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Review

Conservation tillage for cassava (*Manihot esculenta crantz*) production in the tropics

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ABSTRACT

Cassava (*Manihot esculenta crantz*) is often cultivated on tilled plots, traditionally on mounds and ridges with the use of hand hoes or tractor driven implements. These two conditions alter the soil structural parameters and most times increase the vulnerability of soil to erosion or compaction as a result of frequent machine movement under the conventional tillage system. A review of the effects of tillage systems on soil bulk density, total porosity and penetration resistance was conducted to investigate the effectiveness of soil conservation for the optimum production of cassava in the tropics. Tillage treatments under review were: conventional tillage (CT), no-till (NT), minimum tillage (MT) and soil compaction (CP). Our review indicated that the bulk density (BD) in plots under CT was not significantly different ($p < 0.05$) from the value of BD in plots under minimum tillage (MT) within the 0–5 cm soil layer, but was highest in soils under compaction due to traffic passes of heavy duty equipment. Soils under no-till were characterized with lowest bulk density within the 0–5 cm layer, but gradually increased in BD within the 10–20 cm soil layer, which offers the soil some structural stability. However, the difference in bulk densities between plots under NT and CP treatments were highly significant at $p < 0.05$, with CP plots having the highest bulk density within the 0–30 cm soil layer. Total porosity was highest in soils under conventional tillage (CT) comparatively with other tillage systems. Organic matter accumulation in NT treatment resulted to higher total porosity compared with other systems except CT at the surface soil (0–5 cm) but with reduced porosity at the sub-surface soil. Total porosity was least in plots under traffic passes (compacted plots). Statistically, there were no significant differences in total porosity among plots under conventional tillage with mulch residues, conventional tillage without mulch residues and minimum tillage with mouldboard at the $p < 0.05$. However, plots under minimum tillage without mouldboard had lower total porosity. Penetration resistance was higher in NT plots when compared with plots under CT system, except from compacted plots (CP), which offered highest resistance to penetration. A long term experiment showed that cassava root yield was highest under NT with mulch residues, with or without fertilizer application. The reviewed work further confirmed that cassava can be grown successfully under no-till (NT) to give the optimum growth and yield required of the crop, while conserving the soil physical properties.

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1. Introduction

Cassava (*Manihot esculenta crantz*) is a staple food crop and source of calories for hundreds millions of people in both the tropical and subtropical regions of the world (Howeler et al., 1993). The crop is largely cultivated for its nutritional and industrial importance. Cassava is a tropical root crop that yields a large amount of easily extractible starch and when converted to alcohol forms a good bio-fuel to power vehicles. The roots provide food for man and livestock animals. The stem of cassava is a very efficient and effective source of feedstock in a downdraft gasifier for the generation of electricity. The potential for generation of electricity from cassava leaf and tuber was estimated at 16,970 kwh ha^{-1} (Phalla, 2005).

Cassava is a draught resistant crop and will thrive under low soil fertility conditions. However, the production of cassava is far below satisfying the strong demand of the crop for human consumption and for bio-energy purposes, which often result to strong competition in the satisfaction of both food and energy needs of man. The statistics of cassava production among countries that are largest producers of the crop is presented in Fig. 1. Africa continent accounts for about 42% of the world cassava production, while Asia and South America contribute about 37 and 21%, respectively. The numerous advantages derivable from cassava crop justify a thorough review of the existing tillage practices, in order to be able to arrive at a scientific confirmation of the best soil tillage system for the crop.

Tillage is a fundamental practice of agricultural management and it is a way of working on the soil either physically, chemically, mechanically or biologically to create suitable conditions for seedling germination, establishment and growth (FAO, 1993). It is a process by which man disturb, overturns and rearrange the soil to create favourable soil physical condition for crop growth. Tillage operations loosen, granulate, crush or compact the soil particles (Ohiri and Ezumah, 1990). Primary tillage implements offer differential impact on soil loosening (Bowen, 1981) and can alter soil macro and microporosity, and hydraulic characteristics of the soil over time.

The greater retention of crop residues in the surface soil under minimum tillage with the use of chisel plough can increase surface soil organic matter, and soil structural stability and biological activity comparatively with the mouldboard ploughing (Carter, 1992). Over time, such increases coupled with differences in degree of organic matter incorporation could influence the distribution and storage of carbon and nitrogen in the soil. Cassava produces best on loose soil which encourages soil oxygen, prevent root rot and improve yield. The crop requires good soil preparation and adequate measures for erosion control.

Tillage practices must be such that soil is adequately conserved while maintaining high productivity (Howeler et al., 1993). A number of different minimum tillage systems is adopted for soil and water conservation, in order to sustain agricultural productivity. Traditional tillage practices such as pitting, mounding, ridging, and mulching, earth and stone bunding successfully conserved the soil (Kaumbutho and Simalenga, 1999), maintains soil structure and fertility, improve water infiltration, increase soil organic matter and sustain soil organisms. Soil tillage is often needed to control weeds and ensure crop growth ahead of the germination of new flush of weeds. It also encourages the transformation of organic nitrogen to readily available nitrogen for plants use, and creates a fine seedbed for improved germination of small-seeded crops like grains.

Tillage however exposes the soil to all forms of degradation and structural destruction. Soil tillage by use of heavy duty equipment and implements, and even farm animals often result to soil compaction, which hardens the soil and deplete the infiltration characteristics, reduces the fertility of the soil, increase soil bulk density and penetration resistance, and reduces yield in root crops such as cassava, yam and sweet potato. The continuous use of soil in tropical areas without recourse to conservation practices often constrained the soil ecosystems beyond their natural capacity, consequently leading to reduction in soil productivity and sustainability (Jongruaysup et al., 2003).

Therefore, no-till in which weeds are controlled by herbicides and crops planted directly into an untilled seedbed without any

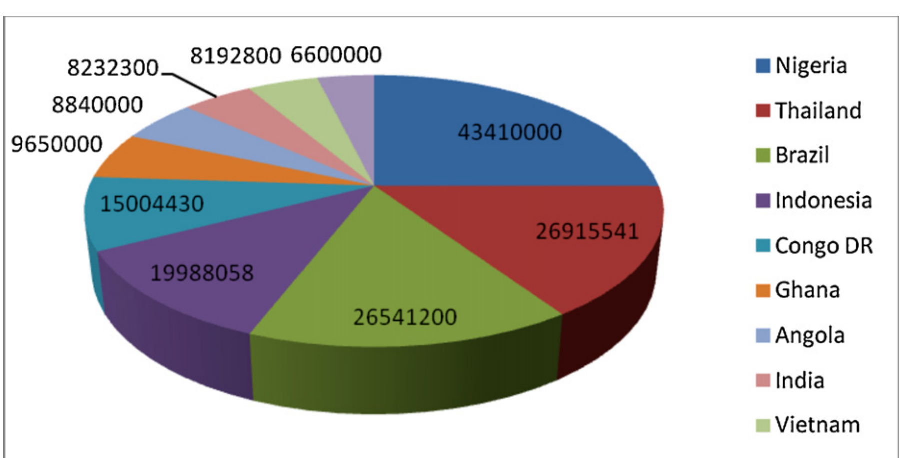

Fig. 1. World ranking of cassava production (FAOSTAT, 2009) Table 1. Dry bulk density (g cm^{-3}) of compacted and uncompacted soil under mouldboard ploughing and chiseling (Arvidsson, 1998).

primary or secondary tillage offers a better option for most farmers from the reduction in cost of farm operations and as well conserve the soil structure and fertility properties. This system is also called zero-tillage or no-tillage system (Lal, 1995). Crop residues often result to layer of mulch which protects the soil from the impact of rainfall and wind and also stabilizes the soil moisture and temperature in the surface layers, thus, creating a suitable habitat for a number of living organisms, from larger insects down to fungi and bacteria. These organisms break down the mulch and mix it into the soil so that it becomes sticky humus which keeps the soil structure stable. Previous studies reported that greater macroporosity or pore continuity result to greater infiltration in no tillage as compared with conventional tillage practices (Ehlers, 1975; Logsdon et al., 1990; Arshad et al., 1999). Anken et al. (2004) reported that though macroporosity was smaller, preferential flow channels were more continuous after nine years of no tillage versus mouldboard plough or chisel plough in Switzerland. Despite these advantages of the conservation tillage for cassava, there exists conflicting interest among cultivators of the crop, who apparently are unaware of the benefits of conservation tillage on the choice of either conventional, minimum or no-till systems for cassava cultivation.

The objective of the paper was to review the impact of soil conservation tillage systems on the physical properties of soil planted with cassava.

2. Background

2.1. Tillage

Tillage is known to have a wide range of effects on soil physical properties, especially moisture availability and conductivity. There have been contrasts in results from tillage research due to different soils, climate and experimental designs. These inconsistencies further necessitates a review of all tillage systems as practiced across most parts of the world in order to be able to make quantitative assessment of their effects on soil physical properties. Various types of traditional soil tillage techniques were adopted in the past by rural farmers before the advent of farm machineries and implements. Some of the traditional and modern tillage techniques are listed and discussed below.

2.1.1. Traditional tillage

Farmers in the tropics employ several traditional method of seedbed preparation. Traditionally, weeds and bush re-growth are slashed manually with cutlass and left on the soil as mulch or burnt in situ. The land is then hand-hoed, often superficially. Farmers also make mounds or ridges manually with hoes or with equipment drawn by draught animals. Mounds ridges and other forms of raised beds are widely used throughout the tropics. On poorly drained soils in southeastern Nigeria, large mounds are constructed. These are often 3–4 m in circumference and about 1 m high. Traditional tillage practices bury organic residues, to slow down their decomposition and thus influence the microbial population for a longer period. Surface residues, while modifying soil temperature and moisture, have shorter life in consequence, with all the associated effects (Mari and Changying, 2006).

Traditionally, farmers mulch the mounds with crop and weed residues. The practice of mixed cropping using the traditional tillage methods provides a continuous cover that protects the soil against erosion and improve soil temperature and moisture regime. The technique of building mound is also useful in concentrating nutrient-rich surface soil. With the native method of cultivation, mounding is quite beneficial especially when mixed cropping is practiced with little or no fertilizer input. Traditional agriculture in the past was compatible with the level of population and ecological environment. Long bush fallow periods were effective in restoring soil fertility for the prevailing level of crop yields and intensity of cropping. Pressure on land has resulted in drastic reduction of the fallow periods and in some countries they have disappeared completely. Intensive land cultivation with low use of inputs due to the farmers' inability to purchase what is necessary has set in. This leads to nutrient "mining of the soils" which is manifested in degraded soils and reduced crop yields.

2.1.2. Plough-till (conventional tillage, CT)

The plough-till (CT) system is based on mechanical soil manipulation of the entire field and involves mouldboard ploughing followed by one or two harrowing. Plough-till embraces soil cultivation based on ploughing or soil inversion, secondary cultivation using discs and, tertiary working by cultivators and harrows. These tools are often drawn by animals or tractors or by other mechanically powered devices. Ploughing removes the vegetation cover and exposes the soil to rainfall, wind and overland flow. However, the technique gives a weed free seedbed, incorporate fertilizer and improve soil conditions. The mechanical soil disturbance involved increases the risk of erosion. Mechanized conventional tillage encourages splash and sheet erosion as it leaves the soil surface bare, under heavy tropical storm occurrences (Shetto, 1999). Conventional flat cultivation systems are commonly practiced in Eastern and Southern Africa. In this practice, the soils are cut, inverted and pulverized, burying most of the crop residues underneath, leaving a clean fine seedbed. Under the impact of raindrops, the soils may cap or crust. Land degradation sets in and this starts with the reduction in vegetative cover, exposing the soil surface to accelerated erosion and leading to reduction in soil organic matter and nutrient content (IFAD, 1992).

The effects of tillage method on soil properties and soil erosion varies depending on soil properties. For example, where the soil has favourable structure with high proportion of water-stable aggregates, and is permeable, mechanical soil disturbance is likely to increase risk of soil erosion. On the other hand, where the soil has a smooth crusted surface and compacted subsoil horizon, massive non-porous unstable structure, carefully judge, timely mechanical tillage is likely to decrease the risk of soil erosion, at least temporarily.

2.1.3. Conservation tillage

Conservation agriculture is aimed at soil and water management in agricultural crop production. The system maintains acceptable profits together with high and sustained production levels in a conserved environment (FAO, 2007). Conservation cannot be over-emphasized considering the ever increasing population of the world that necessitates the production of more food to sustain man and animals (New Standard, 1992). Conservation tillage can be defined as a crop cultivation system that allows minimum disturbance of the soil to allow crops to be sown while ensuring maintenance of crop residues on the surface (FAO, 1993). The crop residue left on the surface reduces rain drop impact and reduces surface water movement, hence soil erosion. Rainfall on land that is not protected by a layer of mulch is left open to the elements of being impacted directly by the rain. But when soils are covered under a layer of mulch, the ground is protected in a way so that the ground is not directly impacted by rainfall (Hobbs et al., 2008). As water runoff and evaporation are reduced, water penetration is improved. The build-up of crop residues and roots in the long term, improves soil structure. The term conservation tillage has been used for varying tillage practices under a wide range of conditions (Mannering and Fenster, 1983). The vague use of the term for differing situations has created confusion and misunderstanding. The term encompasses a broad spectrum of practices ranging from no-till to intensive tillage, depending on soil conditions. Over the last two decades conservation tillage or reduced tillage technologies have been perfected and adapted for nearly all farm sizes, soil and crop types and climatic zones. Grain crops, pulses, sugar cane, vegetables, potatoes, beets and cassava as well as perennial crops like fruit and vines can all be grown using conservation tillage techniques.

Conservation tillage aims to conserve, improve and make more effective use of natural resources through combined management of available soil and water. Improved conservation tillage has the potential to increase soil organic carbon and reduce net emissions of carbondioxide and other greenhouse gases that contribute to global environmental insecurity. Conservation tillage or Zero tillage is now estimated to be practiced on over 105 million hectares (M ha) worldwide, mostly in North and South America (Derpsch and Friedrich, 2009). South America leads with 47% of the world's zero till acreage followed by 38% in North America, 12% in Australia/New Zealand, and 2% in Asia. Brazil is a world leader in successful adoption of conservation agriculture. No-till was introduced to Brazil in the early 1970s, some 10 years after it was started in the U.S. Brazil now has 25.5 M ha under no-till, or 60% of its cropped acreage, compared to 26.6 M ha in the U.S. (Derpsch and Friedrich, 2009). The use of cover crops in no-till systems was pioneered by Brazilian farmers.

Some commonly used practices under the generic term of conservation tillage are described below:

2.1.3.1. No-till (NT). Planting of crop directly into a seedbed that has not been tilled since the previous seedbed preparation is called a no-till or no-tillage system. The maximum amount of crop residue is retained on the surface, and weeds are controlled by chemicals, by residue mulch, by aggressive use of cover crops, or by a combination of these methods. No-tillage system reduces labour, fuel, irrigation and machinery costs (Sorrenson et al., 1998). No-tillage can increase yield because of higher water content and much lower erosion rates due to residue cover. Another benefit of no-till is that because of the higher water content, instead of leaving a field to fallow, it can make economic sense to plant another crop instead. Increased biotic activities, especially of earthworms, which thrive better in no-till improve the soil structure in no-till than in plough-till soils (Lal, 1987a; Lavelle, 1984).

Use of herbicides to suppress grass decreases the activity of earthworms, which is most suppressed, however, in cultivated plots (Lal, 1982). In soils with high biotic activity, surface soil may have a honeycomb-like structure. Soil structure is dependent on the number of visible pores in soil, and the suitability of a soil for no-till culture can be assessed by the number of bio-channels visible during field examination. Gowman et al. (1987) suggest that a large number of visible pores greater than 100 μm in diameter is the best guide for successful application of a no-till system. About 19.7% of total cultivated areas in the US are under the no-till system. The system has been adopted on 45% of total cultivated area in Brazil, and 50% in Argentina and about 60% in Paraguay. Many reasons were adduced to this rapid growth but most importantly are ecological (erosion control, improvement of soil fertility), and economical (less work, higher profits) reasons. Farmers would certainly not have adopted the technology so rapidly (if at all) if it would have been only for ecologic and not for economic reasons.

According to Sorrenson and Montoya (1984), NT is the most cost effective means of controlling erosion in Brazil and according to King (1983), economic analysis of various conservation practices show that no-till is the most cost effective of any practice commonly used in the USA. Other benefits derivable from the use of NT system according to Sorrenson et al. (1997) include: (i) reduced drudgeries and working hours, and lowered permanent farm labour and machinery costs; (ii) cost savings in NT through eliminating contour terracing and the replanting of crops after heavy rain which is often required under CT. (iii) reduced fertilizer, insecticide, fungicide and herbicide usage per crop over time in NT compared to CT. Rainfall simulator test in Parana, Brazil, showed greater infiltration in no-till and minimum till fields compared with ploughed land (Sidiras and Roth, 1985). However, the study does draw attention to the fact that the use of NT and crop rotations call for new management skills, particularly needed to cost effectively control weeds. Farmers require a number of years to master these skills, the key ones being: (i) type and quantity of herbicide used; (ii) scheduling of herbicide application; (iii) the choice and sequencing of cash and green manure crops in rotations; (iv) minimizing the time between harvesting and the sowing of a subsequent crop; (v) managing ground cover and crop residues; and (vi) using spot spraying with weed-specific herbicides or manual labour, where cost-effective, to control sporadic patches of weeds as opposed to blanket spraying with broad-spectrum herbicides. However, a little soil disturbance is allowed during harvesting especially in case of root crop harvesting. A major disadvantage of no-till fallow (sometimes referred to as chemical fallow) is its heavy use of herbicides for weed control and slow soil warming on poorly drained soil.

2.1.3.2. Minimum-tillage. The term minimum tillage has caused the greatest confusion because the minimum cultivation required to grow a crop varies from zero to a complete range of primary and secondary tillage operations depending on soil properties and crops. It is commonly defined as the minimum soil manipulation necessary for crop production or meeting tillage requirements under the existing soil and climatic conditions. It often means any system that has few tillage requirements. It may also mean tillage of any part of the land, e.g. strip tillage or zonal tillage. It could also refer to a "stale-bed" in which the soil is ploughed at the end of the previous crop cycle. The crop is then seeded with a minimum of seedbed preparations performed at the onset of the next rains. This is commonly recommended for soils in the semi-arid tropics in West-Africa (Charreau and Nicou, 1971).

Major advantages of the system includes: quick warm of residue tilled residue-free strip, injection of nutrients into row area and its suitability for poorly drained soils. The disadvantages involve the cost of preplant operation, too much drying, crusting and eroding of strips without residue may occur and the system may not be suitable for drilled crops. A number of minimum tillage practices are adopted around the world, which among others include the followings:

2.1.3.3. Mulch tillage. A tillage system that ensures a maximum retention of crop residues on soil surface is known as mulch tillage or stubble mulch farming. The soil is prepared in such a way that plant residue or other mulching materials are specifically left on or near the surface. Mulch tillage is a broad term. It includes practices such as no-till, disc plant system, chisel plant system, and strip tillage systems. When a grain crop is seeded through the mulch of a chemically killed cover crop, it is called sod seeding. If the cover crop is untreated or only temporarily suppressed, the system is called live mulch. When a cover crop is grown within the cropping cycle to produce mulching material, the system is called fallow planting. Mulch tillage is also within agro-forestry systems, a common practice is alley cropping where annual crops are grown within widely spaced hedges of perennial shrubs. The hedges are planted on the contour and are regularly pruned to provide mulch.

The greater retention of crop residues in the surface soil under chisel ploughing, compared to mouldboard ploughing, can increase surface soil organic matter and biological activity, and soil structural stability (Carter, 1992). Overtime such differences, coupled with differences in degree of organic matter incorporation could influence the distribution and storage of carbon and nitrogen in the soil. Jensen (1994) showed that crop residue particle size, which could be influenced by tillage practices, was an important factor in initial residue decomposition rates. Several studies have shown that tillage practices can have a differential effect on organic matter content associated with soil particle size separates (Cambardella and Elliott, 1992; Angers et al., 1993).

Stubble mulch tillage or stubble mulch farming (sub-tillage) is a crop production system that involve leaving the soil with surface residues cover for controlling water erosion, wind erosion and reduce surface runoff (Unger et al., 1988).

2.1.3.4. Ridge tillage. The practice of planting crops on ridges is widespread in both tropical and temperate climates. The crop row may be planted on ridge top, along both ridge sides or in the furrow. Ridge tillage facilitate mixed cropping system in which more than one crop can be grown simultaneously in the same plot of land, a common practice throughout the tropics and subtropics (Bradfield, 1970). Ridges may be made on contour with graded furrows draining into grassed waterways or the ridges may have short cross-ties to create a series of basins to store water. The later system is called tied-ridge system. However, this system increases soil vulnerable to both wind and water erosion, especially when working against wind and water flow directions. The system is also mostly suitable for annual row crops, and wheel spacing and other machinery modifications may be needed.

2.1.4. Conservation tillage for cassava

The traditional methods of farming have in most cases resulted in soil deterioration without considering the soil improvement and continuous cultivation at constant depth creates zone of high compaction in the surface soil. The depth of the zone of compaction will depend on the farmer practices (Spoor, 2000). Thus, soil management will be responsible for important changes in soil quality parameters, particularly those related to soil structure and water movement. Most of cassava plantations in Thailand are grown in loose textured soils where the soils are easily eroded. In most cases, cassava farmers prepare their land by ploughing with a 3-disc plough followed by a 7-disc harrow and ridger. This causes a very loose soil which is free of weeds and easy to plant. It also causes the soil to be highly susceptible to erosion, while the direct exposure of the soil to sun and rain causes rapid decomposition of organic matter, leaving many soils almost devoid of organic matter and with very poor structure. A minimum tillage or no tillage system often referred to as conservation tillage is thought to be the appropriate technique for these soils.

A broad range of the minimum tillage systems is used to conserve soil and water, and sustain agricultural productivity. No-till is one type of this system, in which the crop is sown directly into an untilled seedbed without any primary or secondary tillage. Previous crop residue is left on the surface and weeds are generally controlled by herbicides. This system is also called zero-tillage or no-tillage system (Lal, 1995). In a Brazilian Oxisol, Roth et al. (1998) reported that bulk density at 20–30 cm depth was significantly lower in no-tillage and minimum tillage systems compared with the conventional tillage system. Accordingly, the total porosity was significantly higher in minimum tillage and no-tillage compared with conventional tillage systems. Jongruaysup et al. (2003) reported that there were certain improved soil structural parameters, with an increase in air porosity under no-till comparatively with conventional tillage. He also found out that soil bulk density under no-till agriculture is lower when compared to the conventional tillage. He attributed these findings to, firstly, the in situ mulching of the plant biomass residues in NT plot. Numerous studies have also indicated that crop residues decrease soil compactability (Gupta et al., 1987; Ohu et al., 1985), while compaction was due to the cultivation practice in conventional tillage system.

Another parameter that could be well improved under the no-till is the saturated hydraulic conductivity of soils and this could probably result from improved soil porosity and reduced bulk density. In addition, it could also be a result of the influence of in situ mulching on soil water content. Unger (1994) pointed out that a major advantage of maintaining crop residues on the surface soil is improved soil water conservation as a result of reduced surface runoff of water and improved soil structure.

Inspite of the seemingly good advantage of weed control under the conventional tillage system, the practice is known to bury residue, increase surface sealing and reduce steady infiltration rate, causing runoff and soil erosion (Connolly et al., 1997). Conservation tillage, in which crop residues are left on the surface to protect soil from raindrop impact and sealing, increases infiltration and reduces runoff is most valued (Blevins and Frye, 1993). Degradation and crusting of unprotected surface soil is clearly of great importance, but degradation of the sub-surface soil by wheel traffic under the conventional tillage system induced compaction can also reduce soil permeability, limit the benefits of residue cover and generate major practical problems in conservation tillage (Li et al., 2001; Tullberg et al., 2001).

Compaction induced by conventional tillage system can result in low water use efficiency (Ishaq et al., 2000), greater losses of plant-available water and less use of fertilizer (Stepniewski and Przywara, 1992). Compaction also causes a severe loss of N due to denitrification. Abbasi and Adams (1999) reported a loss of more than 20% of applied N in compacted grassland soil due to denitrification.

In the overall, the NT soil preparation with high organic matter content from surface residue mulch will promote good root growth of cassava and reduce compaction of soil subsurface layer.

2.1.4.1. Land preparation for cassava. Till versus no-till: Cassava needs a sufficiently loosed-textured soil, not only for initial fibrous root penetration, but also to allow for root thickening. This may not require a thorough manual or mechanized soil preparation. When cassava was domesticated, it was probably cultivated principally by slash-and-burn practices that eliminate competition but does not alter soil structure. The only soil preparation probably used by earlier planters was loosening of the soil locally with a planting stick to bury the stake. The no-till techniques have been successfully applied on more than 100 million hectares worldwide (Verch et al., 2009; Lal, 2007), especially in the North and South America, as well as Australia. The merits of no-till techniques have likewise been practically demonstrated for China and Southern Europe (Wang et al., 2006; Garcia-Prechac et al., 2004; Lal, 2007). The benefits are both ecological and economic in nature. It is ecological in that it protects the soil from water and wind erosion, promotes higher efficiency of water usage in dry areas and carbon (C) sequestration in the soil ensure a sustainable way of farming (Derpsch et al., 1986; Schillinger and Young, 2004). No-till is the most viable and profitable considering the profitability of energy-saving (Nail et al., 2007).

These qualities essentially allowed the adoption of no-till soil preparation for cassava planting. Under degraded slash and burn agriculture or with permanent agriculture, a thorough loosening of the soil is normally required to allow the introduction of the stake and provide well drained, aerated conditions for the root system (Are et al., 2009). Cassava is a hardy crop withstanding many types of stress, but it easily succumbs to excessive soil moisture. And root rot, resulting in extensive yield losses. Soil preparation is necessary to allow good drainage and aeration (Reining, 1992).*Ridges, raised beds or mounds*: Consideration of soil topographical condition is important in the choice of tillage system. The NT system with residue cover is considered most appropriate in areas where soil topography is relatively flat (upland areas), where moisture infiltration is enhanced and excess water drains freely out to maintain a friable soil condition. In the Democratic republic of Congo, there was no significant yield difference from CT as compared with NT plots whenever the field was mulched but cassava root yield was lowest in unmulched, untilled plots (Ezumah and Okigbo, 1980). This observation may have been due to loss of soil organic matter that could protect soil surface layer from erosion and the decrease in soil organic carbon, which could improve soil structure and water retention capacity for enhanced root penetration.

In a related research, Reining (1992) compared conventional tillage with no tillage and minimum tillage systems where cassava was planted in an existing grass sod for three growing seasons and observed no significant difference in root yield of cassava between NT and CT, while the minimum tillage system yielded less than 30% of that obtained in the other two systems. The reduced yield under minimum tillage was thought to have resulted from higher soil bulk density and quick soil clod formation under dry condition. Odjugo (2008) in Nigeria observed highest soil moisture within the 0–15 cm soil depth under no tillage system but confirmed higher yield of up to 46% in the CT compared with NT without mulch. The implication of his finding as compared with previous researches was that the NT, like the CT will enhance root yield of cassava only if the soil superficial layer is mulched with crop residues, while reducing the cost associated with land preparation and soil compaction that could arise from the adoption of CT system.

Significant researches have been conducted in recent years on influence of tillage systems on root crops. Most of the research findings were concentrated on effects of tillage systems on soil physical and chemical properties, some of which are discussed below:

3. Soil physical properties

3.1. Bulk density

Tillage operations loosen, granulate, crush or even compact soil particles and soil factors that influence plant growth, such as bulk density, pore size distribution and the composition of the soil atmosphere may be affected. High bulk density decreases the root length and increases average root diameter of cassava. Lindstrom and Onstad (1984) reported that ploughing reduced soil bulk density while zero tillage has been shown to increase soil moisture retention and infiltration and lower soil temperature. In a related development, concentrations of organic carbon, total N, extractable P, exchangeable Ca, Mg and K have been shown in surface soil of zero till than tilled plots (Dick, 1983).

Bulk densities (BD) within the different layers of soil is a function of tillage system, the soil type and fertilizer management adopted. Arvidsson (1998) on effects of cultivation in reduced tillage on soil physical properties observed high bulk densities within the layer 0–10 cm in compacted soils under chisel and mouldboard plough (Table 1). He observed no difference in bulk densities between the two treatments within the 10–25 cm layer of soil due to soil compaction. Similar results were reported by Christian and Bacon (1990), Arvidsson and Feiza (1995) and Carter (1996).

Alvarez and Steinbach (2009) reviewed the effects of tillage on some soil properties and discovered significantly high bulk density under no-till than in plough tillage, but reported no difference between plough and reduced tillage. This agrees with the findings of Gantzer and Blake (1978) who reported significantly high bulk density with no-tillage treatments compared with conventional

Table 1
Dry bulk density (g cm^{-3}) of compacted and uncompacted soil under mouldboard ploughing and chiseling (Arvidsson, 1998).

Treatment	0–10 cm	10–25 cm
A = ploughing, not compacted	1.11	1.14
A = ploughing, compacted	1.28	1.23
B = chiseling 10 cm, not compacted	1.13	1.28
B = chiseling 10 cm, compacted	1.21	1.27
D = chiseling 20 cm, not compacted	1.14	1.19
D = chiseling 20 cm, compacted	1.27	1.22
A = mouldboard ploughing	1.19	1.19b
B = chiseling, 10 cm	1.21	1.28a
D = chiseling, 20 cm	1.17	1.21b
Not compacted	1.13b	1.20b
Compacted	1.26a	1.24a
Significance tillage	ns	*
Significance compaction	*	*
Significance interaction	ns	$p = 0.07$

Values given different letters are significantly different ($p < 0.05$).

tillage on fine textured soils. However, these authors confirmed increased bulk density in no-till where it was lower than 1.3 g cm^{-3}, the highest value above which no-till had no effect on soil density. In another development, conventional tillage is characterized with significantly high bulk density in the 10–20 cm soil layer compared with controlled traffic with shallow tillage (Wang et al., 2009), a situation might have been caused by random traffic. Similar observation was made by D'aene et al. (2008) in their studies on effects of reduced tillage on physical properties of silt loam soil growing root crops. These authors confirmed higher bulk density under minimum tillage compared with conventional tillage but found no differences in BD within the 25–30 cm layer when comparing minimum tillage with conventional tillage. However, the controlled traffic with shallow tillage had significantly lower bulk density than controlled traffic with no tillage in the 0–10 cm soil layer as shown in Table 2. The findings of Wang et al. (2009) suggested that the no-till soils are characterized with higher bulk density under controlled traffic situation. This indicates that the no-till system offers the soil structural stability in its natural state, most especially in the top soil. This situation is commonly found in soils under NT without surface mulch. Mulch cover loosen the superficial soil layer and promote the build-up of soil organic matter, a situation which is most appropriate for cassava production.

López-Fando and Pardo (2009) observed no significant difference in bulk densities between the no-till and conventional tillage in the 0–5 cm depth of soil, but confirmed that no-till is significantly higher than the conventional tillage at the 5–10 cm depth. Strudley et al. (2008) confirmed the effect of stubble mulch tillage on soil bulk density from the findings of Dao (1996).

Table 2
Mean soil bulk density of three treatments in 0–40 cm soil profile. All values are in g cm^{-3} (Wang et al., 2009).

Treatment	Soil depth			
	0–10 cm	10–20 cm	20–30 cm	30–40 cm
NTCN	1.37b	1.31a	1.36a	1.44a
STCN	1.20a	1.36a	1.41a	1.44a
CT	1.27ab	1.54b	1.41a	1.45a
SD	0.08	0.13	0.05	0.03
SE	0.03	0.04	0.02	0.01

NTCN: controlled traffic with no tillage and full residue cover; STCN: controlled traffic with shallow tillage and full residue cover; CT: random traffic with conventional tillage and partial residue cover; means within the same column in the same soil profile followed by the same letter are not significantly different at $p < 0.05$; SD: standard deviation; SE: standard error.

Table 3
The effect of tillage treatments on air-filled porosity (fa), total porosity (ft), and the ratio of air-filled to total porosity for 0–10 cm depth (Elder and Lal, 2008).

Tillage	fa ($cm^3 cm^{-3}$)	ft ($cm^3 cm^{-3}$)	fa/ft
13 June 2005			
MB	0.23a	0.74	0.32a
NT	0.15b	0.72	0.21b
B	0.19ab	0.73	0.26ab
LSD (0.05)	0.046	ns	0.06
7 July 2005			
MB	0.29a	0.72a	0.40a
NT	0.25b	0.70ab	0.35b
B	0.21c	0.68b	0.30c
LSD (0.05)	0.024	0.031	0.04

Values in each column followed by different letters are significantly different at $p < 0.05$ level.

Tebrügge and Düring (1999) also documented increased soil aggregation and earthworm population as a result of increased residue cover on soil and the consequent reduction of soil bulk density at the upper layer (0–10). The residue cover provided suitable habitats for soil organisms such as earthworms and arthropods, which burrow the soil creating better aeration and infiltration within the soil. These observations clearly support the adoption of no-till with residue cover on soil surface.

3.2. Soil porosity

Primary and secondary tillage operations pulverize the soil, break clods and loosen the soil, and often result to increased soil macropores and total porosity. Rahman et al. (2008) related soil physical, chemical and microbiological properties of an Andosol to land use and tillage and confirmed that total porosity was significantly greater in conventional tillage (CT) compared to paddy soil in which rice was grown with puddling (PD). Glab and Kulig (2008) also documented the influence of mulch and tillage on soil porosity. These researchers reported that mulch addition increased the total porosity in more compacted soil under reduced tillage. Elder and Lal (2008) observed a general trend of total porosity of soil under mouldboard plough (MB) > Bare soil (B) > No-till (NT) as presented in Table 3. However, no significant difference was observed in total porosity up to 4 weeks after tillage operation. Air-filled porosity (fa) was reported to be significantly more in MB than in NT treatment, indicating that MB created macropores compared to NT. Tilled soils had a greater proportion of macropores (>15 μm), relative to NT soils.

Lowest transmission pores content (0.078 $cm^3 cm^{-3}$) at the 0–10 cm soil layer in reduced tillage without mulch (RZ) was reported by Glab and Kulig (2008). The volume of transmission was significantly higher in conventional tillage treatment (Table 4). Reduced tillage without mouldboard plough (RM) reduced volume of transmission pores. Mulching was reported to ameliorate the soil condition in the upper layer (0–10 cm) and increased transmission pores content. Organic material presence in soil increases the transmission pores and consequently enhance root penetration and water movement.

3.3. Penetration resistance of soil

The penetration resistance of soil is a function of its compaction level as well as the volume of voids present within the soil compartment. Osunbitan et al. (2005) reported significant variations in soil penetration resistance among tillage some tested treatments. These authors recorded highest resistance of 0.61 kg cm^{-2} under the more compacted NT soil and least value of 0.15 kg cm^{-2} under intensively manipulated plough and harrowed (PH) plot. However, they observed no significant difference among the soil penetration resistance on all the treatments at the 0–5 cm depth. There were significant departures from this finding at the 5–10 cm and 10–15 cm depths, the NT treatment recording a significantly and consistently high penetration resistance. These authors also confirmed no significant difference in resistance between manually tilled soil and conventionally tilled soil (PP and PH).

They also documented increase in penetration resistance with time after tillage under manually tilled soil (MT), plough–plough (PP) and plough–harrowed (PH) plots but also observed slight decrease under NT treatment. Penetration resistance had a consistent relationship with yield of cassava over different soils (Baver et al., 1972; Vine and Ahmad, 1987), and largely determine yield when soil available water and air were significant. Soil air less than 12 ml air per 100 ml soil will limit cassava growth (Vine and Ahmad, 1987). Arvidsson (1998) reported small differences between the mouldboard-ploughed and chiseled soil in the tilled part of the soil, whereas the penetration was higher in untilled soil. The mouldboard plough was confirmed more efficient than chisel implement in soil loosening. Similar observation was made by Carter (1996). The soil pulverized with mouldboard plough however is susceptible to erosion.

4. Tillage effect on cassava yield

Effect of various tillage treatments on cassava yield depends mainly on soil type, the site history as well as the climate conditions during preparation and planting (Howeler et al., 1993). Lal and Dinkins (1979) and Ezumah (1983) reported higher yield of cassava in untilled soil than in tilled soil in an Oxisol in Zaire. These researchers confirmed NT resulted in low root density, low dry matter and N accumulation in leaves stems and roots. In contrast,

Table 4
Bulk density, macroporosity (>30 μm) and differential porosity of investigated soil for tillage and mulch treatments. Glab and Kulig (2008).

Treatments	Bulk density ($g cm^{-3}$)	Total porosity ($cm^3 cm^{-3}$)	Macroporosity ($cm^3 cm^{-3}$)	Pores		
				Transmission	Storage	Residual
0–10						
RZ	1.35a	0.466b	0.147b	0.078b	0.236a	0.096a
RM	1.25b	0.508a	0.197a	0.112a	0.234a	0.091a
CZ	1.26b	0.503a	0.190a	0.108a	0.237a	0.089a
CM	1.23b	0.514a	0.201a	0.115a	0.228a	0.090a
10–20 cm						
RZ	1.38a	0.458b	0.142b	0.078b	0.220a	0.094a
RM	1.37a	0.463b	0.149b	0.082b	0.214a	0.092a
CZ	1.25b	0.508a	0.210a	0.121a	0.217a	0.087a
CM	1.24b	0.512a	0.210a	0.121a	0.217a	0.087a

Average of 3 years, 2004–2006. Means in columns for particular soil layer followed by the same letters are not significantly different ($p < 0.05$). RZ: reduced tillage without mulch; RM: reduced tillage with mouldboard; CZ: conventional tillage without mulch; CM: conventional tillage with mouldboard.

Table 5
Effect of cultivation and mulching on root yield (t ha^{-1}) of cassava cultivar '02864' at two sites in Zaire (Howeler et al., 1993).

Tillage treatment	Mpalukidi (sandy clay loam)		Kimpese (clay loam)	
	Mulch	No mulch	Mulch	No mulch
Flat	21.8	16.1	6.9	5.6
Ridge	17.4	13.9	8.0	4.8
No-till	20.7	12.4	3.7	2.7
Mean	19.9	14.1	6.2	5.3
LSD (5%)	2.3	1.9	2.2	2.0

Ezumah and Okigbo (1980).

Table 6
Average responses of cassava top biomass, yield and root dry matter content (8 years) and total root HCN (5 years) on dry weight basis to surface plant mulch, fertilizer and tillage in sandy loam soils, northern Colombia (Cadavid et al., 1998).

Treatments	Fertlization				No fertilization			
	Root yield (t ha^{-1})	Top biomass (t ha^{-1})	Root dry matter (%)	Root HCN	Root yield (t ha^{-1})	Top biomass (t ha^{-1})	Root dry matter (%)	Root HCN
CT	5.51	3.18	30.2	158	2.19	1.43	30.1	227
CT + mulch	5.92	3.98	30.9	146	4.66	2.93	30.6	149
NT	4.42	2.77	29.5	150	1.93	1.43	29.2	224
NT + mulch	6.11	3.85	31.0	140	4.66	2.95	30.4	158
Mean	5.49	3.45	30.4	148	3.36	2.19	30.1	189
LSD (5%)	0.77	0.68	0.88	18	0.35	0.49	0.77	0.32

Howeler et al. (1993) observed similarity in the yield of cassava in NT treatment and tilled treatment on a sandy loam soil of Zaire. Similar observation were reported by Maurya and Lal (1979) and Raros (1985). NT significantly decrease yield of cassava in mulch and unmulched plots of Kimpese, Zaire (Ezumah and Okigbo, 1980) but an experiment conducted by Ohiri and Ezumah (1990) in a sandy clay loam Ultisol in humid south-east Nigeria showed that NT and MT had no significant effect on cassava root yield, but significantly increased top yields in the second year, compared with conventional tillage (Table 5). Ofori (1973) in Ghana reported that ploughing increased cassava yield compared with superficial hoeing, while, Okigbo (1979) at Nsukka, Nigeria found that ploughing significantly increased yield only in the first one year out of three years, and that benefits from mulching were significant in all three years. Findings of these researchers implies that NT contribute significantly to above ground biomass yield but the conventional tillage is mostly beneficial in terms of root yield and this may have resulted from pulverization of soil up to the subsurface layer, thus, giving room for ease of cassava root penetration into soil.

Cadavid et al. (1998) on long-term effects of mulch, fertilization and tillage on cassava in a sandy loam soil confirmed an increase in top biomass production of cassava by mulching in every cropping cycle, regardless of tillage and fertilization treatment (Table 6). They concluded that mulching was beneficial for above ground biomass production (stem), which serve as planting material for subsequent cropping season. Mulching is generally known to reduce soil temperature, improve moisture availability to crop and improve the organic matter content of the soil.

5. Conclusion

Our study reviewed and investigated soil conservation techniques, i.e. no-till and minimum tillage systems relatively with the conventional tillage method and soil under compaction, from the reappraisal of the of the different tillage systems on soil physical properties (bulk density, total porosity and penetration resistance) in a field cultivated on cassava. Our research review showed that the NT treatment is characterized with reduced bulk density principally at the surface soil, i.e. 0–5 cm and sometimes up to the 0–10 soil layers due to organic matter layer formation from residues of previous crop. The conservation of the structure of the surface soil and the combined effect of soil water conservation and reduced temperature due to residue cover under the NT contributed greatly to the above ground biomass formation of cassava, relatively with the CT and soil under CP. However, from our review, it was discovered that though penetration resistance was higher in NT than plots under CT and MT, which could have meaningful effect on the root yield of cassava, the NT system is most profitable in terms of nutrients build-up in soil for optimum crop yield. The cost benefits of the NT comparatively with CT could make the NT system an optimum system of cassava production.

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References

Abbasi, M.K., Adams, W.A., 1999. Assessment of the contribution of denitrification to N losses from compacted grassland soil by NO_3 disappearance and N_2O production during anaerobic incubation. Can. J. Soil Sci. 79, 57–64.
Alvarez, R., Steinbach, H.S., 2009. A review of the effects of tillage systems on some soil physical properties, water content, nitrate availability and crops yield in the Argentine Pampas. Soil Till. Res. 104, 1–15.
Angers, D.A., N'dayegamiye, A., Côté, D., 1993. Tillage-induced differences in organic matter of particle-size fractions and microbial biomass. Soil Sci. Soc. Am. J. 57, 512–516.
Anken, T., Weisskopf, P., Zihlmann, U., Forrer, H., Jansa, J., Perhacova, K., 2004. Long term tillage system effects under moist cool conditions in Switzerland. Soil Till. Res. 78, 171–183.
Are, K.S., Oluwatosin, G.A., Adeyolanu, O.D., Oke, A.O., 2009. Slash and burn effect on soil quality of an Alfisol: soil physical properties. Soil Till. Res. 103, 4–10.
Arshad, M.A., Franzluebbers, A.J., Azooz, R.H., 1999. Components of surface soil structure under conventional and no-tillage in northwestern Canada. Soil Till. Res. 53, 41–47.
Arvidsson, J., 1998. Effects of cultivation depth in reduced tillage on soil physical properties, crop yield and plant pathogens. Eur. J. Agron. 9, 79–85.
Arvidsson, J., Feiza, V., 1995. Lăga ringtryck i odling med och utan pl?jning. Internal report 18, Division of Soil Management, Swedish University of Agricultural Sciences, Uppsala (in Swedish, with English summary).

Baver, L.D., Gardner, W.H., Gardner, W.R., 1972. Soil Physics, 4th ed. Willey, New York.
Blevins, R.L., Frye, W.W., 1993. Conservation tillage: an ecological approach to soil management. Adv. Agron. 51, 33–78.
Bowen, H.D., 1981. Alleviating mechanical impedance. In: Arkin, G.F., Taylor, H.M. (Eds.), Modifying the Root Environment to Reduce Crop Stress. ASAE Monograph No. 4, Am. Soc. Agric. Engineers, St. Joseph, MI, pp. 21–57.
Bradfield, R., 1970. Multiple cropping system for the tropics. In: Traditional Agricultural Systems and their Improvements. Symposium Proc., IITA, Ibadan, Nigeria, 16–20 November.
Cadavid, L.F., EL-Sharkawy, M.A., Acosta, A., Sánches, T., 1998. Long-term effects of mulch, fertilization and tillage on cassava grown in sandy soils in northern Colombia. Field Crops Res. 57, 45–56.
Cambardella, C.A., Elliott, E.T., 1992. Particulate soil organic matter changes across a grassland cultivation sequence. Soil. Sci. Soc. Am. J. 56, 777–783.
Carter, M.R., 1992. Influence of reduced tillage system on organic matter, microbial biomass, macro-aggregate distribution and structural stability of the surface soil in the humid climate. Soil Till. Res. 23, 361–372.
Carter, M.R., 1996. Characterization of soil physical properties and organic matter under long-term primary tillage in a humid climate. Soil Till. Res. 38, 251–263.
Charreau, C., Nicou, R., 1971. Ĺamélioration du profil cultural dans les sols sableux et sablo-argileux de la zone tropicale sèche oust-africaine et ses incidences agronomiques. Ĺagronomie tropicale 26, 209–255.
Christian, D.G., Bacon, E.T.G., 1990. A long-term comparison of ploughing, tine cultivation and direct drilling on the growth and yield of winter cereals and oilseed rape on clayey and silty soils. Soil Till. Res. 18, 311–331.
Connolly, R.D., Freebairn, D.M., Bridge, B.J., 1997. Change in infiltration characteristics associated with cultivation history of soils in south-eastern Queensland. Aust. J. Soil Res. 35, 1341–1358.
Dao, T.H., 1996. Tillage system crop residue effect on surface compaction of a paleustoll. Agron. J. 88, 141–148.
Derpsch, R., Friedrich, T., 2009. Global overview of conservation agriculture adoption. In: 4th Congress on Conservation Agriculture, New Delhi, India, February 4–7.
D'aene, K., Vermang, J., Cornelis, W.M., Leroy, B.L.M., Schiettecatte, W., De Neve, S., Gabriels, D., Hofman, G., 2008. Reduced tillage effects on physical properties of silt loam soils growing root crops. Soil Till. Res. 99, 279–290.
Derpsch, R., Sidiras, N., Roth, C.H., 1986. Results of studies made from 1977 to 1984 to control erosion by cover crops and no-tillage techniques in Parana. Brazil. Soil Till. Res. 8, 253–263.
Dick, W.A., 1983. Organic carbon, nitrogen and phosphorus concentrations and pH in soil profile as affected by tillage intensity. Soil Sci. Soc. Am. J. 47, 102–107.
Ehlers, W., 1975. Observations on earthworm channels and infiltration on tilled and untilled loess soil. Soil Sci. 119, 242–249.
Elder, J.W., Lal, R., 2008. Tillage effects on physical properties of agricultural organic soils of north central Ohio. Soil Till. Res. 98, 208–210.
Ezumah, H.C., Okigbo, B.N., 1980. Cassava planting and system in Africa. In: Weber, E.J., Toro, J.C., Graham, M. (Eds.), Cassava cultural Practices Proc. Workshop, Salvador, Bahia, Brazil. IDRC-151C, Ottawa, Ont. Canada, March 18–21, pp. 44–49.
Ezumah, H.C., 1983. Agronomic considerations of no-till farming. In: Akobundu, I.O., Deuatch, A.E. (Eds.), No-Tillage Crop Production in the Tropics. Oregon State University, Corvallis, pp. 102–110.
FAO, 1993. Soil Tillage in Africa: Needs and Challenges. FAO Soils Bulletin No. 69, Rome, Italy.
Food and Agriculture Organization (FAO), 2007. Agriculture and Consumer Protection Department. Rome, Italy. http://www.fao.org/ag/ca/in
Gantzer, C.J., Blake, G.R., 1978. Physical characteristics of LeSueur clay loam soil following no-till and conventional tillage. Agron. J. 70, 853–857.
Garcia-Prechac, F., Ernst, O., Siri-Prieto, G., Terra, J.A., 2004. Integrating no-till into crop-pasture rotations in Uruguay. Soil Till. Res. 77, 1–13.
Glab, T., Kulig, B., 2008. Effect of mulch and tillage system on soil porosity under wheat (Triticum aestivum). Soil Till. Res. Amsterdam 99, 169–178.
Gowman, M.A., Coutts, J., Riley, D., 1987. Direct Drilling, Soil Physical Conditions and Crop Growth. ICI, Plant Protection Div. Ecology station, Jealotťs Hill, UK.
Gupta, S.C., Schneider, E.C., Larson, W.E., Hadas, A., 1987. Influence of corn residue on compression and compaction behaviour of soils. Soil Sci. Soc. Am. J. 51, 207–212.
Hobbs, P.R., Sayre, K., Gupta, R., 2008. The role of conservation agriculture in sustainable agriculture. Philos. Trans. R. Soc. Lond. B: Biol. Sci. 363 (1491), 543–555.
Howeler, R.H., Ezumah, H.C., Midmore, D.J., 1993. Tillage systems for root and tuber crops in the tropics. Soil Till. Res. 27, 211–240.
IFAD, 1992. Soil and Water Conservation in Sub-Saharan Africa. Towards Sustainable Production by the Rural Poor. Areport prepared for IFAD by CDCS, Amsterdam.
Ishaq, M., Hassan, A., Saeed, M., Ibrahim, M., Lal, R., 2000. Subsoil compaction effects on crops in Punjab, Pakistan. I. Soil physical properties and crop yield. Soil Till. Res. 59, 57–65.
Jensen, E.S., 1994. Mineralization-immobilization of nitrogen in soil amended with low C:N ratio plant residues with different particle sizes. Soil Biol. Biochem. 26, 519–521.
Jongruaysup, S., Trelo-ges, V., Chuenrung, C., 2003. Minimum tillage for cassava production in Khon Kaen Province, Thailand. Songklanakarin J. Sci. Technol. 25 (2), 191–197.
Kaumbutho, P.G., Simalenga, T.E. (Eds.), 1999. Conservation Tillage with Animal Traction. A Resource Book of the Animal Traction Network for Eastern and Southern Africa (ATNESA). ATNESA publications, Harare, Zimbabwe, 173 p.
King, A.D., 1983. Progress in no-till. Journal of Soil and Water Conservation Special issue "Conservation Tilllage", 38 (3), 160–161.
Lal, R., 1982. No-till farming. IITA Monograph No. 2, Ibadan, Nigeria.
Lal, R., 1987a. Managing the soils of sub-Saharan Africa. Science 236, 1069–1076.
Lal, R., 1995. Minimum tillage systems. In: Jayawardane, N.S., Stewart, B.A. (Eds.), Advances in Soil Science: Subsoil Management Techniques. Lewis Publishers, Boca Raton, pp. 1–33.
Lal, R., Dinkins, E.L., 1979. Tillage systems and crop production on an ultisol in Liberia. In: Lal, R. (Ed.), Soil Tillage and Crop Production Proc. Ser, No. 2. International Institute of Tropical Agriculture, Ibadan, Nigeria, pp. 221–233.
Lal, R., 2007. Constraints to adopting no-till farming in developing countries. Soil Till. Res. 94, 1–3.
Lavelle, P., 1984. The soil system in the humid tropics. In: Biology International, IUBS, Paris, pp. 1–17.
Li, Y.X., Tullberg, J.N., Freebairn, D.M., 2001. Traffic and residue cover effects on infiltration. Aust. J. Soil Res. 39, 239–247.
Lindstrom, M.J., Onstad, C.A., 1984. Influence of tillage systems on soil physical parameters and infiltration after planting. J. Soil Water Conserv. 39, 149–152.
Logsdon, S.D., Allmaras, R.R., Wu, L., Swan, J.B., Randall, G.W., 1990. Macroporosity and its relation to saturated hydraulic conductivity under different tillage practices. Soil Sci. Soc. Am. J. 54, 1096–1101.
López-Fando, C., Pardo, M.T., 2009. Changes in soil chemical characteristics with different tillage practices in a semi-arid environment. Soil Till. Res. 104 (2), 278–284.
Mannering, J.V., Fenster, C.R., 1983. What is conservation tillage? J. Soil Water Conserv. 38, 141–155.
Mari, G.R, Changying, J.I., 2006. Conservation tillage for the protection of soil quality and sustainability. American-Eurasian J. Sci. Res. 1 (1), 55–60.
Maurya, P.R., Lal, R., 1979. No-tillage system for crop production on an ultisol in Eastern Nigeria. In: Lal, T. (Ed.), Soil Tillage and Crop Production. Proc. Ser. No. 2. International Institute of Tropical Agriculture, Ibadan, Nigeria, pp. 207–219.
Nail, E.L., Young, D.L., Schillinger, W.F., 2007. Diesel and glyphosate price changes benefit the economics of conservation tillage versus traditional tillage. Soil Till. Res. 94, 321–327.
New Standard Encyclopedia, 1992. Standard Educational Operation. New Standard Encyclopedia, Chicago, IL, A-141, C-546.
Odjugo, P.A.O., 2008. The impact of tillage systems on soil micro-climate, growth and yield of cassava (Manihot utilisima) in midwestern Nigeria. Afr. J. Agric. Res. 3 (3), 225–233.
Ofori, C.S., 1973. The effect of ploughing and fertilizer application on yield of cassava. Ghana J. Agric. Sci. 6, 21–24.
Ohiri, A.C., Ezumah, H.C., 1990. Tillage effects on cassava (Manihot esculenta) production and some soil properties. Soil Till. Res. 17, 221–229.
Ohu, J.O., Raghavan, G.S.V., McKeys, E., 1985. Peatmass effect on the physical and hydraulic characteristics of compacted soils. Trans. ASAE 28, 420–424.
Okigbo, B.N., 1979. Effect of preplanting cultivations and mulching on the yield and performance of cassava. In: Lal, T. (Ed.), Soil Tillage and Crop Production. IITA, Ibadan, Nigeria.
Osunbitan, J.A., Oyedele, D.J., Adekalu, K.O., 2005. Tillage effects on bulk density, hydraulic conductivity and strength of a loamy sand soil in southwestern Nigeria. Soil Till. Res. 82, 57–64.
Phalla, M., 2005. Co-generation of Energy and Feed/food in Integrated Farming Systems for Socio-economic and Environmental Benefits. CelAgrid, UTA, Cambodia, 1 pp.
Rahman, M.H., Okubo, A., Sugiyama, S., Mayland, H.F., 2008. Physical, chemical and microbiological properties of an Andisol as related to land use and tillage practice. Soil Till. Res. 101, 10–19.
Raros, R.S., 1985. Evaluation and development of hillside farming techniques for root crop production. Terminal Report. VISCA, Department of Forestry, Baybay, Leyte, Philippines, 29 pp.
Reining, L., 1992. Erosion in Andean Hillside Farming, Hohenheim Tropical Agricultural Series No. 1. Margraf Nerlag, Weikersheim, Germany.
Roth, C.H., Meyer, B., Frede, H.G., Derpsch, R., 1998. Effects of mulch rates and tillage system on infiltrability and other soil physical properties of an oxisol in Parana, Brazil. Soil Till. Res. 11, 81–91.
Schillinger, W.F., Young, D.L., 2004. Wheat-cropping systems research in the world's driest rainfed wheat region. Agron. J. 96 (4), 1182–1187.
Shetto, R.M., 1999. Indigenous soil conservation tillage systems and risks of animal traction on land degradation in Eastern and Southern Africa. In: Kaumbutho, P.G., Simalenga, T.E. (Eds.), Conservation Tillage with Animal Traction. A Resource Book of the Animal Traction Network for Eastern and Southern Africa (ATNESA), Harare, Zimbabwe, p. 173.
Sidiras, N., Roth, C.H., 1985. Measurement of infiltration with double-ring infitrometers and rainfall simulator as an approach to estimate erosion by water under different surface conditions on an Oxisol. In: 10th ISTRO Conf, Guelph, Ontario, Canada, Mimeo, July 8–12, p. 14.
Sorrenson, W.J., Montoya, L.J., 1984. Economic Implications of Soil Erosion and Soil Conservation Practices in Paraná, Brazil. Report for the German Agency for Technical Cooperation, GTZ and Fundaçao Instituto Agronómico do Paraná, IAPAR, 221 pp.
Sorrenson, W., Durarte, C., Lopez Portillo, J., 1998. Economics of no-till compared to conventional cultivations systems on small farms in Paraguay. Policy and

investment implications. Report to the MAG–GTZ Soil Conservation Project, DEAG-MAG, 68 pp., plus annexes.
Sorrenson, W., Lopez Portillo, J., Derpsch, R., Nunez, M., 1997. Economics of no-tillage and crop rotations compared to conventional cultivation cropping systems in Paraguay. In: 14th ISTRO Conference, Agroecological and Economical Aspects of Soil Tillage, Pulawy, Poland, July 27–August 1.
Spoor, G., 2000. Compaction characteristics of swelling clay subsoils. In: Horn, R., van der Akker, J.J.H., Arvidsson, J. (Eds.), Subsoil Compaction Distribution, Processes and Consequences. Advances in Geo-Ecology. pp. 427–434.
Stepniewski, W., Przywara, G., 1992. The influence of soil oxygen availability on yield and nutrient uptake by winter rye (Secale cereale). Plant Soil 143, 267–274.
Strudley, M.W., Green, T.R., Ascough II, J.C., 2008. Tillage effects on soil hydraulic properties in space and time: state of the science. Soil Till. Res. 99, 4–48.
Tebrügge, F., Düring, 1999. Reducing tillage intensity—a review results fro m a long-term study in Germany. Soil Till. Res. 53 (1), 15–28.
Tullberg, J.N., Ziebarth, P.J., Li, Y.X., 2001. Tillage and traffic effects on runoff. Aust. J. Soil Res. 39, 249–257.
Unger, P.W., Langdale, G.W., Papendick, R.I., 1988. Role of crop residues – improving water conservation and use. In: Hargrove, W.L. (Ed.), Cropping Strategies for Efficient Use of Water and Nitrogen. American Society of Agronomy Special Publication No.51, pp. 69–100.
Unger, P.W., 1994. Residue management strategies-great plains. In: Hatfield, J.L. (Ed.), Crops Residue Management, Advances in Soil Science. CRC Press, Inc., Boca Raton, pp. 37–61.
Verch, G., Kächele, H., Höltl, K., Richter, C., Fuchs, C., 2009. Comparing the profitability of tillage methods in Northeast Germany—a field trial from 2002 to 2005. Soil Till. Res. 104, 16–21.
Vine, P.N., Ahmad, N., 1987. Yield development in cassava under different soil physical conditions. Field Crop Res. 17, 175–198.
Wang, X.B., Cai, D.-X., Hoogmoed, W.B., Oenema, O., Perdok, U.D., 2006. Potential effect of conservation tillage on sustainable land use: a review of global long-term studies. Pedosphere 16, 587–595.
Wang, Q., Chen, H., Li, H., Li, W., Wang, X., McHugh, A.D., He, J., Gao, H., 2009. Controlled traffic farming with no tillage for improved fallow water storage and crop yield on the Chinese Loess Plateau. Soil Till. Res. 104, 192–197.