Soil Dynamics in Tillage

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ABSTRACT

The paper provides an overview of the various subsystems of the soil-machine-plant system with special focus on soil-machine dynamics. The parameter and relationships used for analysis of such subsystems as well as research facilities are highlighted. The different approaches for analysis of soil-machine interaction are outlined to include: the Universal Earthmoving Equation, Trial Wedge Approach, Stress Characteristics Approach, Finite Element Method and Similitude Techniques. Applications of these studies are discussed in areas of design optimization for tillage tools, development of new tillage implements and traction devices, energy, soil and water conservation in tillage as well as economics of tillage operations including sustainability. It was noted that most of the work in soil dynamics including the applications have been outside Nigeria. The reasons for this were identified to include: lack of research facilities, lack of data on relevant soil-machine parameters required in soil-machine dynamics modeling, lack of local machinery manufacturing industries; lack of adequate funding for long term research and poor effective network of tillage researchers in Nigeria in particular and Africa in general. In order to improve soil dynamics research and applications, the paper recommends reactivating an earlier proposal to establish a National Tillage Machinery Laboratory at the National Centre for Agricultural Mechanization (NCAM); establishing Regional Centres of Excellence in Tillage Studies; Identification and execution of priority flagship projects in tillage; establishment of National tillage exhibition and competitions; and promotion of investment in local manufacture of tillage tools and machinery.

Keywords: *Soil dynamics, tillage, finite element, stress characteristics, soil mechanics, traction.*

1. Introduction

Food security is a major challenge to developing countries of Sub-Saharan Africa. In order to solve this problem, efforts are currently made by different stakeholders to increase the productivity of agriculture in order to produce more food at lower costs and in a sustainable manner. Some of these efforts are based on increasing the productivity of the land and some on bringing more land under cultivation. Whatever the approach is, these efforts are also challenged with renewed interests on environmental sustainability. In other words, whatever technologies that are used must satisfy the requirements of energy, soil and water conservation in order to ensure sustainability.

In conventional crop production systems, tillage accounts for over 50% of the energy expended from land clearing to harvesting. Therefore, in trying to improve productivity of crop production, more efforts should be devoted to improving the productivity of tillage operations. Tillage itself refers to the mechanical manipulation of the soil in order to provide the conditions necessary for crop growth. Since these conditions vary with crop and soil conditions, it is important to study the different aspects of soil-machine-plant system in order to minimize the deleterious effects of the interaction among the three main components of the system (soil, machine and crop). Attempts have been made in the past to study the soil-machine-plant system (Hadas et al, 1988). However, it appears that most of the studies have concentrated on different aspects such as the soil-machine subsystem, machine-plant subsystem and soil-plant subsystem. (Ekelewe et al, 2005; Ogban and Babalola, 2009; Adeyemi et al, 2007; Aniekwe, 2010; Anazado et al, 1991; Lal, 1979; Onwualu and Anazodo, 1989; Anazodo et al, 1991b; Oni, 1991; Manuwa and Ademosun 2007).

The objective of this paper is to present a critical appraisal of work done in analysis of soil dynamics in tillage with particular reference to Nigeria. In doing this, the paper presents: a descriptions of the soil-machine-crop (SMC) system and all the parameters used in the analysis of the system; analytical tools used in analysis of soil dynamics, applications of the analysis in tillage operations, challenges and the way forward towards optimizing tillage operations in Nigeria.

2. Soil-Machine Crop System

Tillage refers to any manipulation of the soil aimed at providing conditions necessary for crop growth. In a classical modern production system, a machine is used to manipulate the soil in order to provide the conditions required for the crop to grow. These conditions vary according to need including weed control, providing desired soil structure, incorporation of residues, preparation of land for irrigation, mixing fertilizer and other soil amendments into the soil and destroying insects, pest etc, (Anazado et al, 1991). Because of the various requirements, soil type and condition, there are various tillage methods covering a wide spectrum from zero tillage to conventional tillage (Lal, 1979; Young, 1982; Anazodo et al, 1991; Anazodo et al, 1991b). Whatever the type of tillage used, we can understand the interactions by looking at the soil – machine – crop subsystems as a complete system in itself (Hadas et al, 1988). This is illustrated in Fig. 1. The machine, which can be a tillage implement, traction device, planter, fertilizer applicator, excavator etc is used to change the soil condition by breaking it up or compacting it. In reaction, the soil offers some resistance to the machine resulting in wear and tear, high energy demand and hence high production cost. By analyzing the soil-machine interaction, it is possible to optimize this process. On the other hand, the soil provides the environment which the crop requires for growth. In so doing, the crop also replenishes the soil with organic matter or depletes nutrients in the soil. Analysis of the soil-crop system ensures optimization of crop yield and at the same time ensuring sustainability in terms of soil and water conservation, and energy conservation (Aikpokpodion et al, 2009; Anekwe, 2010; Ayuba etal, 2000; Adeyemi etal, 2007).

The field of soil dynamics has been developed to identify various subsystems above, identify various parameters for each subsystem and to explain the interactions among the machine, soil and crop (Gill and Vandern Berg, 1968). The machine is usually characterized by a number of parameters including draught, energy required, speed, width, depth was rake angle. The soil is characterized by cohesion, structure, angle of internal friction, cone index, dry density and soil nutrients. The soil-metal interface is characterized by angle of soil-metal friction, adhesion, wear factors etc. The crop is characterized by germination, weed control, leaf area index, and yield. Analysis of the entire system and the subsystems provides the tool to predict the performance of the machine, crop and soil. The main aim of soil dynamics analysis is to conserve energy, soil, and water, then ensuring high yields at low costs and sustainability of production.

Most of the studies are carried out through field experiments, laboratory experiments in soil bins, and simulation of soil-tool interaction using existing passive earth pressure theories with modifications to account for inertial effects (Mamman et al, 2004; Mamman and Oni, 2007; Manuwa and Ajisafe, 2010; Onwualu and Watts, 1999).

These analysis can be used to optimize the design and performance of different types of tillage machinery from hand tools (hoe, spade, digger) to animal drawn implements (ox-plough) to tractor mounted implements (disc ploughs, mould board ploughs, ridgers, rotary tillers etc) (Oni, 1981; 1983; Onwudinjo eta al, 1997; Onwualu, 1997). The analysis has also been used to develop new tillage practices, machines and related equipment (Adekoya and Buchele, 1983; Ekeleme eta al, 2005; Asi and Singh, 2009; Ogban and Babalola, 2009; Onwuji and Braida, 1983; Tripplett and Van Doren, 1977; Wijewardene, 1979).

3. Analysis of Soil-Machine Dynamics in Tillage

The analysis of soil dynamics in tillage mostly involve determination of cutting forces for tillage implements as a function of soil, over burden (surcharge) tool and soil-tool factors. Once the cutting force is determined, it can be used with velocity or tool speed to obtain power requirement and specific draught using appropriate equations (Onwualu, and Watts, 1998; Gill and Vandern Berg, 1968; McKyes, 1985; Payne 1956).

A number of approaches have been used in this analysis. These include: the Universal Earthmoving Equation (UEE), Trial Wedge Approach, Stress Characteristics Approach, Finite Element Approach and Similitude (dimensional analysis) Technique.

3.1 The Universal Earthmoving Equipment (UEE)

The Universal Earthmoving Equation (UEE) is an additive equation used to estimate soil cutting force per unit width of blade (Reece, 1964). Although the equation was developed for earthmoving of bulldozer blades, it has been modified and applied both in passive and dynamic analysis of soil-machine interaction (McKyes, 1985). This is given as:

$$P = rgd^2Nr + cdNc + QdNq + CadNca + rv^2dN_a \quad \text{........................} (1)$$

Where,

P = soil cutting force per unit width of blade,

r = bulk density, g = acceleration due to gravity,

d = tool depth,

c = cohesion,

Q = surcharge,

Ca = soil-metal adhesion,

v = speed.

The N-factors represent different terms considered in soil-tool interaction as follows:

Nr = N-factor for density

Nq = N-factor for surcharge

Nc = N factor for cohesion

Nca = N-factor for adhesion

Na = N-factor for acceleration

These factors could only be determined by the use of charts as they are functions of an unknown rupture distance which is a function of the rake angle and soil failure angle. The difficulty in using the charts led to the search for other methods that can lead to closed form solutions.

3.2 Trial Wedge Approach

The Trial Wedge Approach is based on assuming a soil failure pattern usually referred to as a wedge. Different geometries have been assumed by different researchers defined by the dimensions of the wedge, rake angle and soil failure angle. Most of the wedge geometry are patterned after bearing capacity theory for foundations. The cutting force is expressed through equilibrium analysis as a function of the wedge geometry, rake angle, soil factors (cohesion, density), angle of internal function, tool factors (width, speed, depth, rake angle) and soil – soil metal function. Different approaches have been used to solve the resulting equations including use of charts, log-spiral method and minimization of the force with respect to the unknown failure angle to obtain a closed form solution. The trial wedge approach has been used for different applications including passive and dynamic analysis for two dimensional (wide blade) and three dimensional (narrow times) (Onwualu and Watts, 1998; McKayes, 1985).

Although this approach has been used widely, one major constraint is that it is mostly applicable to plane tools and has not been successfully applied to curved tools of complex geometry.

3.3 Stress Characteristics Approach

The approach theoretical framework for the Stress Characteristics Approach was given by Mckyes, (1985) based on earlier formulations by Sykolovski (1960). It is assumed that when the soil is subjected to a load, instead of the soil failure pattern being a wedge as in trial wedge approach, a series of shear failure planes referred to as slip (or characteristic) lines are developed. These can be grouped into two groups of slip lines at a characteristic angle to each other by assuming a soil failure geometry similar to the wedge approach. The geometry is divided into grids defined by intersection of the slip lines. Passive earth pressure theory is used to develop equations for stresses along the slip lines. The variations of these stresses for each element of the grid are described in terms of partial differential equations. Solutions can be obtained in closed form for simple cases, but for complex tools the numerical technique of finite difference is used (McKyes, 1985; Onwualu, et al, 1997; Reece and Hettiaratchi, 1989).

In addition to determining cutting forces, this approach can be used to determine stress distribution in the soil mass and hence can be used to predict the final state of the soil.

3.4 The Finite Element Method (FEM)

The fundamental principles of the Finite Element Method (FEM) and its application in solving Agricultural Engineering problems were outlined by Obetta and Onwualu, (1996).

Yong and Hanna, (1977) first proposed a Finite Element Model for a two dimensional soil failure under a wide blade. The analysis was used to determine both soil forces and stress field. Since then, a number of researchers have applied the FEM to analyse soil-machine dynamics (Xie and Zhang, 1985).

Chi and Kushwaha, (1987) developed a three dimensional FEM for a narrow blade. Chi and Kushwaha, (1988) developed model which was used to predict soil forces. The FEM is the most flexible of all the approaches because it allows the researcher to assume any soil failure pattern, any tool geometry and computations can be done for any set of conditions. The only constraint is the complex mathematical (numerical) computations.

3.5 Dimensional Analysis

The earliest known method of analysis of soil-machine interaction is by analysis of the similitude of the system. By using relevant parameters to describe the soil-toll-system, different terms referred as Pi-terms are formed. Using Buckingham-Pi theorem, relationships are established between different Pi terms. The results are usually validated in scale model experiments and results later scaled up to describe actual full scale implements.

4. Applications of Soil Dynamics in Tillage

For the analysis of soil-machine dynamics to be useful, it must be applied to solving real life problems. In other words, it must be able to contribute towards improving the processes and machinery required for providing a sustainable tillage system. In this case, such a system should modify the soil to provide optimal conditions necessary for crop growth and yield and at the same time ensuring sustainability in terms of conserving energy, soil and water and ensuring non-destruction of soil structure. Some of the applications of the practical applications include: design optimization of tillage tools and traction devices, development of new tillage implements and traction devices, energy, soil and water conservation and providing technical and scientific basis for evolving a sound economics of tillage.

4.1 Optimization of tillage Tools

As already noted, there are many tillage implements from hand tools to animal drawn ploughs and different tractor mounted plough tillers, harrows, etc. Although these machines are already designed and in use, engineers continue to work on them especially with respect to modifying them to address conservation issues and other issues relating to soil structure destruction. These involve changes in the tool parameters (width, depth, sharpness, rake angle, smoothness etc) and the manner in which they engage and fail the soil depending on how the tool forces are applied to the soil. By studying and manipulating the tool and soil parameters, it is possible to optimize the design and operation of these tools (Asi and Sign, 2009).

4.2 Development of New Tillage Implements

In the development of any tillage implement or related machinery, there is need to understand soil failure pattern, soil movements, and interaction between these and the machine. These will enable the designer to determine the best way to fail the soil, the best way to make the soil move through the surface of the blade or indeed how to reduce the soil strength without necessarily inverting or pulverizing the soil. The analysis of soil dynamics also enables the designer to determine maximum tool forces, soil bearing capacity, etc which will enable him determine appropriate sizes of components of the machine.

4.3 Energy Conservation in Tillage

In modern day tillage, especially with new knowledge in precision agriculture, the conventional tillage system of plough, harrow, and ridge in separate operations is no more in vogue. In the classical conventional method, the concept is to apply a force much higher than the bearing capacity or strength of the soil such that the soil fails and shatters. It is also inverted, pulverized and so on. All these consume excessive energy in terms of tractor fuel consumption. In addition, it results in frequent wearing of the tillage tool, all resulting in high cost of tillage and hence crop production. With advance in soil dynamics, it is now possible to have on-board computers that can assess the soil condition, and apply just the minimum force required at a particular place and depth, thus achieving real time process control and energy conservation (Onwualu and Watts, 1993; Onwualu and Watts, 1999).

4.4 Soil and Water Conservation in Tillage

Environmental concerns have made it mandatory that tillage must ensure soil and water conservation. Thus, new and existing tillage tools must be used in such a way as to conserve the soil in terms of maintaining a stable soil structure, ensuring a good balance of soil nutrients at all times and ensuring that soil water is not allowed to evaporate excessively. The study of soil dynamics enables the engineers and indeed the tillage practitioner to understand how to appropriately combine the tool and soil factors in such a way that the balance of the soil ecosystem is not destroyed. This has led to the emergence of a number of conservation tillage practices with their associated tools and machinery (Wijewardene, 1979).

4.5 Economics of Tillage

The total understanding of soil-machine dynamics enables scientists and engineers to handle tillage as an economic venture which it is. In an attempt to develop a guide to selection of optimum tillage system for any particular soil, crop and environment, Anazodo et al, (1991) presented the optimization scheme shown in Fig. 2. To be able to apply this scheme to any situation, an in-depth understanding of soil dynamics is required.

5. Challenges of Soil Dynamics Research in Nigeria

The analysis presented above show that only a few of the studies in soil dynamics have been carried out in Nigeria. Yet there is the need to adapt these studies to Nigeria soil conditions.

Some of the challenges or constraints why contributions to advances in soil dynamics have eluded Nigeria and indeed most of sub-saharan Africa are identified below.

5.1 Lack of Research Facilities

Adequate research facilities are required for serious work in soil dynamics. These include a soil bin, a soil mechanics laboratory, computational machines (computer) and access to literature. All these are lacking in the Nigerian environment. Thus, most researchers concentrate on field experiments and measurements to compare effects of different machinery applications on the soil and hence crop.

5.2 Lack of Data on Relevant Soil-machine Parameters

A robust modeling exercise requires input data. Some of these are soil parameters (Ca). Data on these for different soil types and conditions are not available. This can be linked to lack of laboratory facilities for measurements.

5.3 Poor Research Funding

Every research requires funding. In general research funds are scarce in Nigeria. The little funds available are channeled to other areas where policy makers feel are more important. As a result, it is difficult to sustain a large pool of researchers working on soil dynamics.

5.4 Poor Networking among Tillage Research

Many researchers in soil dynamics in Nigeria work in isolation. As a result they are not aware of what their colleagues are doing elsewhere. Sometimes networking is more with Europe and North America than among colleagues within the same country.

5.5 Low Level of Mechanization of Nigerian Agriculture

In general, the use of agricultural machines in Nigerian agriculture is low. This means that application of research in agricultural machinery is low. This of course includes tillage machinery.

5.6 Lack of Local Agricultural Machinery Manufacturing Industries

Most agricultural machinery in Nigeria are imported. The few machinery manufacturers produce mostly processing machines. The implication is that there are no major tillage machinery manufacturers that should be demanding for the results of tillage machinery research.

6. Recommendations

6.1 National Tillage Laboratory

In order to provide state of the art facilities for research, there is the need to reactivate the earlier proposal of establishing a National Tillage Laboratory at the Centre for Agricultural Mechanization (NCAM), Ilorin. Such a laboratory will include an indoor and outdoor soil bin with appropriate instrumentation, a good soil mechanics laboratory, an instrumentation laboratory, field plots for carrying out tests and for carrying out tillage experiments, and a computation laboratory with computers and appropriate software for analysis of soil-machine dynamics.

6.2 Regional Centres of Excellence in Tillage Studies

To complement the National Tillage Machinery, there is need to encourage the emergence of regional centres of excellence in Tillage Studies. These can be located in institutions that have already started with serious tillage projects. These include: University of Nigeria, Nsukka; Federal University of Technology, Akure; Ahmadu Bello University, Zaria, University of Maiduguri, Maiduguri and any other appropriate centres. These centres should be well equipped and should some how be linked to each other toward conducting tillage research.

6.3 Priority Research Needs

In addition to setting up good infrastructure for tillage studies, we need to identify priority areas of research. Different multidisciplinary teams can then be encourage to work on the projects on a long term basis. Some priority research areas include:

- Development, evaluation and promotion of conservation tillage systems
- Establishment of a database of work going on all over the country on tillage, soil compaction and traction.
- Determination of soil, machine and crop parameters required in tillage studies as functions of soil, location, etc.
- New approach to modeling soil-machine-plant system dynamics
- Studies on soil structure, nutrient dynamics, weed control, and agronomy of different crops as function of different tillage methods and machinery.

6.4 Investment in Local Manufacture of Tillage Tools and Machinery

Nigeria is large enough to support a viable agricultural machinery manufacturing industry. There is need to attract investments in this sector. There are many tillage related tools to be manufactured including hoes, shovels, diggers, plough, (disc, mould board), chisels, jab planters, multi-operational cultivation machines, etc. For this to work, there is need to promote the use of machines in agriculture, more than is currently being done.

6.5 Certification of Imported Machines

We must also ensure that imported tillage and traction machinery are certified by NCAM. This will ensure standardization. In addition, information on proper use of these machines should be disseminated through more training, seminars and workshops.

6.6 National Tillage Machinery Exhibition and Competition

One way to promote the adoption of good tillage practices and machinery is by conducting national exhibitions on tillage. The national exhibition will include hand tools, animal drawn implements and tractor mounted ones, including those made in Nigeria and imported. The competition can be in different categories including machinery/tool design, soil and water conservation, practices that ensure sustainability etc.

7. Conclusion

In this paper, we have shown that the study of soil dynamics in tillage has advanced considerably from the days of scale model tests of tillage tools to complicated computer based modeling of the entire soil-machine-crop system. However, it is noted that most of these advancements were made outside Nigeria with the result that we continue to use machines and techniques largely imported into the country, which may not be fully adapted to Nigerian soil types and conditions. In order to reverse the trend, case is made for more research in soil dynamics, establishment of a National Tillage Laboratory and more promotion and adoption of improved conservation tillage practices and machinery. These we believe will provide a good foundation for ensuring food security and increasing the use of machines in production agriculture in Nigeria.

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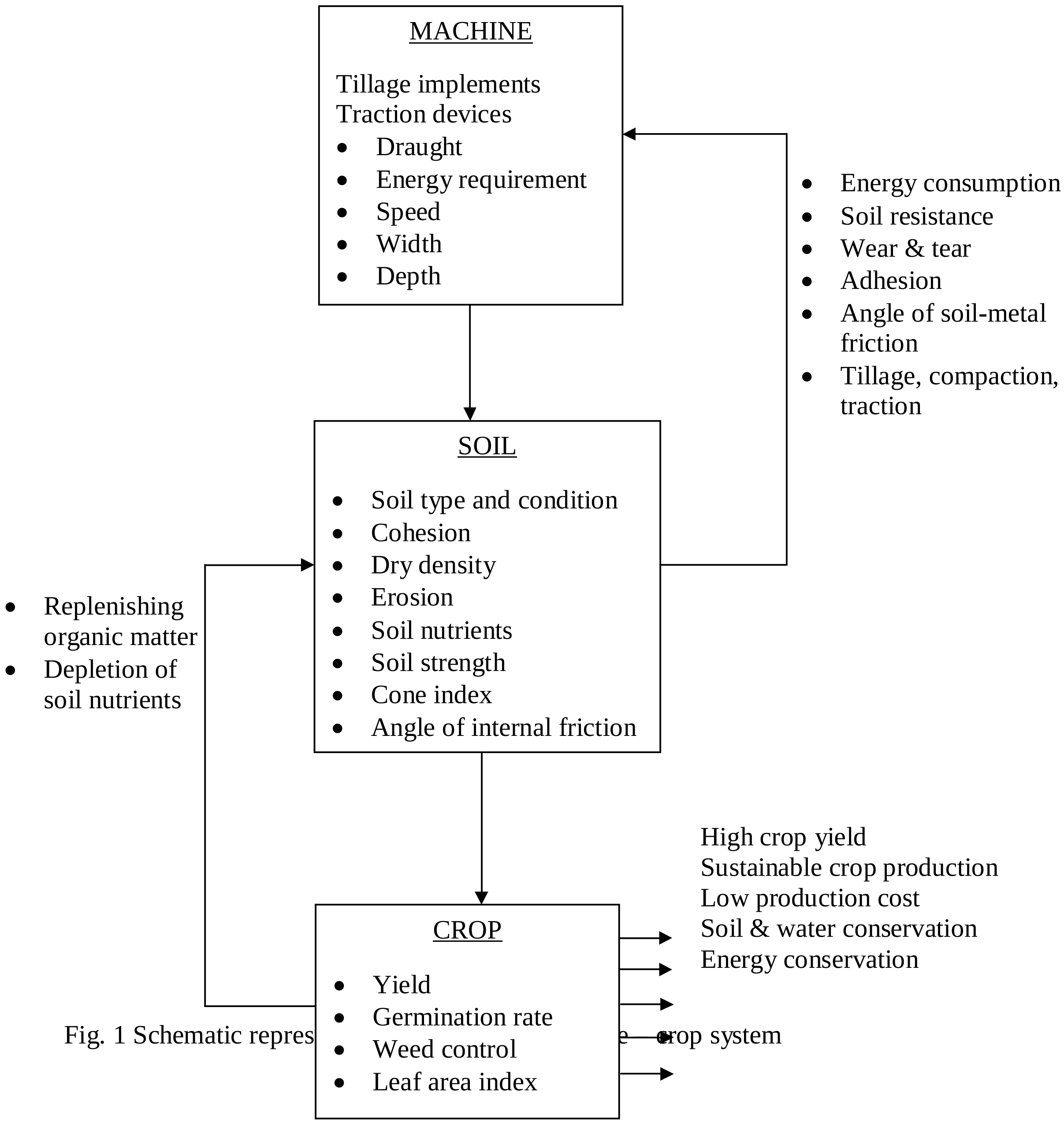

Fig. 1 Schematic repres[illegible]e crop system

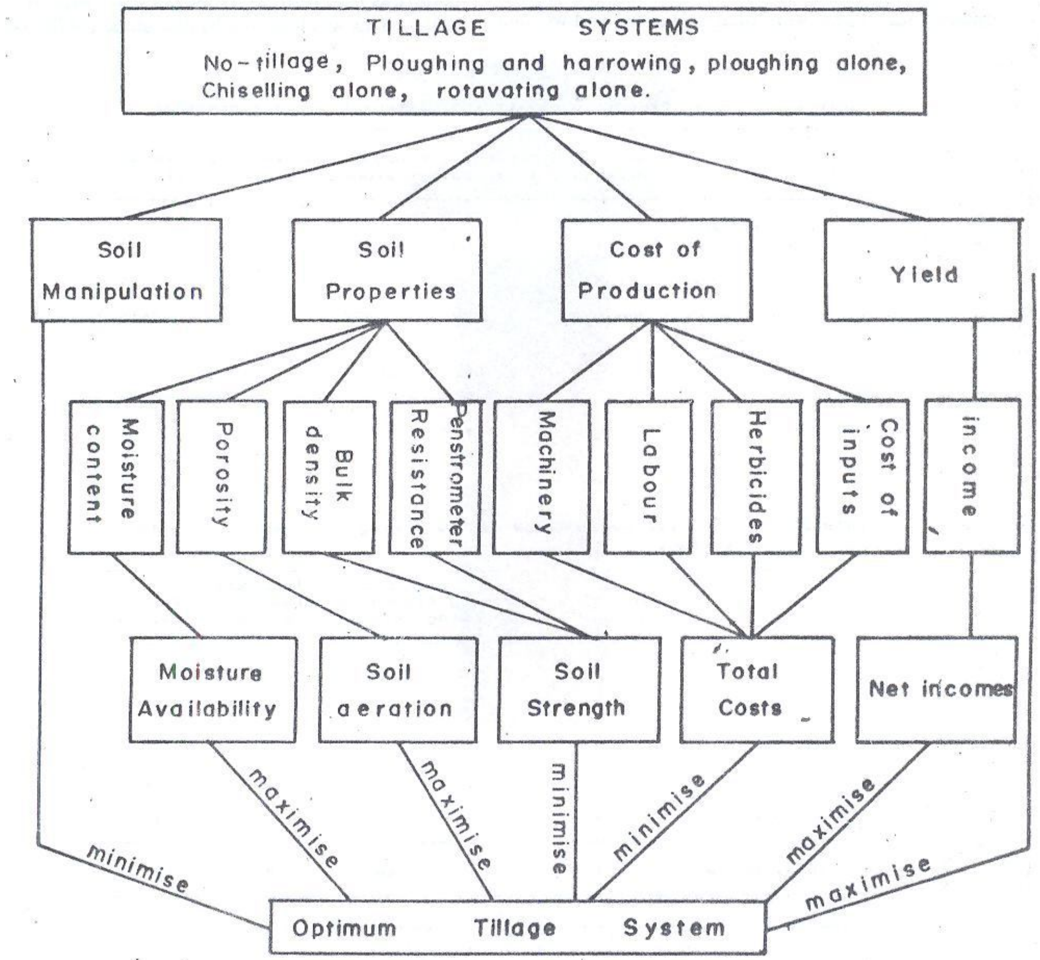

Fig. 2 Optimum Tillage System Selection Scheme (Anazodo et al 1991)