the other hand, are fairly large in size and located far from the homesteads, and are generally physically insecure. As a result of the insecurity, transport problems and the fact that most smallholder farmers are risk averse because of their limited resources, these fields receive minimal inputs, if any. These observations are in agreement with those of Roberts et al.[48] who, in a study involving two resource-poor communities in KwaZulu-Natal, also concluded that ‘homefields’ had higher fertility than ‘outfields’ because they received better management.

Gauteng

The restoration of organic matter in cultivated soils through the introduction of grass leys into cropping systems was investigated in the 1960s in the vicinity of Pretoria.[49,50,51,52] This research showed that in the absence of a suitable legume, the grass ley can fulfil its essential purpose of replenishing the organic matter content of soil and regenerating its crumb structure. The conditions are that the grass must occupy the soil for a period of more than three years, is not grazed excessively and is heavily fertilised with nitrogenous fertilisers. This practice, however, proved not to be economically viable for farmers and so a subsidised government scheme for grass leys was introduced. However, this was not particularly successful, for unknown reasons.

A field investigation reported on by Belay et al.[53], which was initiated in 1939 in Pretoria, demonstrated the beneficial effects of manure on soil organic matter. Organic carbon and total nitrogen values measured in the 0 mm – 200 mm soil layer were, respectively, 0.58% and 0.059% for the control plots, 0.56% and 0.07% for the NPK (nitrogen : phosphorus : potassium fertiliser) plots, 0.89% and 0.105% for the manure plots, and 0.95% and 0.117% for the manure plus NPK plots. These results suggest that inorganic fertilisers in comparison with manure did not result in a substantial build-up of organic matter in the long term.

Mpumalanga

Du Preez and Claassens[54] investigated the changes of organic phosphorus fractions in Avalon and Clovelly soils, near Ermelo, fertilised once with phosphorus. Over 15 years of maize cultivation, the $NaHCO_3$-P_o and NaOH-P_o decreased in the Avalon soil. In the Clovelly soil, neither $NaHCO_3$-P_o nor NaOH-P_o showed any definite trends. No explanation was given for these differences between the two soil forms.

Soil organic carbon contents of the 0 mm – 150 mm and 150 mm – 300 mm layers of conventionally tilled, stubble-mulched and no-tilled fields were compared at Morgenzon (sandy loam Glencoe form), Pretoria (sandy clay loam Hutton form), Koster (sandy clay loam Hutton form) and Viljoenskroon (sandy Avalon form) by Van der Watt[55]. Only at Morgenzon did stubble-mulch tillage unquestionably result in a 38% increase in the organic carbon content of the top layer, when compared with conventional tillage. Van der Watt[55] suggested that sampling times, sampling depth and the number of samples taken should receive greater attention in future studies to establish possible changes in soil organic carbon.

Crop production under irrigation

In addition to the study of Van Antwerpen and Meyer[31] on irrigated sugarcane, only one other study was done to establish organic matter changes as a result of crop production under irrigation.[56] This study focused on 21 farms at Ramah, Riet River and Vaalharts irrigation schemes, which had aridity index values of 0.13, 0.16 and 0.17, respectively. Adverse changes in organic carbon contents were recorded in the upper 0 mm – 200 mm layer of irrigated Addo, Augrabies, Clovelly, Hutton, Kimberley and Plooysburg soil forms in comparison to uncultivated soils that served as a reference. Organic carbon increased at eight farms, decreased at nine farms and was not affected at the remaining four farms. Similar changes in total nitrogen were recorded at these 21 farms. Neither the cultivation and irrigation history of the farm, nor the properties of the soils provided any obvious explanation for these contrasting findings. It is likely that irrigation, with the concomitant increase in biomass production, to some extent counteracted the effect of cultivation in causing a decline in organic matter. Annual biomass production of veld in the vicinity of the irrigation schemes is usually less than 0.8 ton/ha, while the biomass production of irrigated wheat on the schemes is more than 20-fold that of veld, namely 17 ton/ha.

Conclusions and recommendations

Studies on the influence of arable crop production on soil organic matter have focused mainly on the degradation thereof. Only a few studies have addressed the restoration of soil organic matter in degraded cropland. It can be concluded, however, that cropping under dryland resulted in significant losses of soil organic matter, which was not always the case with cropping under irrigation. The restoration of soil organic matter is very slow upon the introduction of conservation practices like zero, minimum and mulch tillage. Reversion of cropland to perennial pasture also resulted in discouragingly slow soil organic matter restoration. These changes in soil organic matter content occurred in the upper 0 mm – 300 mm layer, but in most cases only in the upper 0 mm – 50 mm layer. The extent of the changes was dependent *inter alia* on land use, soil form and environmental conditions. Loss of soil organic matter resulted in lower nitrogen and sulphur reserves, but not necessarily in lower phosphorus reserves. Depletion of soil organic matter coincided with chemical changes in the composition of amino sugars, amino acids and lignin. It also resulted in a decline of water stable aggregates, which are essential in the prevention of soil erosion. Even after a half century, not all of native vegetation-derived organic matter is replaced by crop-derived organic matter.

Despite this knowledge of soil organic matter changes as a result of arable crop production, it is not possible to confidently recommend best management practices for maintaining or even restoring this component in degraded cropland. Cultivation practices known to be suitable for this purpose, like conservation tillage, green manuring, cover crops, longer rotations and permanent revegetation should be investigated in long-term trials to establish best management practices. Trials of this nature should be coordinated and done on carefully selected ecotopes across the country, to enhance the extrapolation of findings.

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