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Land Preparation Methods and Soil Quality of a Vertisol Area in the Central Highlands of Ethiopia

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Land Preparation Methods and Soil Quality of a Vertisol Area in the Central Highlands of Ethiopia

Bodenbearbeitungsmaßnahmen und Bodenqualität auf einem Vertisol im zentralen Hochland von Äthiopien

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Table of Content

1 Introduction

1.1 The rationale of soil quality concerns

The increased awareness of soil as a critically important component of the earth's biogeosphere has stimulated interest in the concept and assessment of soil quality (Glanz, 1995). Demand on soil resources for enhancing food security, improving water quality, disposing wastes and mitigating climate changes has raised in response to population growth. This increased demand intensified anthropogenic activities and amplified pressure of degradation. Although the threats of land degradation are widespread, it is more extensive and intensive in the poorer regions, where the land users entirely depend on the inherent capacity of the land for their basic needs.

The ever increasing population pressure exacerbates the situation. The world population of 6 billion in 2000 is expected to increase to 9 billion by 2050, with 8 billion (86%) living in developing countries (Lal, 2004). Therefore, soil quality (SQ) management for enhanced productivity and sustained environmental services is important in developing countries, characterized by high risk of soil degradation and poor institutions.

Soil erosion by water and wind has been recognized as a major agent of land degradation for a long time. Consequently, studies have often focused on quantifying soil and plant nutrient losses through field measurements or using simulation models. However, there is increased global emphasis that sustainable soil management requires more than erosion control. As a consequence, the SQ concept with a holistic focus evolved through the 1990s (Karlen *et al.*, 2003).

Although the precise definitions of SQ are still variable and controversial, the fact that soil serves various functions in agro-ecosystems remains the central idea (Ellert *et al.,* 1997). Commonly it is defined as the capacity of a specific kind of soil to function within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality and support human health and habitation (Larson and Pierce, 1994; SSSA, 1995).

Soil quality can be enhanced or degraded in response to the prevailing management systems. The effects of soil management systems on sustainability can be monitored by evaluating soil quality. Sustainable management systems are those that enhance the environment, natural resources, and related dimensions of society (Larson and Pierce, 1991). Agricultural sustainability is the management of resources to satisfy the changing human needs while maintaining or enhancing the natural resource base, and avoiding environmental degradation.

Different approaches have been explored to apply the SQ concept in assessing the sustainability of soil management systems. The approaches often relate SQ with the production and the environment functions of the soils (Doran and Perkin, 1996). This is because agricultural productivity and environmental quality influence the standard of human living (Pierzynski *et al.*, 1994; Acton and Gregorich, 1995).

1.2 Scope of soil quality issues

The SQ paradigm priority may vary with the level of societal development. It was developed in the temperate regions with the objective of approaching air and water quality standards (Pedro *et al*., 2003). The major emphasis here is the environmental role of soil, although agricultural productivity remains important. It is often focused on issues related to large nutrient and energy inputs to agricultural lands, which often lead to environmental pollutions (Pedro *et al*., 2003). Contrastingly, the major focus in the tropics is related to food security, rural poverty and ecosystem degradation (Pedro *et al*., 2003). Soil quality degradation is often emphasized as a constraint to crop productivity and overall agricultural sectors, especially in tropical Africa (Kayombo and Lal, 1993; Hoffman and Carroll, 1995). The effects of SQ deterioration due to water erosion and nutrient depletion on soil productivity are essentially manifested in the least developed countries, where farmers are highly dependent on inherent land properties and unable to ameliorate soil quality.

1.3 Soil quality issues in Ethiopia

The rampant land degradation and decline of its productivity is among the underlying reasons for poverty, food and ‘human needs insecurity’ and increased vulnerability to the recurrent drought in Ethiopia. The Ethiopian population currently estimated at 72 million is increasing annually at 3%, and further escalates the pressure on land and other natural resources. Consequently, per capita landholding is continuously decreasing with the current average of only 1.1 ha per household, average household size being 7. The problem of degradation is particularly escalating in the highlands, where over 88% of human and 77% of the livestock population are accommodated.

In addition to technological inputs to properly manage the fragile land areas, enhancing the productivity of the well-endowed lands such as the Vertisols is an alternative to ease the pressure on the vulnerable lands. Vertisols are among the high potential soils covering about 8 million ha in the highlands of Ethiopia (Jutzi and Mesfin, 1987), but are not efficiently utilized. They are regarded as marginal for crop production, due to land preparation problems at low moisture content for tillage and their sticky nature at high moisture levels. Several alternative management systems have been investigated during the last two decades to narrow the rift. As a follow-up, the current study compared alternative land preparation methods for increased crop productivity and enhanced soil quality.

1.4 The need for stakeholder participation

Since SQ depends on the intended functions of soils, the direct users of the soils should participate in defining the important functions, setting the criteria and indicators of its quality as well as in its evaluation process. This does not only lead to the development of appropriate management systems but also to the enhancement of their adoption. For the same reason, Andrews *et al*. (2002b) implemented participatory SQ assessment in California’s Central Valley. In this study, the smallholder farmers participated in establishing SQ criteria for various uses and in assessing their potentials.

1.5 Hypothesis

The hypotheses tested in this study include:

- Farmers have unique SQ concept and indicators of evaluation relevant to their management objectives and can evaluate the soils for the primary management goals.
- The alternative land preparation methods meet the triple objectives of reducing soil erosion, improving SQ and ecological sustainability without compromising the economic benefits.

1.6 Objectives

- to determine local soil functions and SQ indicators to establish a minimum data set for the area.
- to evaluate and recommend alternative land preparation methods in terms of SQ and functions
- to test the Soil Management Assessment Framework (SMAF) as a tool for SQ assessment under the conditions of the area.

2 The issue

2.1 Soil and land quality degradation

Empirical studies indicate that severe degradation of soils' productive capacity has occurred on over 10% of the Earth's vegetated land as a result of soil erosion, excessive tillage, and overgrazing etc. (Lal, 1994). Findings from a project of the United Nations Environmental Program on Global Assessment (UNEPGA) indicated that 40% of the world's agricultural land has been adversely affected by soil degradation, soil erosion being a major cause (Lal, 1994). Although it is a natural geologic process, soil erosion is accelerated by human activities. Fuelled by the combined effects of anthropogenic activities like poor farming practices, overgrazing, deforestation, soil erosion, salinity and alkalinity, and the use of livestock manure and crop residues as fuel, land degradation in Ethiopia is hastening desertification (Cesen, 1986; World Bank, 1984). Consequently, about 72% of the total land area of the country falls within the UNEP's definition of desertification (Hawando, 1995).

The problem is extensive in the highlands (above 1500 m asl) which comprise 44% of the total landmass and account for 95% of the cropped land (Heweg and Stillhardt, 1999). Accommodating about 88% of the 72 million human populations and two-third of the livestock (Kruger *et.al.*, 1996), the highlands belong to the areas in Africa with the highest population densities (Ehui *et al.*, 2003). Estimates show that 50% of the agricultural land in the highlands is severely degraded, while 54% of the remaining areas are highly susceptible to erosion (Kebede *et al.*, 1996). Serious erosion is estimated to have already affected 25% of the highlands, out of which 4% are so seriously eroded to be productive again (Million, 1996).

The Soil Conservation Research Project (SCRP) of the Ministry of Agriculture also estimated that soil erosion is affecting nearly half of the agricultural land, resulting in soil loss of 1.5 to 2 billion t a^{-1}, which is equivalent to 35 t ha^{-1} (Dejene, 2003). This corresponds to 1 to 2 billion US$ a^{-1} (an amount comparable to the country's annual budget). Similarly, Hurni (1988) estimated an average soil loss of 42 t ha^{-1} a^{-1} from the highlands. Further, Hurni (1993) and Heweg and Stillhardt (1999) estimated that soil losses in the highlands might reach annual rates of 200 – 300 t ha^{-1}. Despite the disparities of the estimates, all suggest that the rate of soil degradation is not acceptable.

In short, two major problems can be recognized re-enforcing each other, constricting the situation in a vicious circle with decreasing diameter (Fig. 2.1). On the one hand, the food, feed and fuel needs of the farm households could not be met from the degraded and fragmented plots to which they cling. Due to the meagre productivity of the land, which is too poor to supply crop needs, the farm households are increasingly impoverished. On the other hand, the resources are continually exploited because of inappropriate management and poor technological inputs, since the farmers are too poor to invest. In the challenge of breaking the vicious circle, farmers need not only financial but also technological support with their active participation.

Since a seriously degraded soil is not to be recovered by a generation (Hudson, 1995), allowing the status quo to continue may slowly but surely lead to a complete failure of the ecosystem. Therefore, immediate attention and action is required, if sustainable development of the country's economy, which fundamentally rests on agriculture, and the national security and political stability, is to be a reality.

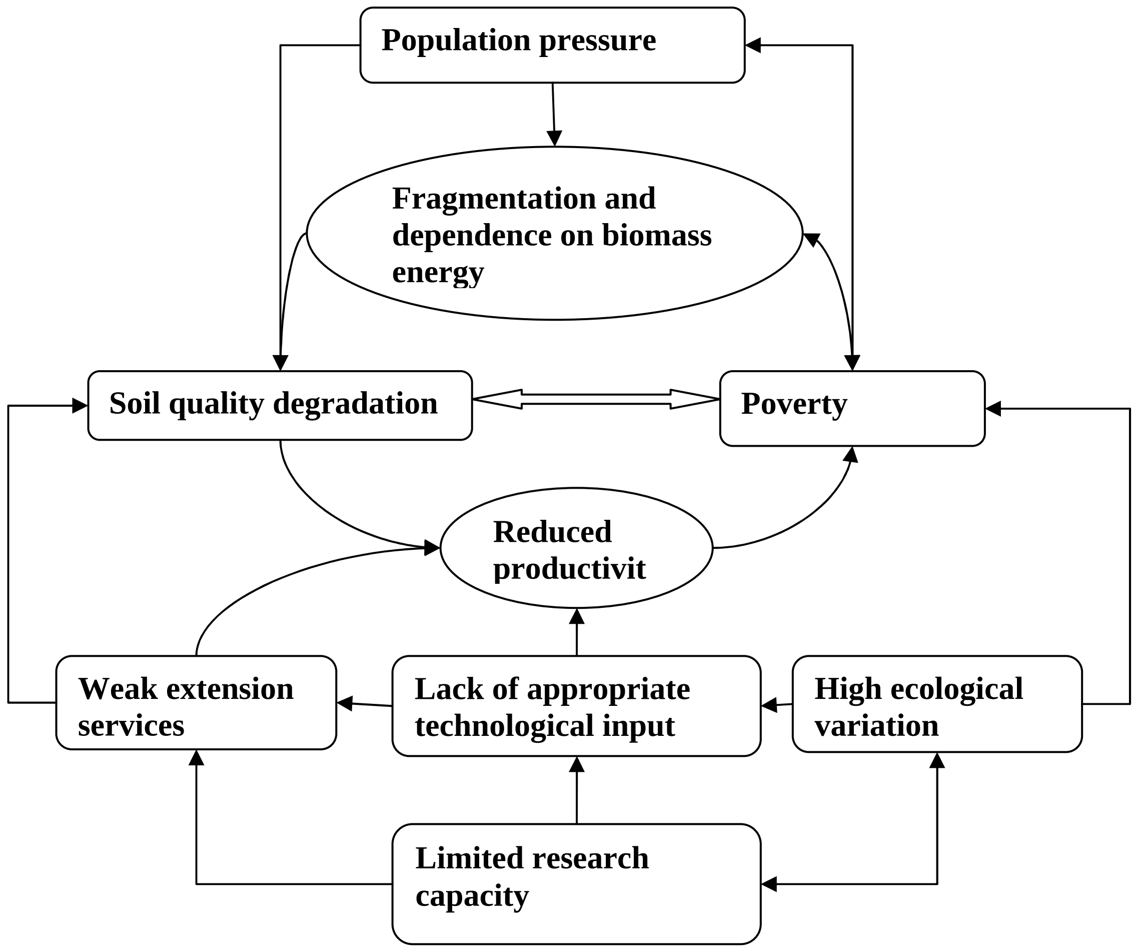

Fig.2. 1 A simplified relationship between poverty and SQ degradation in the highlands of Ethiopia

2.2 Soil conservation efforts in Ethiopia

As a response to the problem of land degradation due to soil erosion, an enormous effort has been underway to implement soil and water conservation practices on farmers' fields. Several governmental and non-governmental organizations developed and implemented various projects. In most of the endeavours, standard technical practices were tried with more emphasis on physical soil conservation measures. The major strategy was to minimize soil loss from the field through construction of barriers, with little attention to organic matter (OM) depletion, soil fertility decline, soil physico-chemical and biological degradation (Dejene, 2003; Teklu and

Selamyihun, 2001). In other words, SQ issues, which address the multiple functions of soil in maintaining productivity, environmental well-being and integrate the physical, chemical and biological attributes (Papendick and Parr, 1992; Rodale Institute, 1991), were not dealt with.

Moreover, a limited attempt was made to technically and socio-economically evaluate the measures before they were widely applied. The offsite effects of soil erosion such as flooding and water pollution were less emphasised (Dejene, 2003). Since the implementation had been associated with political systems and involuntary participation, the farmers were involved merely to provide their land and labour. Consequently, it is widely acknowledged that the soil conservation policies and activities of the past decades have not been successful (Debele, 1994; Pender and Ehui, 2000; Nedesa, 2002).

Therefore, strategies for easing pressure on fragile lands through evaluating potential alternatives should be investigated, in addition to the innovative and adaptive research and development activities to efficiently use the areas prone to degradation. Among the potential alternatives, in this regard, could be the use of the hitherto underutilized areas of land. A considerable area of the Vertisols in the highlands, which are relatively stable with respect to soil erosion, and the vast area of the lowlands both in the humid and the dry areas are not sufficiently utilized. While a huge capital investment may be required for the later, simple technologies with modest effort can make the former practical.

2.3 Potential and management of Vertisols

Vertisols (from the Latin, *vertere* = turn) are churning heavy clay soils, that contain a high proportion of swelling clays such as smectites. When drying out, they form deep wide cracks from the surface downwards at some period in most years (Deckers *et al.*, 2001). They cover a total of 311 million hectares or 2.4% of the global land area**,** out of which about 150 million ha is potential cropland. In the tropics, they cover some 200 million ha or 4% of the land surface (Driessen and Dudal, 1991). In eastern and central Africa, Vertisols constitute a major part. They make up over 10% of the Ethiopian landmass covering about 13 million hectares, of which about 8 million ha are in the Central Highlands.

Because of their relatively high inherent fertility, they can be very productive, when properly managed. However, their unique physical properties are the greatest limitations to the dominantly low-input agriculture. They require a careful management in order to tap the potential, while avoiding decline in soil quality. The wide-scale use of Vertisols has occurred only in the last four decades, and there are large areas, particularly in Africa, which are yet to be used (Deckers *et al.*, 2001). A thorough understanding of the properties and processes of these soils is crucial to develop and implement farming practices that will keep them productive for the current and future generations. To this end, the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) has made significant contributions both in land management technology and cultivars development to enable the sustainable use of these soils (Eswaran *et al.*, 1999).

According to Mesfin (1998) montmorillonite (smectite) dominates the clay minerals of the Ethiopian Vertisols, with little aluminium inter-layering. They are extremely diverse and occur under various climatic conditions, where Pellic and Chromic Vertisols are plentiful (Mesfin, 1998). The Pellic Vertisols are the majority with over ten million hectares (Debele, 1985). They have the moist chroma of less than 1.5 throughout the upper 30 cm.

Although it was claimed that they typically occur in areas of elevation less than 1000 m asl and on relatively flat topography (Ahamed, 1983), Vertisols in Ethiopia are found above 2000 m asl (Fisseha, 1992). Also, Ethiopian Vertisols occur on a wide range of slope up to 15% (Jutzi *et al*., 1988) though the majority occur on slopes less than 5%, against the claims of Mohr *et al.* (1972) and Debele (1985), who assert that Vertisols occur on slopes less than three percent.

However, their productivity is often constrained by their hydro-physical properties, that their percolation rate is very low. As land preparation is a problem under insufficient moisture content as well as under wet conditions, and due to the traditional late planting to avoid waterlogging, crop yields from these soils are often very low (Teklu et *al.*, 2004; Teklu, 1997, 1998; Demeke, 1998).

Traditionally, farmers cultivate the land early in the season using the short rain (April-May), and keep it bare during the main rain season with occasional tillage until they plant low yielding crop species or varieties late in the season (August – September) after the excess water naturally drained away so that the crops grow on residual moisture. In good years (if the rain extends to September and October), the harvest may be very good. However, as this often fails, the consequence can range from substantial yield reduction to total crop failure. The practice exposes the bare cultivated land to the erosive summer rainfall (June-July) (Teklu, 1997; Teklu *et al.*, 1998). The use of tolerant crops is another traditional alternative. Tef (*Eragrostis tef*), Ethiopia’s staple cereal, is among the few crops, that tolerate a mild water logging condition, and hence is well preferred in areas where the temperature is warm enough for the crop. However, as the altitude increases over 2000 m asl, its performance gets poorer because of the reduced temperature.

Various cultivation practices aimed at draining the surface water are used in different parts of the highlands. Hand made Broad Bed and Furrows (BBF) are practiced in some localities like Enewari in North Shoa, but its high labour requirement is a constraint to its wider application. Ridges and furrows (RF) is a common practice in *Caffee Donsaa* areas. Although it is meant to drain the excess moisture and could have allowed early planting, farmers plant late, may be due to its limited drainage efficiency, as the water often stagnates in the furrows than being disposed (Teklu, 1997). The late planting accompanied by high tillage frequency (5-9 tillage operations) under the RF system results not only in reduced crop yield, but also affects SQ by exposing it to erosion, increased OM oxidation and soil structural deterioration (Teklu and Gezahegn, 2003). The high tillage frequency also destroys all the herbs, which could otherwise cover the soil surface against rainfall and runoff or grazed by the livestock.

A surface drainage technology known as "Broad Bed and Furrow" (BBF), constructed by Broad Bed Maker (BBM), has been developed and popularized after on- station and on- farm testing in various areas in the highlands (Teklu *et al.*, 2001). Despite a considerable effort of popularization, the BBF technology is not well adopted. This was often attributed to various socio-economic, cultural and technical constraints. Weed infestation induced by early planting, time available for BBF preparation, and difficulty in appropriate site selection are among the technical constraints that limited the success and adoption of the technology (Deckers *et al.*, 2001; Fassil *et al.*, 2001).

To comprehensively address the issues and provide alternative systems, which ensure land cover during the main rainy season and allow production of livestock feed, need to be developed, in addition to the surface drainage practices. Spatial and temporal multiple cropping systems might be potential alternatives to be evaluated both economically and ecologically for such purposes. In addition, reducing tillage practices could be potential options (Teklu *et al.*, 1998).

3 Assessment of land and soil quality

3.1 Function and evaluation of land

3.1.1 Land and its functions

Land is a holistic concept (FAO, 1976). It is a delineable area of the earth's terrestrial surface, encompassing all attributes of the biosphere immediately above or below the surface, including those of the near-surface climate, the soil and terrain forms, the surface hydrology (including shallow lakes, rivers, marshes and swamps), the near-surface sedimentary layers and associated groundwater reserve, the plant and animal populations, the human settlement pattern and physical results of past and present human activity such as terracing, water storage or drainage structures, roads, buildings, etc. (FAO, 1995). Soil functions as a living space, input for production, climate regulator, storage, waste and pollution controller, hydrologic and biotic environmental function, and as archive and heritage (FAO, 1996). Each of these functions requires a pertinent quality of land to be fulfilled.

3.1.2 Land qualities and indicators

Land qualities are complex attributes that affect the suitability of the land for a specified use in a distinct way (FAO, 1976). Land quality is the condition of land relative to the requirements of land use, including agricultural production, forestry, conservation and environmental management (Pieri *et al.*, 1995). Land quality indicators (LQI) are used increasingly to provide convenient descriptions of current state or condition of the resource and to gauge its performance, and predict responses. Indicators are statistics or measures that relate to a condition, change of quality, or change in state (FAO, 1976). In this context, three types of indicators are distinguished: pressure indicators, state indicators and response indicators (FAO, 1996).

The LQI programme has been developed to harmonize the combined objectives of food production and environmental protection (FAO, 1996). They are intended to address the major land-related issues of national and global significance, such as land-use pressures, land degradation, and soil and water conservation, as well as policy related questions (Fig.3.1). It was planned to be used for policy and programme formulation at various levels to promote and monitor technologies, policies and programmes to ensure better use of natural resources and sustainable land management.

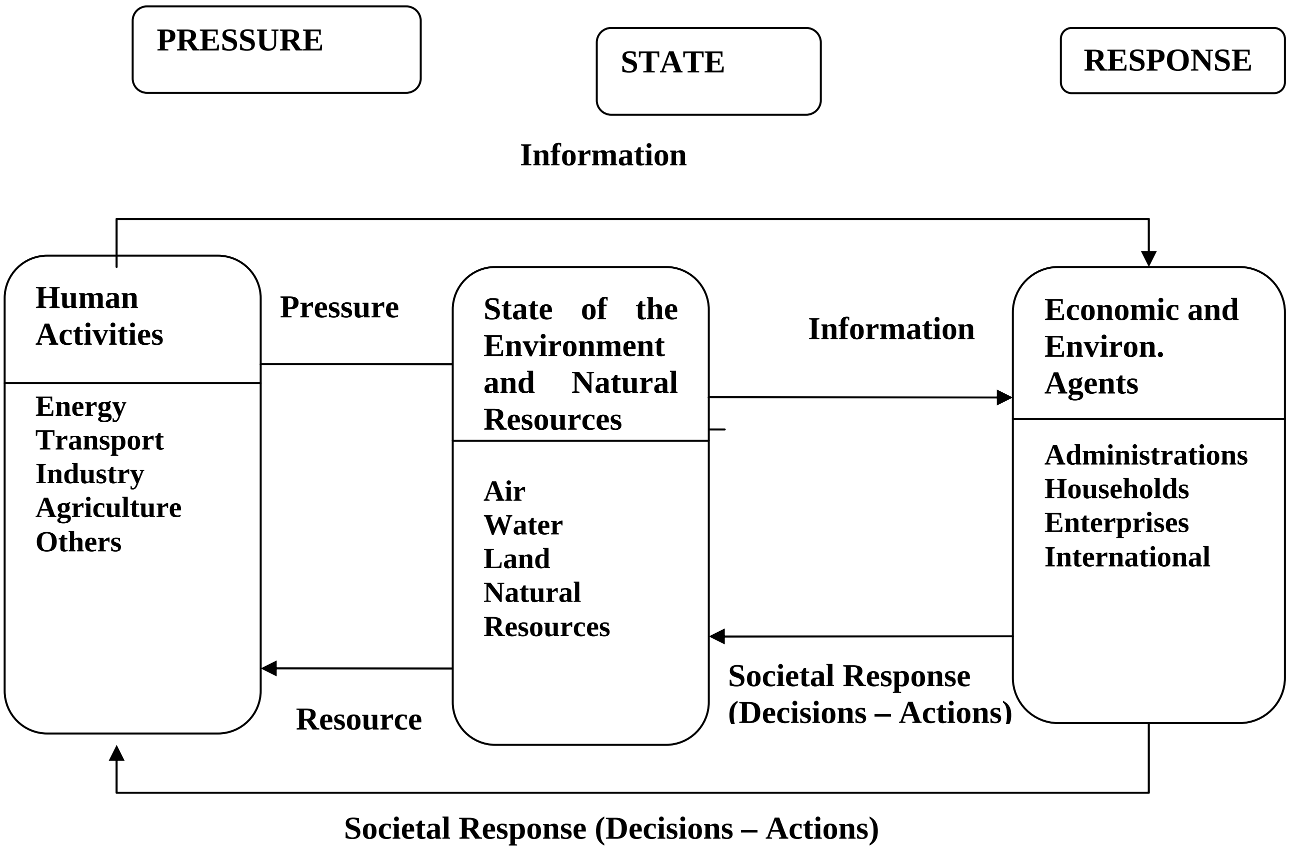

Fig. 3.1 Pressure-state-response framework (FAO, 1996)

3.1.3 Land evaluation procedures

Land evaluation is the performance assessment of land for specific purposes, involving the execution and interpretation of surveys and studies of land forms, soils, vegetation, climate and other aspects of land in order to identify and make a comparison of promising land use types in terms applicable to the objectives of the evaluation (FAO, 1976; 1993a; 1996). The assessment is often made in terms of production, sustainability and inputs requirement for a given production and economic outputs (Igue, 2000). In addition, the soils buffering capacity for industrial wastes, their originality and nature conservation aspects are considered in developed countries (Stasch *et al.*, 1991; Sydow *et al.*, 1992). The rationale of land evaluation is matching of land use or crop requirements with land and climate qualities to arrive either at a land suitability classification or quantitative crop yield estimation (Dent, 1993).

Land evaluation requires a clear identification and definition of objectives for the land to be evaluated (FAO, 1976). The objectives should be weighed in a political process by individuals and national or international decision-makers (Stomph *et al.*, 1994). Two general approaches (known as the two- stage approach and the parallel approach) were formulated by the FAO framework (FAO, 1976) to be followed with respect to the natural resources assessment and socio-economic analysis. In the two-stage approach, a quantitative land evaluation (bio-physical factors) is followed by a socio-economic analysis and hence the interrelation between the two stages is limited. In the parallel approach, however, the assessment of bio-physical factors runs simultaneously with the socio-economic analysis. This interactive approach is expected to yield more precise results in a shorter time.

3.1.4 Review of land evaluation systems

Land evaluation systems have existed for a long time (Igue, 2000) and continuously evolved. Among the early systematic attempts of land evaluation, the German soil evaluation “Deutsche Bodensschätzung” (Rothkegel and Herzog, 1935) and Land Capability Classification (Klingebiel and Montgomery, 1961) used soil and climate parameters such as texture, structure, soil depth, slope and precipitation correlated with single parameters of productivity to arrive at a specific value or capability classification, respectively (Igue, 2000; Graef, 1999). These easy quantitative approaches were limited to a specific region or purpose, and lack crop specific information (Igue, 2000).

The parametric (Sotrie Index) developed by Storie (1950) in order to classify the land for taxation purposes in California, which was later, refined (Storie, 1976) and applied internationally was also another quantitative approach (Peterman, 1978; Sys *et al.*, 1993; Boye *et al.*, 1997; Gaiser and Stahr, 1998; Graef, 1999). The parametric methods express the land value as a quantitative index, thus can be used for quantitative land evaluation (Sys, 1993).

The FAO/ITC-Ghent evaluation method is a semi-quantitative approach for bio-physical land evaluation developed at the ITC, University of Ghent (Sys *et al.*, 1993). Since it does not incorporate socio-economic parameters, the approach is essentially based on a number of simple crop growth functions and several crop requirements. In this approach, the parametric indexing method which enables a quantitative evaluation has been advocated (Storie, 1950; 1976). Attempts have also been made to use the Soil and Terrain Database (SOTER) approach, which was initiated to utilize current and emerging information technology to establish a World Soils and Terrain Database, containing digitized map units and their attribute data (ISSS, 1986b) together with a climate database in the FAO/ITC-Ghent method (Gaiser and Graef, 2001; Graef *et al.*, 2001).

As it incorporated bio-physical, socio-economic and technical issues, the FAO Framework for land evaluation (FAO, 1976) is a more holistic quantitative approach (Igue, 2000). In the Framework, land is categorized into five suitability classes ranging from S_1 (highly suitable) over S_2, S_3, and N_1 to N_2 (permanently not suitable) (Igue, 2000). The Agro-ecological Zones Project was an attempt for a better quantification, but on a small scale (FAO, 1992).

The traditional soil survey, classification and interpretation activities as described above have defined Land Capability Classes, a Storie Index, and other Land Inventory and Monitoring indices based primarily on inherent soil properties (Karlen *et al.*, 1997). Each is important and useful for certain applications, but none are the same as assessing dynamic SQ (Karlen *et al.*, 2003), which is based on the dynamic soil properties. The later builds upon the former but not vice versa.

3.2 Concept, definition and features of soil quality

3.2.1 Concept of soil quality

High rates of soil erosion, losses of OM, reductions in fertility and productivity, chemical and heavy metal contamination, and degradation of air and water quality have sparked interest in the concept of SQ and its assessment (Larson and Pierce, 1991; National Research Council, 1996; Doran and Parkin, 1994; Karlen *et al*., 2001). The concept was formally initiated when Alexander (1971) suggested developing 'Soil quality criteria' in reference to agriculture's role in environmental improvement. Subsequently, Warkentin and Fletcher (1977) introduced the SQ concept at an international seminar on soil environment and fertility management for intensive agriculture. The concept was needed to facilitate better land use planning, because of the increasing number of functions that the soil resources must either provide or accommodate (Karlen, *et al*., 2003).

Soil quality is a holistic concept, which recognises soil as part of a dynamic and diverse production system with biological, chemical, and physical attributes (Swift, 1999; Sanchez *et al*., 2003). It is related to the concept of soil capability, which is as old as civilization itself (Carter *et al.*, 2004). Although, there has been an interest in soil and land quality from the beginning of agriculture (Carter *et al.*, 2004), the SQ concept is continuously evolving (Warkentin, 1995). In its current context, however, it is relatively new (Arshad and Cohen, 1992; Doran and Parkin, 1994). As a concept, it differs from traditional technical approaches that focus solely on productive functions of soil (Swift, 1999; Sanchez *et al*., 2003).

To understand SQ in its modern context, the complexity of soil and its functions have to be recognized. Soil should be recognized as a complex system of minerals, organic compounds, soil solution, soil gases and living organisms that interact continuously in response to natural and imposed biological, chemical, and physical forces. In addition, soil should be accepted as a living system, which represents a finite resource vital to life on earth (SSSA, 1995). Soil quality cannot be seen in isolation, but must be linked to certain types of land use and the associated management (Bouma *et al*., 1998).

3.2.2 Definition of soil quality

There are various and sometimes conflicting definitions of SQ in the current literature. However, 'the capacity of the soil to function' is the central idea in most of the definitions (Karlen *et al.*, 1997). The term quality implies value judgment or degree of excellence of soil for a specific purpose (Schjonning *et al.,* 2004). In addition to the intended use of a particular soil, the specific definition of SQ is dependent on its inherent capabilities (Andrews *et al.*, 2004). Therefore, SQ is defined in a more elaborated manner, as the capacity of a specific kind of soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation (Larson and Pierce, 1994). Similarly, the "Soil Science Society of America's Ad Hoc Committee", defined soil quality as the capacity of soil to function, where critical soil property dependent functions include soil's ability to support plant and animal growth, to filter and retain matter and nutrients, and to regulate water flow through the soil system (Karlen *et al*., 1997). More recently, SQ is defined as the capacity of soil to function within land use and ecosystem boundaries, to sustain biological productivity, maintain environmental quality and promote plant, animal and human health (Karlen *et al*., 1998; Carter *et al*., 1997).

In addition, various terms such as fitness for a specific purpose (Carter *et al.*, 1997), suitability for chosen uses (Warkentin, 1995), and capacity to function (Karlen *et al*., 1998) have been emphasized in the basic definitions. In other words, soils with good quality give us clean air and water, abundant crops and forests, productive rangeland, diverse wildlife and beautiful landscapes. In the context of agriculture, SQ is a measure of soil's fitness to support crop growth without becoming degraded or otherwise harming the environment (Action and Gregorich, 1995). Soil provides these productivity and environmental services by performing five essential functions (Karlen *et al.*, 1997):

I. ***Regulating water movement***: Soil helps to control where precipitation and irrigation water goes. Water and dissolved solutes flow over the land surface or into and through the soil depending on the quality of the soil.
II. ***Sustaining plant and animal life***: The diversity and productivity of living things depends on soil functions.
III. ***Filtering and transforming potential pollutants***: The mineral and microbes in soil are responsible for filtering, buffering, degrading, immobilizing, and detoxifying organic and inorganic materials in the soil.
IV. ***Cycling nutrients***: Carbon, nitrogen, phosphorus and many other nutrients are stored, transformed, and cycled through soils.
V. ***Supporting structures*****:** Buildings need stable soil for support, and archaeological treasures associated with human habitation are protected in soils.

3.2.3 Features of soil quality

An important feature of SQ is the delineation between inherent and dynamic soil properties (Carter *et al*., 1997; Karlen *et al*., 1997; USDA-NRCS, 2001). Inherent SQ

(Fig. 3.2) refers to the soil's natural ability to function, which is related to a soil's natural composition and properties as influenced by the basic factors and processes of soil formation. Dynamic SQ (Fig. 3.3) is related to soil properties, which change because of human decisions on soil use and management (Karlen *et al.*, 1997). Consequently, both inherent and dynamic properties and processes interacting within a living dynamic medium determine SQ (Karlen *et al.*, 2003). In other words, the current SQ is the product of the inherent and dynamic SQ as well as the balance between the degradation and aggradations processes, which are influenced by the management systems.

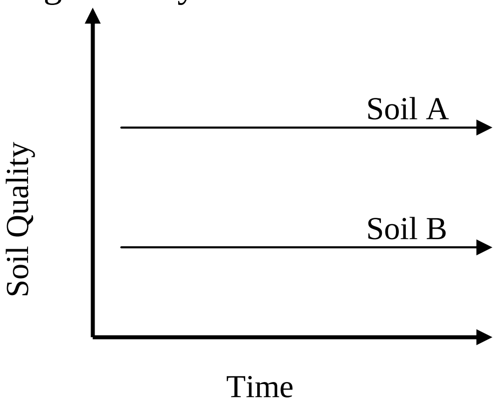

Fig. 3.2 Inherent Soil Quality

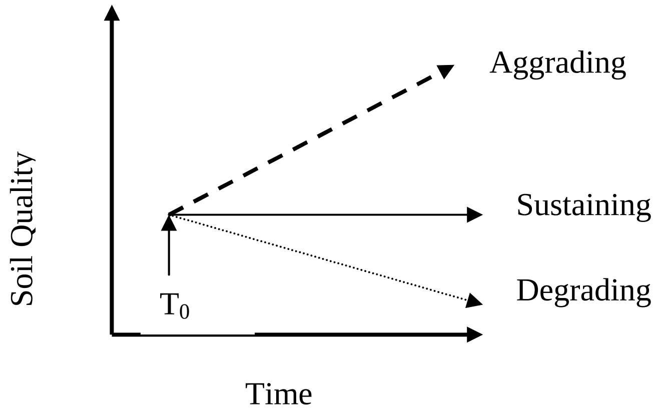

Fig. 3.3 Dynamic Soil Quality

3.3 Dynamic soil quality and management

Soil quality is holistic, reflecting biological, chemical, and physical properties and processes interacting within soils. Soil management options affect these properties and processes differently. Generally, the need for improved and sustainable soil management places the emphasis on managing and improving dynamic SQ attributes (Carter *et al.*, 1997). The soil organic matter (SOM), soil structure, soil depth, water and nutrients holding capacity are among the dynamic soil attributes, which are often affected by the management systems within short time.

3.4 Soil quality and functions

The capacity of a soil to function depends upon its inherent properties, which depend on its genesis and the dynamic changes in these properties which are the functions of the management systems (Gajri *et al.*, 2002). In the literature, the term soil potential is frequently referred to mean the capacity of land units or soils to render products and environmental services (Neef, 1979; Stahr and Renger, 1986).

As SQ is related to the management goal and the functions (ecosystem services) the soils are required to serve, it is not possible to establish universal indicators (Doran and Perkin, 1994; Bouma, 2004). This is because the different functions that the soils provide require different indicators (Blum, 1977). The important soil functions include water and solute retention and flow; physical stability and support; retention and cycling of nutrients; buffering and filtering of potentially toxic materials; and maintenance of biodiversity and habitat (Daily *et al*., 1997).

Harris *et al.* (1996) categorized soil functions into productivity, environmental and health aspects. Soil quality affects both quality and quantity of the products or services obtained from the soil under a given management system and input levels. To link the assessment with the functions, Carter *et al.* (1997) set the following general sequence of SQ evaluation as:

- define the soil functions of concern
- identify specific soil processes associated with those functions and
- identify soil properties and indicators that are sensitive enough to detect changes in the functions or soil processes of concern.

3.4.1 Soil quality and productivity

Soil quality indices and indicators should be selected according to the soil functions of interest and the defined management goals for the system (Andrews *et al.* 2002a). Agricultural productivity is the major recognized production function of soils. Soil quality affects crop productivity through its important functions such as nutrient cycling, physical stability and support, resistance and resilience and water relations (Andrews *et al.,* 2004). A good quality soil stores and cycles nutrients, and allows crops to grow and use nutrients efficiently (USDA-NRCS, 1997, Andrews *et al.,* 2004)). In such soils, nutrients become available when the plants need them, reducing the chance of nutrients being lost from the root zone through leaching, from the surface by runoff or above the crop canopy by volatilization. This leads not only to optimum storage and utilization of nutrients, but also to reduced environmental risks. Among the important soil parameters related to nutrient cycling, soil pH, potentially mineralisable nitrogen and microbial biomass are often considered as indicators of SQ (Karlen *et al*., 1996; Sparling, 1997).

Soil erosion and runoff are among the detrimental factors in SQ management. Nutrients and SOM contained in the topsoil is often lost by erosion or washed out with runoff water (USDA-NRCS, 1997). This does not only increase agricultural production cost due to the additional nutrient but also raises the risk of water pollution and leading to higher societal costs.

Soil compaction is another major constraint with respect to agricultural soil quality. Compact soils restrict the movement of roots and nutrients in the soil, and hence reduce nutrient uptake and restrict air movement and gas exchange in the root zone, which leads to nutrient loss (USDA-NRCS, 1997). Therefore, good soil aggregation is required for better water and nutrient movement through the soil (Arshad *et al*., 1996). Higher aggregation in surface soils allows pore space for water infiltration and gas exchanges. Influenced by SOM and soil biological activities, soil aggregate stability and bulk density are often considered as indicators for soil physical stability and support (Doran and Prkin, 1994; Arshad *et al.,* 1996; Karlen *et al*., 1996).

When nutrients are applied to the soil surface, water is required to move them into the root zone (USDA-NRCS, 1997). This requires sufficient infiltration capacity of the soil. The movement of nutrients improve their availability to the plants and reduces their susceptibility to runoff and volatilization. As soil moisture is an important attribute determining soil productivity function, plant available water capacity, is often considered as indicator of water relations (Lowery *et al*., 1996; Smith and Doran, 1996; Andrews *et al*., 2002a, b).

3.4.2 Soil quality and sustainability

The link between SQ and sustainability is important (Bouma *et al*., 1998), because SQ must be maintained or enhanced to meet the increasing demands for food, feed and fibre; and to sustain environmental integrity and to attain sustainable economic development. Economic development is sustainable when the needs of the present generation are met without compromising the ability of the future generation to meet their own needs (WCED, 1987). This can be achieved through sustainable land management systems. Dumanski (1993) stated that sustainable land management combines technologies, polices and activities aimed at integrating socio-economic principles with environmental concerns simultaneously to:

1) Maintain or enhance production and services
2) Reduce the level of production risk
3) Protect the potential of natural resources and prevent degradation of soil and water quality and
4) Be economically viable and socially acceptable

Andrews *et al.* (2002b) argue that the management goals are often individualistic, primarily focused on on-farm effects, but can also be societal. The societal goals in SQ management include the broader environmental effects of land management decisions such as soil erosion, agrochemical contamination of soil and water or subsidy imbalance (Andrews *et al*., 2002b).

On the other hand, Larson and Pierce (1991) suggest that SQ management should not be limited to productivity. They argue that emphasizing the onsite effect, like productivity alone, might have contributed to SQ degradation in the past. Endorsing the same, Andrews *et al.* (2002a) assert that, when management goals focus on sustainability rather than only productivity, SQ can be viewed as a component of agro-ecosystem sustainability (Fig. 3.4). Therefore, SQ assessment contributes to the evaluation of higher-level sustainable management goals (both individual and societal). Thus, management decision for sustainable agro-ecosystem requires results of SQ assessment as an important input.

3.5 Soil quality assessment

The obvious purpose of SQ assessment is to monitor the effect of management systems on SQ attributes and to avoid practices that damage SQ and negatively affect its capacity to function (Gary *et al.,* 2000). Soil quality assessment can be spatial or

temporal. It involves a spatial or temporal monitoring of the various management effects on soil functions to support policy decisions about the management systems.
There are no universally accepted methods and tools for SQ assessment. Among the promising tools available is the Soil Management Assessment Framework (SMAF), which was developed and used for indexing SQ in the USA (Andrews *et al.*, 2004). The framework was designed to follow three basic steps (Andrews, 1998): indicator selection, indicator interpretation, and integration of the indicator values into an index (Fig. 3.5).

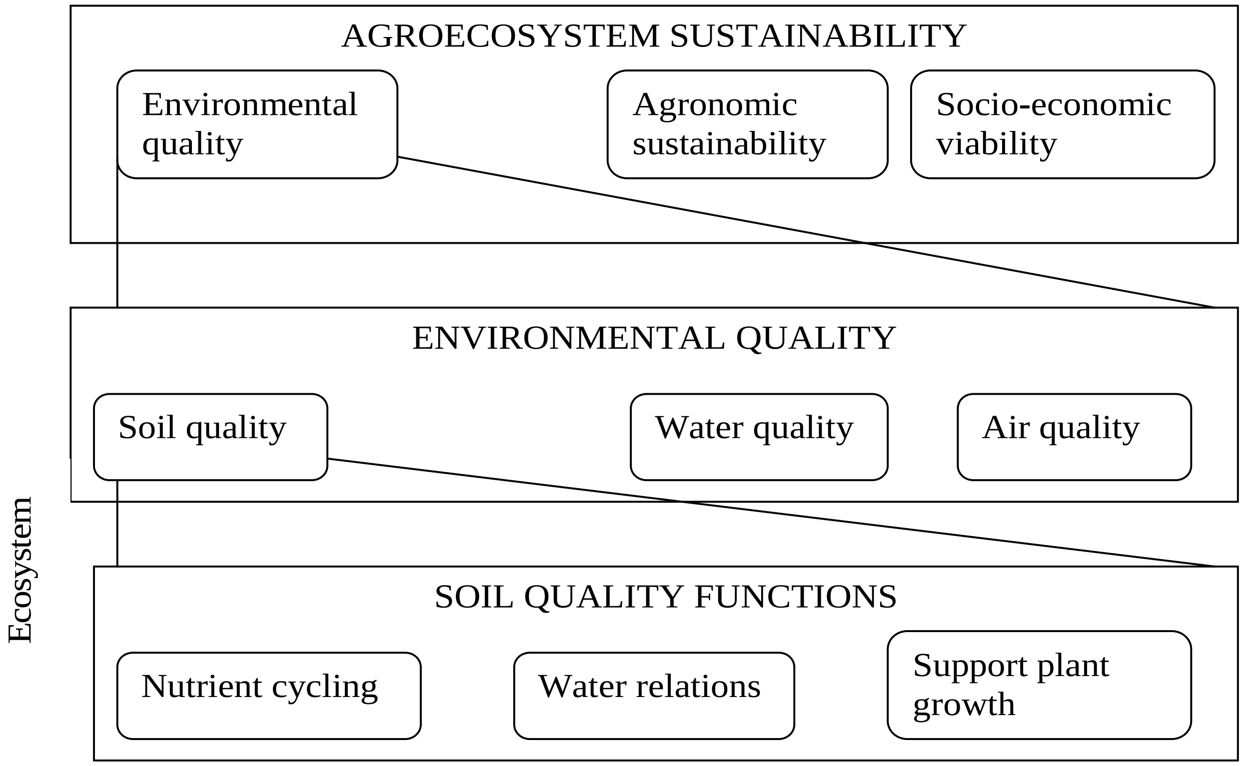

Fig. 3.4 Nested hierarchy of agro-ecosystem sustainability showing the relationship of SQ to the larger agro-ecosystem (adapted from Andrews *et al.*, 2002a)

3.5.1 Indicators of soil quality

Relevant and reliable indicators for specific functions under agro-climatic and socio-economic circumstances are essential since SQ cannot be directly measured. Indicators can be loosely defined as key attributes of the soil system that have greatest sensitivity to changes in soil function (Andrews *et al.*, 2004). They are measurable physical, chemical and biological attributes (Doran and Perkin, 1996) or morphological and visual features (USDA-NRCS, 2001) of soils or plants, which provide information how well the soil can function. Useful indicators are those that can be assessed by qualitative or quantitative methods (USDA-NRCS, 2001), and which are easy to measure and able to evaluate changes in soil functions, assessed in a reasonable duration, sensitive to variations in climate and management.

Gary *et al*. (2000) suggest that SQ indicators must well correlate with quantifiable soil functions. They further suggest that useful indicators; 1) must respond to external changes (natural or anthropogenic) in a measurable way, 2) must be adaptable for use by individuals with a range of background and skills, 3) must be found in existing database that are accessible and of value to SQ assessment, and 4) must be easily integrated into larger ecosystem-scale models, including socio-economic models. The best SQ indicators are those soil characteristics that show significant change between one to three years, with 5 years being an upper limit of usefulness (Stott *et al*, 1999).

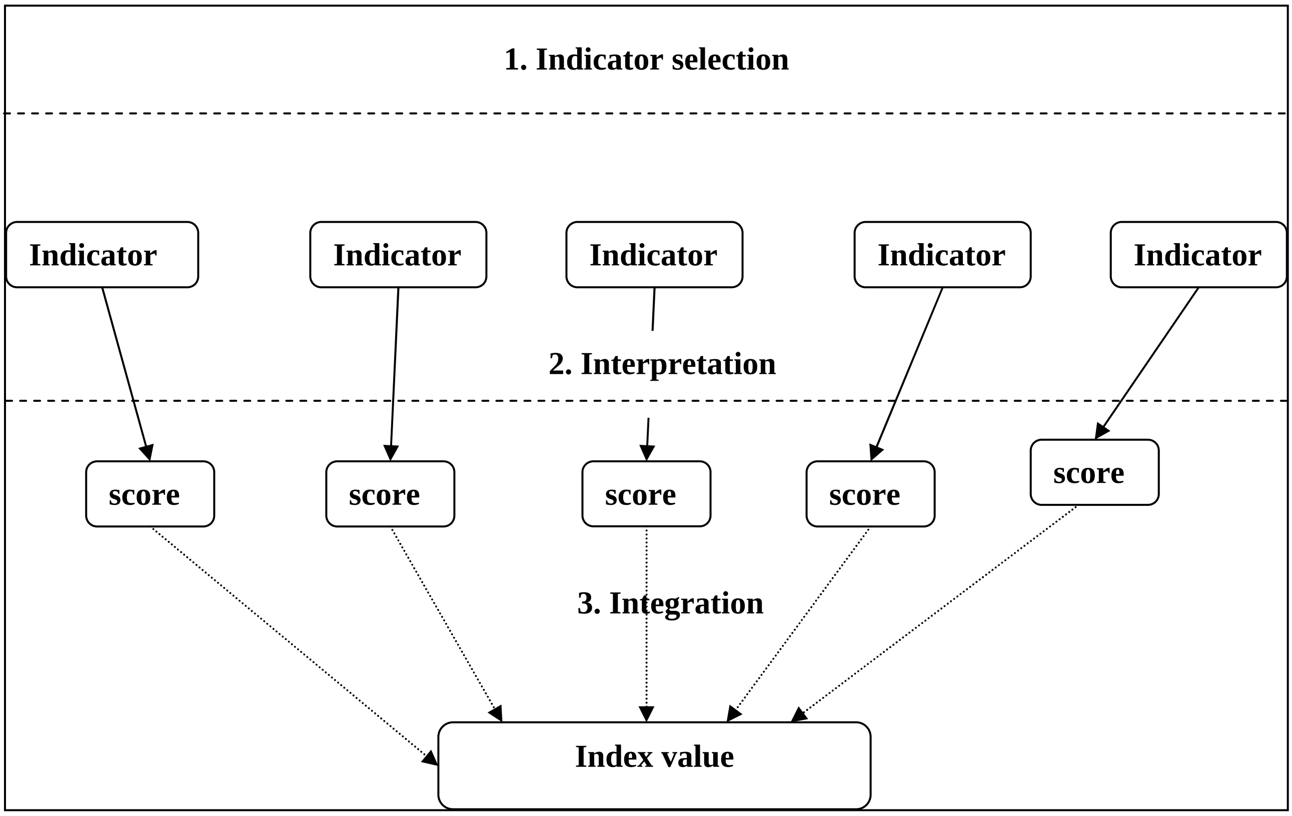

Fig.3.5 Flow chart indicating the three steps followed in development of soil quality index (Andrews *et al.*, 2004).

3.5.2 Comparison of indicators

Indicator value data are meaningful only if a baseline or some reference condition is available for comparison or if relative comparisons between management systems are made. While baseline values are initial conditions, reference values of indicators are established to represent a soil functioning at full potential (Stasch and Stahr, 1993; Karlen *et al*., 1994). Seybold *et al*. (1998) described two approaches of comparison of indicator values: monitoring of trends and comparison against reference values. Monitoring of trends requires establishment of a baseline values for the indicators and measuring of changes in those indicators over time. If the change in an indicator is positive, the soil can be regarded as improving with respect to that indicator. While the converse shows degradation, a no-change trend would indicate a sustaining system (Seybold *et al.*, 1998).
In a relative comparison the effects of different management systems on SQ indicators are investigated. In this approach, an improvement of SQ indicators under a management system as compared to those under another system is considered relatively improved.

3.5.3 A minimum data set

As it is impractical to measure every soil attribute (USDA-NRCS, 2001), the smallest set of soil properties or indicators known as a minimum data set (MDS), which must be measured or characterized to assess SQ, need to be determined (Larson and Pierce, 1991; Bouma, 1989; Arshad and Cohen, 1992; Doran and Parkin, 1994). The selection of the site specific MDS is most often based on expert opinion (Doran and Perkin, 1994), although statistical procedures, such as principal components or factor analysis can also be used (Andrews and Caroll, 2001). Both approaches produced similar results in a comparison of indexing approaches using data from a vegetable production study on irrigated soils in northern California, USA (Andrews *et al*., 2002a). However, it is recognized, that the use of objective statistical methods reduces the possibilities of disciplinary biases (Walter *et al*., 1997).
Among the soil parameters, (1) SOM, (2) soil structure, (3) soil and rooting depth, (4) infiltration and bulk density, (5) water holding capacity, (6) pH, (7) electrical conductivity, (8) available nitrogen, (9) phosphorus, (10) potassium, (11) microbial biomass carbon and nitrogen, (12) potentially mineralisable nitrogen, and (13) soil respiration are generally proposed as potential members of MDS (Doran *et al*, 1996; Seybold *et al*, 1998; Doran and Parkin, 1994). Additional parameters may be included depending on the local circumstances of the soil and the objectives of the study.

3.5.4 Scoring and integrating indicators

Traditional soil survey, classification and interpretation activities have defined Land Capability Classes, a Storie Index, and other Land Inventory and Monitoring indices based primarily on inherent soil properties (Karlen *et al*., 1997). All are important and useful, but none is the same as indexing dynamic SQ. According to Karlen *et al*. (2003), the latter builds upon the former but not vice versa. Soil quality indices are

decision tools, which effectively combine a variety of information for multi-objective decision-making (Karlen and Stott, 1994).
Evaluation of individual parameters of soil is one way of studying the impact of soil management on SQ (Bucher, 2002). However, these parameters are generally interdependent and, more importantly, practices like tillage and rotation systems may affect each parameter differently confounding the assessment of the overall quality (Weil *et al.,* 1996). Therefore, SQ assessment might be enhanced, if the individual parameters could be integrated in a meaningful way to an index (Dick, 1994; Bucher, 2002).

3.5.4.1 Indicator scoring

There are various ways of scoring and combining indicators into indices (e.g. linear, nonlinear, optimum, more is better, more is worse) depending upon the soil function (Fig. 3.6) (Andrews and Caroll, 2001). Linear scoring may be desirable for indicators that change gradually along a continuum. Non-linear scoring accommodates threshold and optimum values as well as transition areas, where small changes in indicator values represent large changes in soil function and thus the indicators' score (Herrick *et al*., 2002). Andrews *et al.* (2002a) found out, that non-linear scoring functions more accurately reflected soil function, when compared to a linear method. In addition, step function may be appropriate in some cases. For instance, indicators that measure 'contaminated versus non-contaminated' situations step functions can be applied (Karlen *et al*., 2003).

3.5.4.2 Integrating score values

Several alternatives have been proposed to combine the indicator score values to create indices. Multiplicative (Pierce *et al*., 1983) and additive models (Karlen *et al*., 1994) are among the proposed methods. According to Weil *et al.* (1996), multiplicative models may exaggerate the importance of any one parameter; especially if the value for that parameter is near zero. Thus, additive models (**Eq. 3.1**) may be more useful in assessing SQ, despite their sensitivity to the units of each parameter (Andrews *et al*., 2002a).

$$SQI = \left(\frac{\sum_{i=1}^{n} Si}{n} \right) * 10 \qquad 3.1$$

S represents the scored indicator value and **n** is the number of indicators in the MDS.

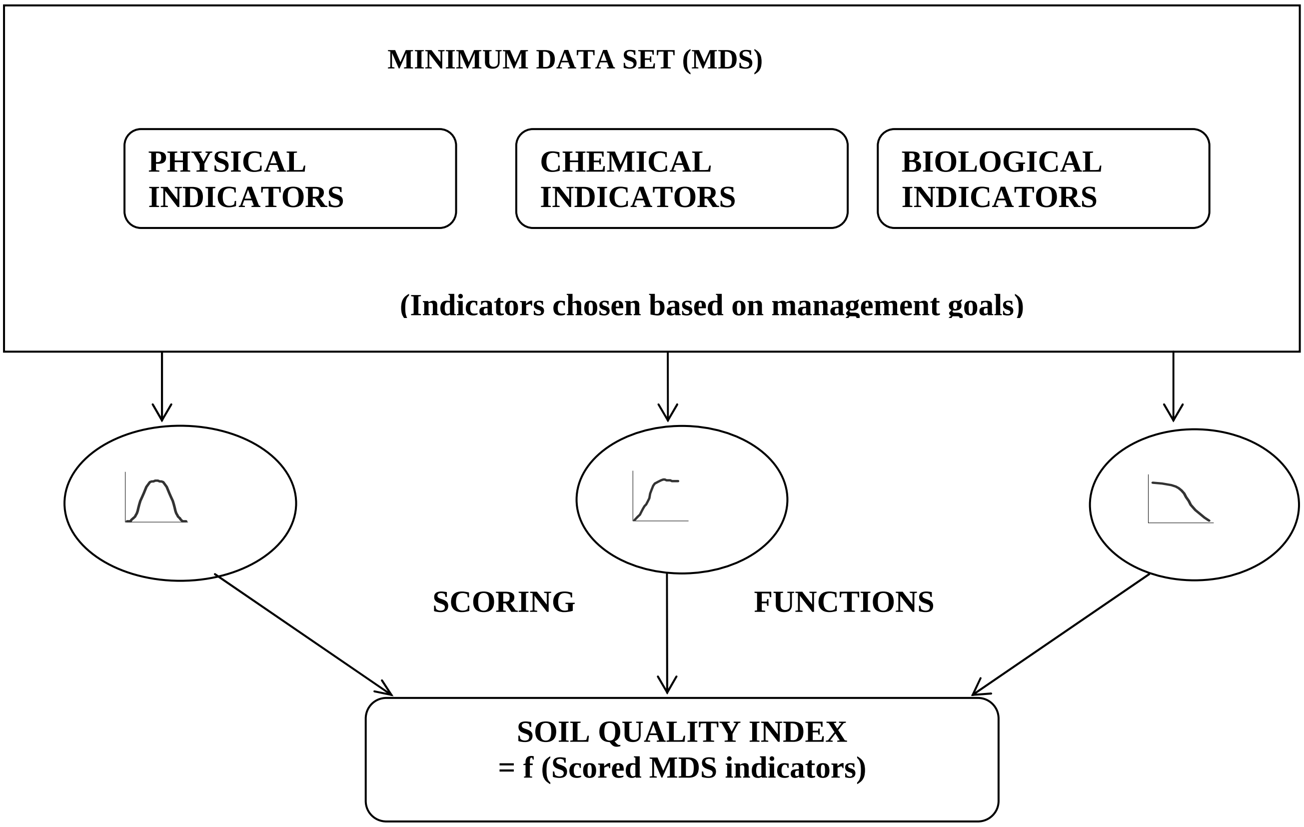

Fig.3. 6 Conceptual model for converting minimum data set indicators to index values (adapted from Andrews, 1998)

3.5.5 Significance of soil quality assessment

The industrialization of agriculture and the concomitant increase in societal concerns on environmental protection and food quality in industrialized countries (Schjonning *et al*., 2004) on the one hand, and continued land resources degradation and 'basic human needs insecurity' in developing countries on the other, have put the focus on agricultural management and its impact on soil quality. The need for assessing SQ as an element of agro-ecosystem sustainability is a rational response to these societal concerns. Most SQ research efforts intend to use science for better decision making regarding soil management practices and to make the best use of the finite soil, water and energy resources (Doran, *et al.*, 1996; Herrick, 2000; Karlen *et al.*, 2001). SQ monitoring supports land managers to scrutinize the sustainability of land use systems. In other words, understanding SQ leads to management systems that optimise soil functions for the current and future generations. Improving SQ can provide economic benefits in the form of increased productivity; nutrient and pesticides use efficiency, water and air quality enhancement and amelioration of greenhouse gases. However, the primary objectives of SQ management may vary depending on ecological or socio-economic circumstances.

Karlen *et al.* (2003) argue that many people around the world intuitively understand and use the SQ concept to improve their soil management practices. They further suggest the importance of the concept under various environmental and socio-economic settings. Ouedraogo *et al.* (2001) explain the importance of SQ for Sub-Saharan Africa, while Lamarca (1996) emphasises the need of SQ for the Latin American conditions. The SQ issues are particularly important for the two billion people who are malnourished and an equal number who live below the poverty line in developing countries, where the extent and prospect of the environmental degradation is soaring (Eswaran *et al.* 1999).

Nevertheless, the case of industrialized countries is more elaborate, with a major emphasis on the over all environmental protection as opposed to land degradation in developing countries. For Germans, the Federal Soil Protection Act (BbodschG, 1998) recognized soil as 1) a basis for life and habitat for animals, plants and soil organisms, 2) part of natural systems, especially water and nutrient cycles; and 3) a filter and buffer; with water quality and protection. In New Zealand, Kiwi land managers have accepted SQ as a tool for sustainable land management decision (Shepherd *et al.*, 2001). These elucidate that SQ concept and management is an important tool for sustainable soil resources management practices regardless of the level of societal development.

3.6 Shortcomings of soil quality concept and analysis

Although the SQ concept and assessment approaches have been used worldwide under different socio-economic circumstances and ecological settings, the concept, scope and the tools of analysis have been strongly criticised. Among the recent publications in this regard is the "Research Editorial by Conservation Professionals" (Letey *et al.*, 2003). As this article summarized most of the issues mentioned else where, it is a prime source for this section.

They start by claiming that the SQ concept has deeply divided the soil science community. They further state that it was institutionalized and advocated without full consideration of the 'concept weakness' and contradictions. As a summary, the deficiencies are itemised as follows:

Lack of standard**:** In the SQ analysis, there is no standard to which SQ indicators can be compared, but higher soil quality index (SQI) numbers are interpreted as higher soil quality.

Lack of functional relationship**:** Establishing a functional relationship between SQ and SQ indicators is decisive in SQ assessment. However, such functional relationships cannot always be established empirically. This is particularly true for indicators with only indirect effects on plant growth, such as SOM and water stable aggregates. Consequently, there is a potential subjectivity and opportunity for value-laden biases that may skew the analyses.

Weighting factor*:* There is a lack of clarity as to what weighting factors should be given to individual indicator values.

Adding indicators values**:** The appropriateness of summing the indicator values to get an index is doubtful.

Complexity of considering diverse functions: Considering many diverse functions, with a different quality requirement, simultaneously makes the analysis more complex. Combining all of these functions into one SQ index number is prohibitive. The advocates of SQ concept have also recognized these shortcomings of operational predicament, which results when individual indicators show conflicting trends or favour opposing functions (Carter *et al.*, 1997).

Index values to compare: Assuming a reliable SQI can be determined, there is confusion and contradiction as to which SQI values can be compared. Possible scenarios include:

1. Comparing all soils
2. Comparing temporal or spatial variation and
3. Comparing treatment or management-induced changes on a single soil.

***Water quality not addressed*:** although some soil properties promoted as positive for SQ can greatly increase the probability of surface and groundwater degradation, the SQ paradigm does not address water quality issues.

Crop specificities: Although crops differ in their response to many soil attributes, and a soil of high quality for one crop may be low quality for another, no consideration is given to crop specificity.

4 Materials and methods

Ethiopia is a landlocked country in eastern Africa, bordered by Eritrea, Sudan, Kenya, Somalia and Djibouti to the North, west, south and east, respectively. It is located within the tropics between 3°24` and 14°53` N; and 32°42` and 48°12` E (Fig. 4.1) (Alemayehu, 2003). With an area of 1.13 million km^2 (Mulugeta, 2004) and divided into nine regional states, one City Council and one City Administration, it is the third largest country in Africa.

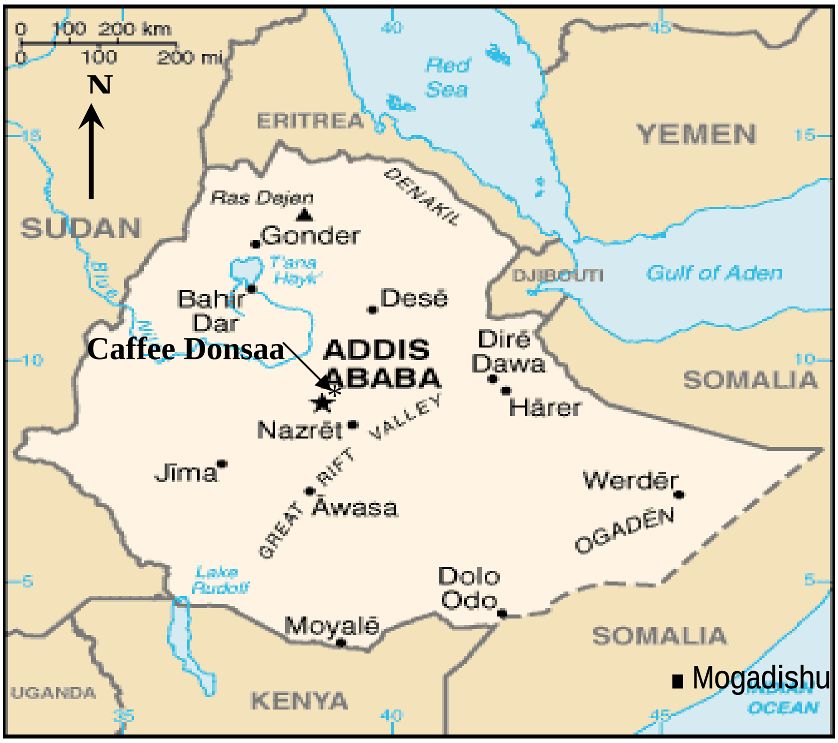

Fig. 4.1 Location map of Ethiopia

4.1 Characteristics of the study area

4.1.1 Location

The study was conducted in a small watershed (about 100 ha) which was identified in *Habru Seftu* peasants association, in Gimbichu district (08°57' N; 39°06'E) at about 40 km northeast of Addis Ababa, in the eastern part of Oromia regional state (Fig.4.2). The watershed has been a demonstration site for improved Vertisol management technologies in the area since 1997. A research station was situated in the upper part of the watershed since over two decades for development of crop production technologies for the Vertisols in the central highlands.

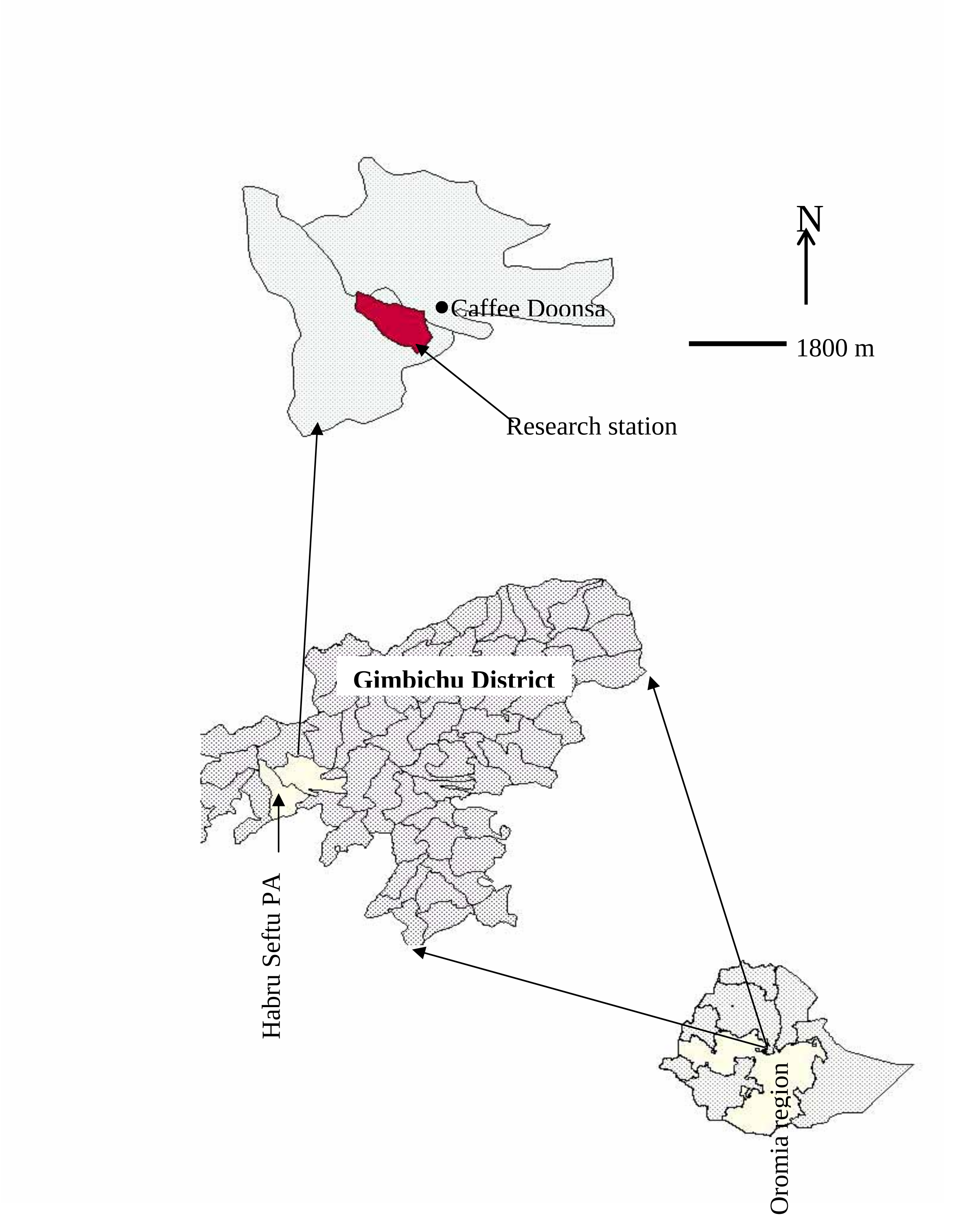

Fig. 4.2 Location of the study area at Caffee Doonsa in Ethiopian highlands

4.1.2 Geology and hydrology

Geologically, Ethiopia lies at the northern end of the continental part of the Eastern Rift. The geology of Ethiopia can be grouped into the pre-Cambrian basement complex of various grades with unaltered sedimentary rocks and igneous intrusions; the Mesozoic mantle sediments, deposited during a transgression in the upper Jurassic; and the cover deposits (Mohr, 1961, 1962). Another important event is the Trap Series molten lava outpour at the beginning of the Mesozoic era.

The highlands are made up of folded and fractured crystalline rocks covered by sedimentary limestone and sandstone, and by thick layers of volcanic lava (Mohr, 1971; 1986 Rogers *et al.*, 1965). The highland is divided in to the western and eastern highland plateaus (Mohr, 1971; 1986 Rogers *et al.*, 1965) by the rift valley that constitutes part of the East African rift system. The altitude ranges from 126 m below sea level in the Dalol (Afar) Depression on the north-eastern part of the rift valley to the highest mountain, Ras Dejen (4,620 m asl) (Alemayehu, 2003). Mountains, steep slopes, valleys and plateaus occur between these extreme altitudes leading to a significant variation in climate, soils and vegetations.

4.1.3 Climate

High climatic heterogeneity that is suitable for different agricultural production systems characterises the country. The mean annual temperature ranges from 34.5°C in the Danakil depression to less than 0°C on the Mountain Ras Dejen (4,620 meters). In the vast areas of plateaus and marginal slopes, the mean annual temperatures are between 10° and 20°C.

The highlands receive higher rainfall than the lowlands, except the lowlands in the west. While the average annual rainfall of the highlands exceeds 900 mm, in the lowlands it is erratic with averages below 600 mm. Based on moisture regimes 50% of Ethiopia was classified as having sufficient moisture for annual crops and another 16% as reliable for perennial crops (FAO 1984a).

Situated at an altitude of 2400 m, the study area is characterized by an average annual temperature of 17° C and average annual rainfall of 1000 mm, which is bi-modally distributed (Fig. 4.3), although the small rains can some times be inadequate or simply absent.

4.1.4 Farming system and land use

A small-scale production of mixed crops and livestock characterise the farming system in the area. The land use around *Caffee Doonsa*, is mostly cultivated field crops, while the marginal lands along the roadsides, gully bottoms or flood plains are the major grazing ground (Teklu *et al.*, 2004). The major crops grown include wheat (*Triticum spp.)*, tef *(Eragrostis tef)*, lentil (*Lens culinaries Medik)* and chickpea (*Cicer arietinum*) often in rotation, while forests are disappearing, except for few eucalyptus trees (*Eucalyptus globules*) in the backyard. Gully erosion is a major problem due to the characteristics of the soil, intensive tillage, heavy summer rainfall, steep slope and complete removal of crop residues. Although fertilizer application for cereals is common, and some times exceeds the recommended rates, the recovery rate is low, because of the moisture stress induced by late planting and losses through runoff. The use of cow dung as fuel is another serious problem associated with soil management in the area.

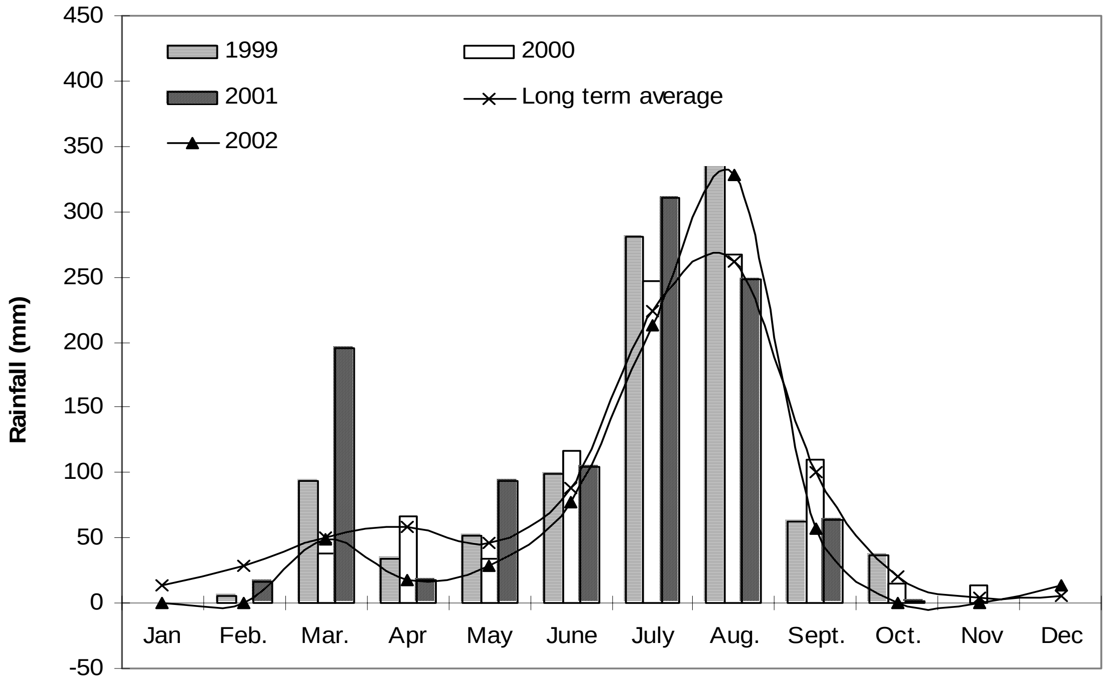

Fig.4.3 Rainfall distribution at Cafee Donsaa area

4.2 Components of the study

The study has two components. The first part dealt with an on-farm assessment of SQ in a small watershed, where the farmers were fully involved in appraisal of the quality of their soils. This was complemented by a systematic characterization of the soils following standard soil survey procedures. The second part was conducted in a research station located within the boundary of the watershed.

4.2.1 On farm assessment of soil quality

A Participatory Rural Assessment (PRA) technique as described by Chambers (1992) was employed for the study. Although not intended, the participating farmers were all men of different age and wealth groups. There are few with female head households in the area, and all were too timid to come out for a meeting with men. Therefore, 36 male farmers having a piece of land in the watershed area were randomly selected to participate in a 3 day farmers' workshop organized to develop SQ criteria and to classify the soils in the watershed into different quality groups. Group discussion was moderated with a guide using a pre-formulated checklist to describe soil functions and to define SQ with respect to them.

The major soil functions recognized in the area were listed and ranked using pair-wise technique (Chambers, 1992). In this procedure, differently coloured cards were used for the different soil functions. The facilitator showed the labelled cards two at a time, asking, “Which is the more important soil function? “ As the participants made the comparisons, the results were recorded in a matrix, and the result was obtained by counting the number of times each function “won” over the others. Soil quality was defined as it related to the functions identified, and the soils were then arranged in an appropriate order.

SQ indicators used by the farmers were also recorded and used to develop SQ groups, which were ranked according to their area coverage and qualities as above. The suitability of soils for different crops grown in the area, and the problems associated with the 3 SQ groups are summarized and mapped both on the ground using local materials and on a white board. The SQ map was then verified by a transect walk through the watershed. Finally, crop yields were determined from 21 farmer plots (7 from each SQ group) in order to verify their claims.

4.2.2 Soil characterization

4.2.2.1 Field description of the soils

Following the characterisation and evaluation according to the participatory Rural Assessment (PRA) technique as described by Chambers (1992) together with farmers, soil survey was carried out to see how the farmers’ evaluation was related to that based on scientific procedures and establish a soil data base of the area. To this effect, a reference profile was opened and described for each of the three SQ groups as categorised and mapped with the farmers (Fig. 4.4). In addition, two transects were auger sampled at 100 m intervals; in such a way that all the three SQ groups were traversed. The Soil Survey Handbook (Hodgson, 1976) was used as guidance in the description of the profiles and transects.

Three lead profiles were opened on the ridge, middle and foot slopes in the watershed, with the local slope gradient of 7, 5 and 3 percent, representing Carii, Abolse and Kooticha, respectively, the three SQ groups as identified by the farmers. As the colour and structure of the profiles were homogeneous along the depth, the boundary distinction or the layering was diffuse or gradual, that marking of the layers arbitrarily rounded to the nearest 10 cm.

4.2.2.2 Soil sampling from profiles and farmers fields

Following the soil profiles description, samples were taken from each layer. Corresponding to the profiles, 21 farmers fields (7 from each SQ group) were sampled with auger at 0-30, 30-60 and 60-90 cm depths. The sampling locations have been geo-referenced using Global Positioning Systems (GPS). The samples were analysed following standard procedures for each parameter (section 4.2.4)

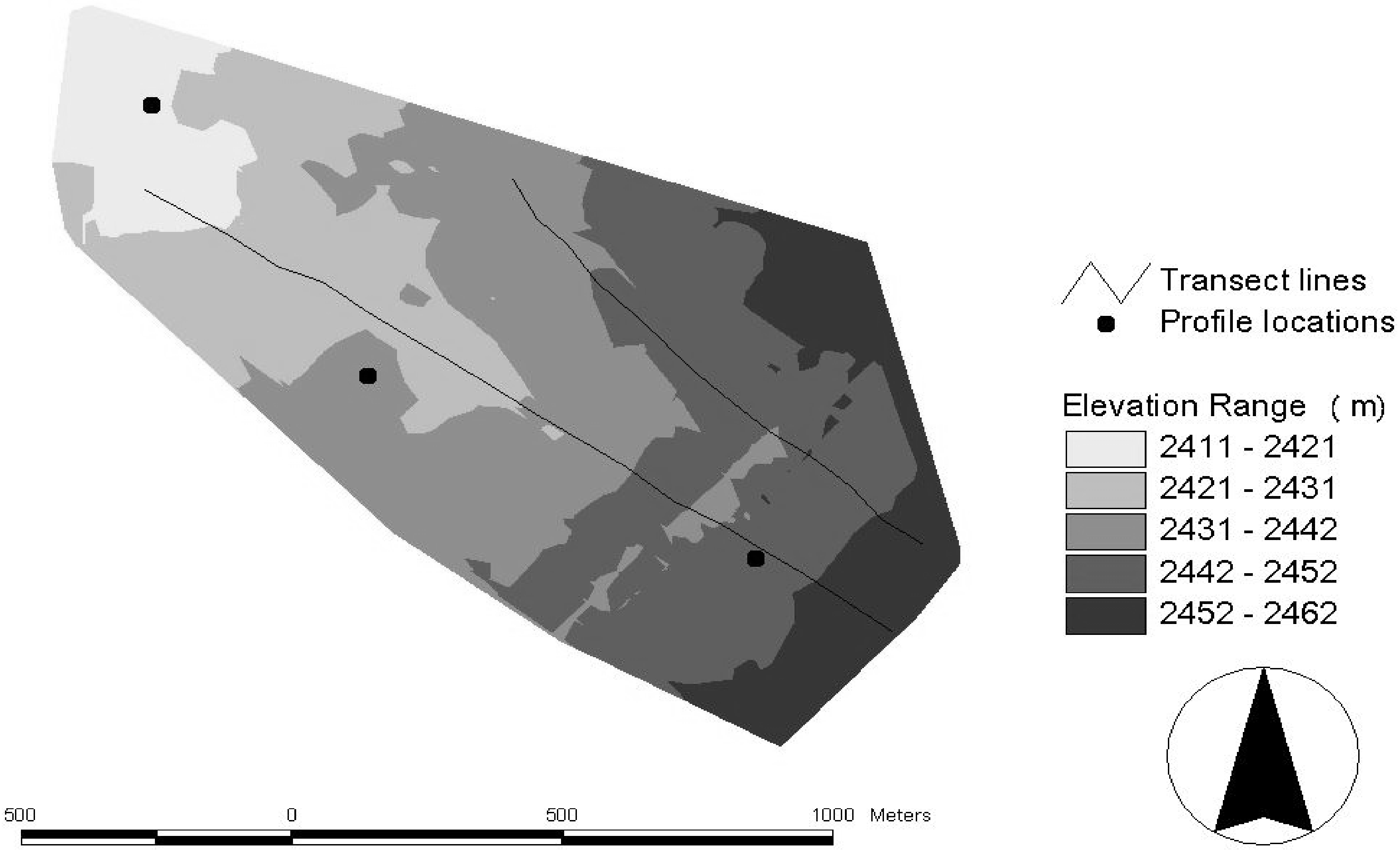

Fig. 4.4 Sampling locations and elevation map of the watershed area

4.2.3 On-station assessment of soil quality

The experiment was conducted for six consecutive rainy seasons (1998- 2003) at *Caffee Doonsa* (2400m asl) in the experimental station established as a representative of highland Vertisol areas located in the watershed area (*see section 4.1.1*). Smectite clay mineral with high cation exchange capacity, high pH soil (Table 4.1) and mean annual rainfall of 900 mm and temperature of 17^0C characterize the area.

Table 4.1 Some physico-chemical characteristics of the soil in the study area

Depth (cm)	Clay content (%)	Smectite (%)	pH (H_2O)	Organic carbon (%)	CEC (cmol.kg^{-1} soil)
-40	73	96	7.9	0.70	98
-80	75	97	8.2	0.76	92
-120	75	91	8.0	0.49	87
-150	75	96	8.1	0.66	83

4.2.3.1 Treatments and experimental design

Four methods of land preparation were evaluated on permanent plots (22 m x 6 m) similar to Wischmeier and Smith (1978). The experimental design was randomized complete block, with three replications (Fig. 4.5). The treatments were:

Broad Bed and Furrows (BBFs) were constructed by the broad bed maker (BBM), which is an oxen-drawn traditional wooden plough, modified for the construction of raised beds and furrows. With an effective bed width of 80 cm and 20 cm furrows, it is intended to facilitate surface drainage through the furrows between the beds (Jutzi and Mesfin, 1987) so that the crops grow on the beds. The crops were sown at the end of June or beginning of July (Table 4.2), depending on the onset of the rain.

Ridge and Furrow (RFs) were constructed with the traditional thyne-plough after the seed is broadcast by hand such that, the crops grow on the ridges, permitting the excess water to drain out of the field through the furrows. These are parallel narrow structures of about 20 cm high and 30 cm wide. The crops were sown late in the season (Table 4.2). This is a local practice to avoid the problem of water logging in Vertisols. The land preparation starts early following a small rain during April and May. As it involves occasional tillage operations until planting, soil erosion is its major consequence. This is considered as a control for this experiment.

Green Manure (GM) refers to a practice, where a legume is grown using the short rain to cover the soil during the heavy rain season. In this study, Vetch (*Vicia desicarpa)* was sown in May (Table 4.3) to be chopped and ploughed under, while still green ten days before planting and incorporated into the soil by two tillage operations. The test crops were sown after the final tillage in the same manner as RF (Table 4.2), except for tef. The practice is meant to reduce soil erosion, when late sowing is unavoidable and to improve SOM content and thereby the SQ and hence crop productivity.

Reduced Tillage (RT) plots were kept intact fallow until they were sprayed with non-selective herbicide glyphosate (N-(phosphonomethyl)glycine) at 4L ha^{-1} 10 to 15 days before sowing. Similar to RF and GM, the crops were sown late August or early September (Table 4.2), except for tef. The seeds are broadcast and covered by a single tillage using the local plough for wheat and lentil, while tef was broadcasted on freshly tilled field. This is meant to minimize pre-sowing soil disturbance, reducing OM oxidation and maintaining surface cover to reduce soil erosion.

The treatments were kept permanent while three crops: wheat (*Triticum durum Desf.)*, lentil (*Lens culinaries Medik)* and tef *(Eragrostis tef)* were rotated following their traditional sequence. Improved crop varieties, *Boohai*, *DZ-01-196* and *Ada'a* for wheat, tef and lentil, respectively were used. The planting date varied with the treatment and crop type as well as the onset of the rain (Table 4.2). Each crop was repeated twice making two complete cycles. As tef is water logging tolerant, a flat seedbed was used that BBF and RF were expressed only through their residual effects. All cultural practices other than the treatments were implemented according to the recommendation for the respective crops (Table 4.3). Nitrogen in the form of Urea and phosphorus in the form of TSP were applied at 80 kg N. ha^{-1} and 10 kg P. ha^{-1}, respectively, except for lentil in which only 10 kg P. $ha^{-1}$was applied. Weed and pests were controlled by hand and chemicals, respectively, whenever applicable. Yield components were determined and the data were subjected to analysis of variance.

4.2.3.2 Soil sampling from the station

Soil core samples at 0-30, 30-60 and 60-90 cm depths for BD (Arshad *et al.*, 1996) and corresponding auger samples for soil moisture (Lowery *et al.*, 1996) were collected every ten days during the growing periods of the first five years (1998-2002). Intensive sampling was made in 2002. To this effect composite soil samples were taken from the plots at two depths (0-15 cm and 15-30 cm) using for chemical and biological analysis during the growing stage. This was followed by profile sampling after harvest at three depths (0-30, 30-60 and 60-90 cm) for physical and chemical analysis, followed by surface crusts collection by hand.

4.3 Soil analysis

4.3.1 Soil physical analysis

Double ring infiltrometer was used to determine the infiltration capacity (Lowery *et al.*, 1996), annually after harvesting. Soil compaction was measured (in 2002) in the field using a cone penetrometer (Bradford, 1986; Arshad *et al.*, 1996) at tillering stage and after harvest. Correspondingly, auger sampling was made for moisture content determination. Pocket penetrometer and calliper were used to measure the strength and thickness of the surface crusts, respectively.

Table 4.2 Sowing and harvesting dates of the crops for the different tillage systems

Year	Treatment	Crop type	Sowing date	Harvesting date
1998/99	BBF	Wheat	16 Jul	17 Dec.
	GM		6 Aug	24 Dec.
	RF		27 Aug	13 Jan.
	RT		27 Aug	13 Jan
1999/2000	BBF	Lentil	28 Jul	14 Dec.
	GM		20 Aug	6 Jan.
	RF		24 Aug	11 Jan.
	RT		3 Sept	18 Jan.
2000/01	BBF	Tef	12 Aug	5 Jan.
	GM		12 Aug	5 Jan.
	RF		12 Aug	5 Jan.
	RT		12 Aug	5 Jan.
2001/02	BBF	Wheat	18 Jul	6 Dec.
	GM		27 Aug	9 Jan.
	RF		27 Aug	9 Jan.
	RT		27 Aug	9 Jan.
2002/03	BBF	Lentil	30 Jul	16 Dec.
	GM		23 Aug	9 Jan.
	RF		23 Aug	9 Jan.
	RT		23 Aug	9 Jan.
2003/04	BBF	Tef	12 Aug	5 Jan.
	GM		12 Aug	5 Jan.
	RF		12 Aug	5 Jan.
	RT		12 Aug	5 Jan.

Air-dried and ground (<2 mm) soil samples were used for the laboratory analysis. Particle size distribution was determined by the Bouyoucos hydrometer method (Bouyoucos, 1962). The wet sieving method (Arshad *et al.*, 1996) was employed for determination of water aggregate stability of surface soil samples. A pressure extractor with 1 bar and 15 bar ceramic plates was used to determine soil water content at field capacity (1/3 bar) and permanent wilting point (15 bar), respectively. Total soil porosity was estimated from BD according to Blake and Hartge (1986).

4.3.2 Soil chemical analysis

The analysis was conducted on ground and sieved (< 2mm) samples. Schoffield and Taylor (1955) method for pH (1:2.5 H_2O), Walkley-Black (Walkley and Black, 1934) for C_{org}, Kjeldhal method for nitrogen (N) and Olsen method (Olsen *et al.*, 1954) for available phosphorus, respectively, were employed. For the cation exchange capacity (CEC), the principle of mass action was applied. In the procedure, the exchange sites were saturated with Na^+ by adding excess sodium acetate solution to displace the adsorbed cations from the exchange complex. Then the sodium was substituted by NH4OAC (buffered at pH 7), and the concentration of Na^+ in the extract was measured using flame photometer. After correcting for moisture content, the result was expressed in (cmol kg^{-1}) soil. Similarly, the exchangeable cations were substituted by adding excess NH4OAC (pH = 7), and the concentrations of Na^+, K^+ and Ca^{2+} were determined with flame photometer, while atomic absorption spectrophotometer (AASP) was used for magnesium ions.

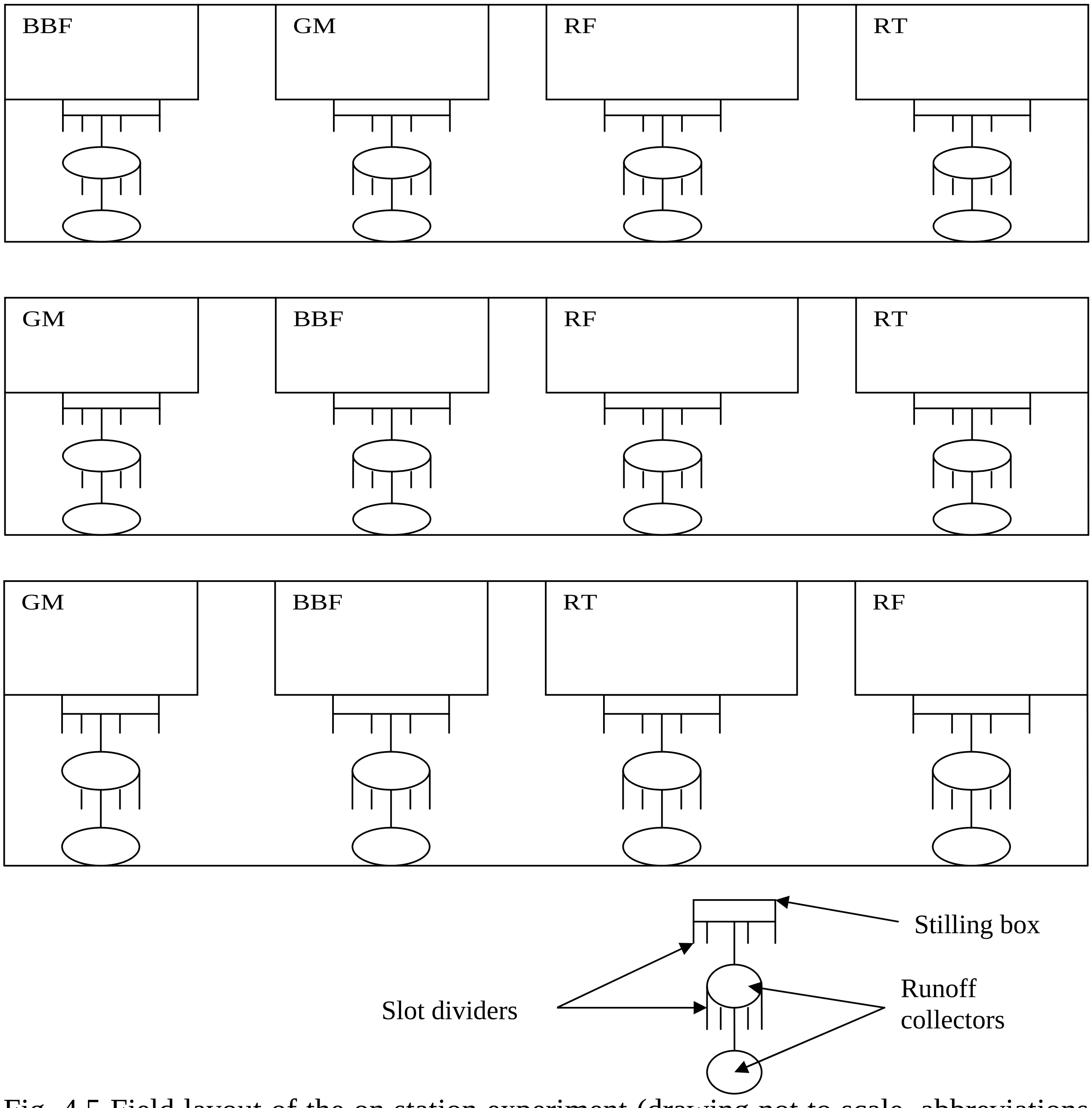

Fig. 4.5 Field layout of the on station experiment (drawing not to scale, abbreviations compare text 4.2.3.1)

Table 4.3 Schedule of major cropping activities under the alternative land preparation methods

Date§	Cropping activities			
	BBF	GM	RF	RT
Wheat phase				
March-April	Tillage	Tillage and sowing of cover crop	Tillage	-
May	Tillage	-	Tillage	-
June	Tillage	-	Tillage	-
July	BBF preparation and sowing	Chopping and incorporation of green manure	Tillage	Herbicide spray
August	-	Tillage and sowing	Tillage sowing	Tillage and sowing
September	Weeding	-	-	-
October	-	Weeding	Weeding	Weeding
November	-	-	-	-
December	Harvesting	-	-	-
January		Harvesting	Harvesting	Harvesting
Lentils phase				
March-April	Tillage	Tillage and sowing cover crop	Tillage	-
May	Tillage	-	Tillage	-
June	Tillage	-	Tillage	-
July	BBF preparation and sowing	Chopping and incorporation of green manure	Tillage	Herbicide spray
August		Sowing	Sowing	Sowing
September	Weeding	-	-	-
October		Weeding	Weeding	Weeding
December	Harvesting	-	-	-
January		Harvesting	Harvesting	Harvesting
Tef phase*				
March-April	Tillage	Tillage and sowing of cover crop	Tillage	-
May	Tillage	-	Tillage	-
June	Tillage	-	Tillage	-
July	Tillage	Chopping and incorporation	Tillage	Herbicide spray
August	Tillage and sowing	Tillage and sowing	Tillage and wing	Tillage and sowing
September	Weeding	-	-	-
October	-	Weeding	Weeding	Weeding
November	Harvesting	-	-	-
January		Harvesting	Harvesting	Harvesting

§ The exact date of the operations is variable. * Tef does not require broad-bed and furrow

4.3.3 Soil biological analysis

The soil samples were taken to the laboratory immediately after sampling to determine microbial biomass carbon (MBC) using the substrate-induced respiration (SIR) method (Anderson and Domsch, 1978). Accordingly, 100g of the field moist soil was thoroughly mixed with 400mg glucose, and 20g of the mixture was weighed to 4 nylon bags each. Each bag was mounted into a 500 ml laboratory bottle filled with 20 ml 0.1M NaOH solution. The bottles were immediately closed with gas-tight caps, and incubated for 4 hours at 22^0C together with 2 blanks. Then, the samples were immediately removed from the bottles and the absorbed CO_2 was precipitated as $BaCO_3$ by adding 2 ml of 0.5M $BaCl_2$ solution. The remaining NaOH was titrated against 0.1M HCl using 3-4 drops of phenolphthalein solution as indicator. Schinner *et al.* (1996) method (**Eq. 4.1**) was used to calculate the results.

$$mg\ CO_2\ 100\ g^{-1} h^{-1} = \frac{(B - S) * 2.2 * 100}{4 * SW\ * dm} \qquad 4.1$$

Where	B	Mean volume of HCl consumed by blanks (ml)
	S	Mean volume of HCl consumed by samples (ml)
	4	Incubation time (h)
	100	Conversion factor (100 g dm)
	2.2	Conversion factor (1 ml 0.1 M HCl corresponds to 2.2 mg CO_2)
	SW	Initial soil weight (g)
	dm	Soil dry matter (%)

Assuming a respiratory quotient of 1.1 mg CO_2.100 g^{-1} dm. h^{-1} corresponds to 20.6 mg biomass-C.100g^{-1} dm. Thus, this factor was used to convert the CO_2 into MBC.

4.3.4 Soil mineralogical analysis

The clay fraction (<2µm) of the profile samples was separated through repeated dispersion and sedimentation. Then, X-ray diffraction (XRD) method was used to analyse the clay fraction after air-drying, K^+ and Mg^{2+} saturation, spray with glycol, and heating to 400 and 600°C, respectively. The relative intensities of the XRD peaks were used to quantify each clay mineral type (Alexiodes and Jackson, 1966 and Cradwick and Wilson, 1972).

4.4 Runoff and soil loss assessment

Multi-slot divisors (Pathak *et al.*, 1997, FAO, 1993b) were used for measuring surface runoff. Each plot was hydrologically isolated on the surface by Iron sheets that were installed along the boundaries. Runoff from each plot was measured every 24 hours. The runoff samples were allowed to stand for at least 48 hours until the sediments had completely settled; the water was decanted and the sediment oven dried. The dry sediment was weighed and stored for nutrient analysis. The product of the sediment concentration and the total runoff per plot per day (**Eq.** 4.2) was used to determine the daily sediment loss.

$$S = \frac{R * Sc}{1000} \qquad 4.2$$

where S= sediment loss (kg.ha^{-1})
R = daily runoff (L ha^{-1})
Sc = sediment concentration of runoff (g L^{-1}) and 1000 is a factor to convert g to kg.

Due to the limitation of sample quantity and to reduce analysis cost, the sediment samples were bulked for 10 days. Following the procedures in *section 4.3*, C_{org}, total nitrogen (N_t), and available phosphorus were determined. For comparison, surface soil (0-15 cm) was sampled and analysed for these nutrients.
A single factorial model (F-test) was conducted using SAS statistical package in order to compare the effects of the treatments on runoff, soil loss, nutrient and C_{org} content of the eroded sediments and that of the original surface soil, and crop yield data. The paired t-test was used for comparison of the nutrient concentration and C_{org} content of the sediments and the surface soils. A simple correlation analysis was conducted to test the relationship between nutrient and C_{org} concentration in the eroded sediment and concentration in the surface soil. In addition, nutrient enrichment ratio (ER) was determined by dividing the concentration of a nutrient in the sediment by its corresponding concentration in the surface soil (**Eq.** 4.3) as:

$$ER = \frac{CS}{CSo} \qquad 4.3$$

where CS = Nutrient or C_{org} content of the sediments
Cso = Nutrient or C_{org} content of the original surface soil.

4.5 Crop performance

4.5.1 Crop productivity

Yield and yield components of the crops were recorded during the experiment period (1998-2002) but the data from 2003 was also included since the performance of the crop in 2002 was very poor. The data were subjected to Analysis of Variance (ANOVA). One factor factorial model was applied on the yearly data, for the agronomic characteristics. However, a model with one factor randomized complete block design combined over years was implemented for the grain and straw yields. Accordingly, each crop was considered as if it was sown in two consecutive years. In comparing the long-term agronomic performance of the treatments, Relative Productivity Index (RPI) (Teklu et *al.*, 2004), which was defined as the ratio of the treatments mean grain yield to the mean grain yield of all the treatments (**Eq. 4.4-4.6**) has been employed to overcome the difficulty of comparing different crops.

$$RPI = \frac{\overline{y}}{\overline{Y}} \qquad 4.4$$

$$\overline{y} = \frac{\sum_{i=1}^{n} yi}{n} \qquad 4.5$$

$$\overline{Y} = \frac{\sum_{i=1}^{N} \overline{yi}}{N} \qquad 4.6$$

where y_i = yield of a treatment (kg.ha^{-1})
n = number of replications
N= number of treatments.

4.5.2 Economic analysis

A gross margin analysis was carried out to compare the economic feasibility of the systems. In this analysis, only the variable cost items induced by the alternative treatments, including tillage types and frequency, labour and herbicide use were considered. Weeding and other cropping activities were assumed constant. An average of four tillage practices using oxen drawn plough is common for most crops grown in the area. The first tillage requires an average of 6 oxen days per ha, while the subsequent requires 4-5 oxen days per ha depending on the strength of the soil. The cost of one oxen day in the area is set at 30 Birr a day (8.65 Birr = one US$) although this may increase during the critical times. Additional labour cost for chopping the green manure crop before the first tillage and herbicide cost were considered for GM and RT, respectively. The average market price of the grain at harvest was considered, assuming that farmers sell their grains immediately. Straw price was estimated based on the price of 10kg bale of the various straws at Bushoftu, a near by town.

4.6 Integration of soil quality indicators

Of the soil attributes determined, the ultimate SQ indicators were selected using expert opinion approach. The selected indicators were converted to score values (between 0 and 1) using the non-linear scoring functions. The scored values were integrated into indices using additive model (**Eq. 4.7**), and the indices were subjected to ANOVA to test the significance of the treatment effects.

$$SQI = \left(\frac{\sum_{i=1}^{n} Si}{n} \right) * 10 \qquad 4.7$$

where SQI = soil quality index
Si = score values for individual indicators and
n= number of indicators used

5 Participatory soil and land quality assessment

As it is the case in most sub-Saharan African countries (SSA), continued degradation of agricultural land caused decreased productivity and increased environmental risks in Ethiopia. As a result, there is an enormous need for sustaining the productivity of the resource base through improved management of soil quality. The success of management interventions in maintaining or enhancing SQ depends on our understanding of how the soil responds to agricultural use and practices over time (Gregorich *et al.*, 1994). This requires long term monitoring under prevailing ecological settings and management systems. Farmers for whom soil is the basic input for agricultural production closely associate themselves with it, and hence have a cumulative knowledge of its behaviours. Thus, it makes sense to involve them regardless of the scale of their operations in identifying SQ indicators based on their management goals and in valuing the soil resources. Such an approach is believed to promote not only the development and dissemination of relevant and acceptable technologies for sustainable SQ management, but also farmers’ ability to analyze their resource bases.

The highlands of Ethiopia, where Vertisols represent about 8 million hectares, are believed to substantially contribute to the food security of the country, because of their relatively higher yield potential. However, the hydro- physical properties of the soils present immense problems leading to under utilization of the potential. Broad bed and furrows (BBF) as a surface drainage system was among the technologies disseminated during the last 2 decades as an alternative to the traditional practices. Yet its large-scale adoption was impeded by technical constraints such as inappropriate site selection for the various crops, which have led to occasional crop failures. This necessitated farmers’ involvement not only in technology generation and implementation, but also in resource characterization and evaluation, and development of sustainable technologies. This study was conducted to establish criteria that could be used for quality assessment of the soils with respect to the major crops in the highland Vertisol area and to establish a link between the traditional and scientific SQ information in the area.

5.1 Soil function and soil quality

5.1.1 Soil functions

During the Focused Group Discussion (FGD), the farmers made a long list of the local soil functions (Table 5.1) and prioritized them. The soil functions as described by the farmers could be roughly categorized in to **production, construction, raw materials** and **environment,** corresponding to the internationally recognized functions (FAO, 1996). The production related functions received high ranking, while the other functions were secondary for subsistent farmers concerned for their families’ daily bread. While comparing the soil functions (two at a time), there was sometimes long and heated debate before consensus was reached or a vote taken when agreement could not be reached. However, there was little disagreement whenever comparing crop production function against other functions since the farmer's life is based on this activity. In comparing the environment related functions with other non-production related ones, one participant gave unconditional priority to water related issues. As a result, settlement was only by vote whenever the consensus was to be otherwise. Among the production functions, crop production was given a leading priority (Table 5.1). Although forest production and grazing are ranking second and third in terms of importance, one can hardly find these land use types in the area, partially due to the severe land shortage induced by the population pressure.

Table 5.1 Major functions of soils as recognized and ranked by farmers at Caffee Doonsaa

No.	Soil function	Relative value	Rank	Category
1	Crop production	11	1	Production
2	Forest production	10	2	Production
3	Grazing	9	3	Production
4	Pottery	8	4	Raw materials
5	Source of water (spring)	7	5	Environment
6	Pond construction	6	6	Construction or environment
7	House construction	5	7	Construction
8	Industrial raw material	4	8	Raw materials
9	Silo	2	9	Raw materials
10	Waste disposal	2	9	Environment
11	Fire control	2	9	Security
12	Beehive	0	10	Raw materials

5.1.2 Soil quality

In an attempt to define SQ, the farmers agreed that it should be defined in relation to the functions. They explained that a soil could be best for one function and worst for the other. Identification of simple and function related SQ indicators was an important step in SQ assessment. In order to compare their soils, the farmers depended on a set of soil attributes, most of which are related to physical characteristics. The major soil attributes considered as indicators include: colour, carbonate concretions on the surface, depth and compaction/strength, heaviness/texture, cracking nature, water retention capacity, crop performance (fertility), vulnerability to erosion and slope gradient.

Based on these characteristics and a long term farming experience in the area, they classified their soils into five SQ groups (Table 5.2) (*Abolse, Kooticha, Carii, Sogiddo* and *Gombore*). However, most of them do not have *Sogiddo* and *Gombore*, because these groups generally do not exist in the watershed area, were the participating farmers' plots are located.

Table 5.2 Area coverage of SQ groups around Caffee Doonsaa as recognized by farmers

Soil type	Relative value	Area (%)	Rank
Abolse	30	30.8	1
Carii	28	28.8	2
Kooticha	20	20.6	3
Sogiddodo	14	11.5	4
Gombore	8	8.2	5

According to their assessment, the three top-ranking groups cover the whole of the watershed. As elaborated in Table 5.3, *Kooticha* is a black heavy clay soil located either on the plateau or in depressions (Fig. 5.1). Wide and deep cracks up on drying and swelling when wet characterize this soil. *Carii* is a dark grey soil located often on moderate to steep sloping areas. High carbonate concretions on the surface characterize *Carii* soil. It is a shallow soil due to erosion and some times the subsoil is exposed. *Abolse* is a mixture of *Kooticha* and *Carii*. This is some times also referred to as *Besteqelil*. It is a very dark heavy soil with some carbonate concretions on the surface. It is located on gentle to moderately sloping areas.

Table 5.3 Characteristics of the three SQ groups in the watershed

Soil type	Characteristics	Advantages	Disadvantages
Kooticha	Black, very heavy, highly water logged, fertile, deep, wide cracks, located on flat land	Less erosion, Productive	Drainage problem Difficult for tillage Heavy soil High fertilizer demand
Abolse	Very dark, heavy, fertile water logged, deep, wide cracks, some carbonate concretions, located on gentle slope	Productive low fertilizer demand, not difficult for tillage	None
Carii	Dark gray, slightly heavy, relatively shallow, weedy, cracking, more carbonate concretions, poor fertility and eroded	No water logging Easy for tillage	High fertilizer demand Less water holding capacity High erosion

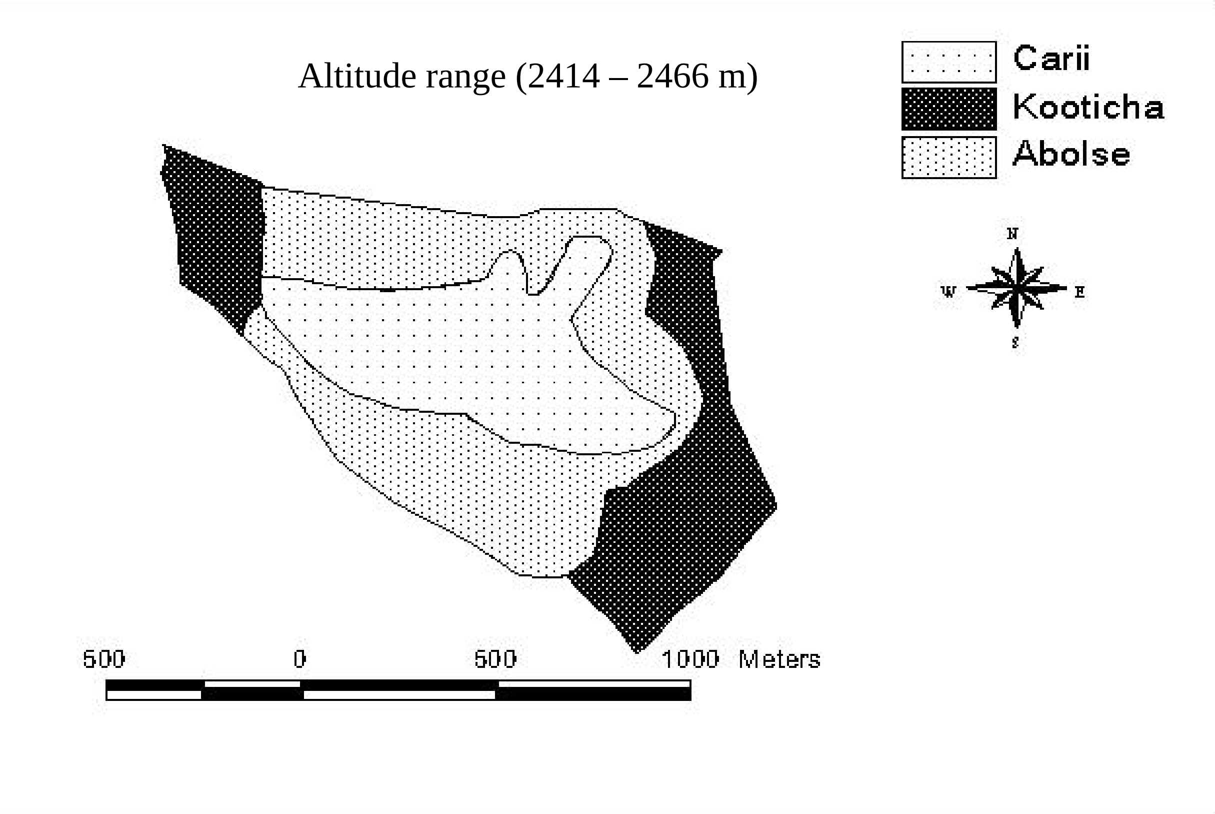

Fig. 5.1 Soil map of the watershed area based on farmers' criteria

5.1.3 Soil quality and crop production

For crop production function, *Abolse*, *Kooticha* and *Carii* in that order are preferred, while *Gombore* and *Sogiddo* are favoured for Forest/Tree plantation and grazing (Table 5.4). This may explain the unavailability of forest and grazing lands in the area, despite their being important, high-ranking soil functions.

Table 5.4 Ranking of the different SQ groups for the three top ranking land use types in the area

Land use type	Carii	Abolse	Kooticha	Gombore	Sogiddo
Crop production	3	1	2	5	4
Forest	4	3	5	1	2
Grazing	5	3	4	1	2

Of the 10 crop species grown in the watershed area (Table 5.5), Wheat (*Triticum spp.)*, Tef *(Eragrostis tef*), Chickpea (*Cicer arietinum*) and Lentil (*Lens culinaries Medik)*, are the major ones covering 64% of the total cropped area. According to their assessment, *Abolse* is excellent for all the four major crops (Table 5.6), while *Carii* is excellent for Lentil but not suitable for Chickpea. On the other hand, *Kooticha*, which is found on flat areas with severe water logging problem is also assessed to be very good for all the major crops, if suitable drainage system is applied or appropriate sowing date is used. Gombore and Sogiddo, which are preferred for grazing and forest, have shown lower suitability for the crops.

Table 5.5 Relative importance of the major crops grown in the watershed in terms of area coverage

Crop type	Relative value	Area coverage (%)	Rank
Wheat	80.5	18	1
Tef	70.5	16	2
Chickpea	66.0	15	3
Lentil	66.0	15	3
Lathyrus	40.0	9	4
Fenugreek	38.5	9	4
Faba bean	34.5	8	5
Field pea	24.5	6	6
Barley	22.0	5	7
Linseed	7.0	nil	8

Table 5.6 Suitability of the SQ groups for the major crops in the area

Soil type	Wheat	Tef	Chickpea	Lentil
Abolse	S1	S1	S1	S1
Carii	S2	S2	S2	S1
Kooticha	S2	S2	S2	S2
Sogiddo	NS	S2	NS	S2
Gombore	S3	S3	NS	NS

S1 = Very good, S2 = Good S3 = fair, NS = not suitable

Fig. 5.2 reveals that *Abolse* gave the highest grain yield (4573 $kg.ha^{-1}$) of wheat followed by *Kooticha*, which gave 4411$kg.ha^{-1}$. This corroborates the claims of the farmers. Apart from this, *Abolse* gave the highest Harvest Index (HI) of 0.45 compared to 0.42 and 0.39 for *Kooticha* and *Carii*, respectively. Although they would be happy with higher straw yield as it is the major livestock feed, the farmers give priority to higher grain yield to feed their families and to sell in order to pay taxes and input costs.

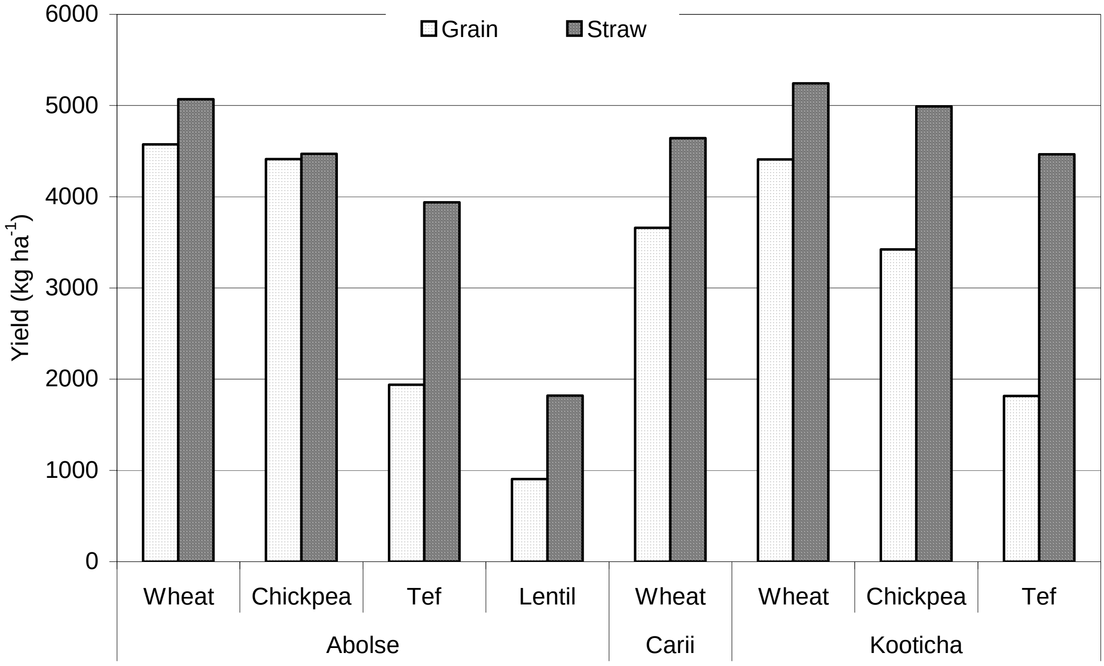

Fig. 5.2 Productivity of the three soil quality groups

6 Characteristics of the soils in the watershed area

An effective and sustainable land resources use and development of improved technologies requires a thorough understanding of the resource. Soils exist in great variety and exhibit ranges of properties. This makes the survey and characterization of the soil resources at various scales essential. The scale of the survey depends among others on the intended use, extent of variability and resource available. This study, aimed at generating SQ information necessary for sustainable use of the soil resource for crop production, attempted to characterize the Vertisols in a small watershed within the Central Highlands of Ethiopia.

Vertisols are churning heavy clay soils that may contain a high proportion of swelling clays such as smectites. Up on drying, they form deep wide cracks from the surface downwards at some period in most years (Deckers *et al*., 2001). Vertic horizon is a subsurface horizon with a thickness of at least 25 cm, containing 30% clay or more, and which because of shrinking and swelling has either shear planes or wedge-shaped structural aggregates with shiny and grooved curved surfaces known as slickensides (Deckers *et al*., 2001). It extends to between 40 and 90 cm depth below the surface. The sliding of crumb surface soils into the cracks and the resultant shearing push the subsurface soil upwards. In this way, surface and subsurface soils are mixed, a process referred to as churning or (hydroturbation) peloturbation (Mesfin, 1998).

Pedoturbation (Peloturbation) limits the differentiation of soil horizons and in many cases obscures evidences of leaching, differential weathering and soil aggregate formation in different parts of the profile. Although the majority of Vertisols are dark and smectitic with the development of minimal horizon differentiation, their chemical, physical and biological characteristics vary widely (Mesfin, 1998).

Vertisols occupy less than 2.5 percent of the earth’s ice-free land surface, but they are extensive in parts of Africa, Australia, South America and India where they are increasingly in use for agriculture (Deckers *et al*., 2001). In tropical areas, Vertisols cover some 200 million hectares or 4 percent of the land surface. In eastern and central part of Africa, they constitute a major part. Vertisols are estimated to cover 12.7 million hectares (10% of the Ethiopian landmass). About 8 million ha of these are in the central highlands, where the climate is relatively favourable for crop production as well as human and livestock settlement.

Because of their relatively high inherent fertility, they can be very productive, when properly managed. However, their unique physical properties are the greatest limitations to the dominantly low-input agriculture. They require a careful management in order to tap the potential, while avoiding decline in soil quality.

The wide-scale use of Vertisols has occurred only in the last four decades, and there are large areas, particularly in Africa, which are yet to be used (Deckers *et al*., 2001). A thorough understanding of the properties and processes of these soils is crucial to develop and implement farming practices that will keep them productive for the current and future generations. To this end, the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) has made significant contributions both in land management technology and cultivars development to enable the sustainable use of these soils (Eswaran *et al.,* 1999).

According to Mesfin (1998) montmorillonite (smectite) dominates the clay minerals of the Ethiopian Vertisols, with little aluminium inter-layering. They are extremely diverse and occur under various climatic conditions, where Pellic and Chromic Vertisols are plentiful (Mesfin, 1998). The Pellic Vertisols are the majority with over ten million hectares (Debele, 1985). They have the moist chroma of less than 1.5 throughout the upper 30 cm.

Although it was claimed, that they typically occur in areas of elevation less than 1000m asl and on relatively flat topography (Ahamed, 1983), Vertisols in Ethiopia are found above 2000m asl (Fisseha, 1992). Also, Ethiopian Vertisols occur on a wide range of slope up to 15% (Jutzi *et al*., 1988) though the majority occur on slopes less than five percent, against the claims of Mohr *et al.* (1972) and Debele (1985), who assert that Vertisols occur on slopes less than three percent.

Thus, the Vertisols in Ethiopia occur on flat to undulating topography, where the classical types are situated on the pyroclastic parent materials in the central highland plateaus with volcanic rock intrusions (Mesfin, 1998). According to Mitiku (1987) and Ahmed (1983), Vertisols of the central highlands of Ethiopia have been developed from basalt of Tertiary age. Eylachew (2001) also indicated that the Ethiopian highlands Vertisols were developed through a slow and continuous in-situ weathering of basalt, diorite, rhyolite, and limestone and granite parent materials.

The major climatic factor associated with Vertisols in Ethiopia is the seasonality of precipitation, which allows for annual wetting and drying of the solum leading to a particular weathering regime associated with smectite synthesis. The annual changes of precipitation and temperature encourage weathering for a long time of the year, and for the accumulation of basic cations in the dry seasons (Crompton, 1967).

Vertisols are extremely variable and therefore require specific management (Deckers *et al*., 2001). Farmers are keen about the variation and have developed a local system of classification and management for each group (See Chapter 5 of this thesis). In order to develop and disseminate appropriate technologies to address the specific constraints of each group and to have a mutual understanding with the farmers, each group need to be investigated, following standard scientific procedures. This may bridge the communication gap between the farmers, development agents and researchers operating in the area.

6.1 The reference profile

6.1.1 Physical characteristics

The vegetation cover at the time of the profile description was wheat stubble for *Carii* and *Abolse*, while *Kooticha* was situated in a chickpea field. The surface soil was dry with wide (10 –15 cm) and deep (80-90 cm) cracks occurring intensively in a regular pattern. Although the surface soil (the upper few centimetres) was slightly lighter grey for all the profiles, the rest of the profiles were very dark or black in colour homogenously along the depth. Consequently, the boundary distinction (or the layering) was diffuse or gradual, that marking of the layers arbitrarily rounded to the nearest 10 cm for the reference profiles. The soil structure was either angular or subangular blocky (Table 6.1), with a plenty of slickensides in the lower part of the first layers and the upper part of the second layers for all the profiles. Most of the colours for the soils in the area were found on the 10YR page of the Munsell colour chart (Table 6.2).

Since the fields were under small cereals or legumes for decades, only very fine to medium sized roots, dead or alive were observed. Although the soil was deep or very deep, only moderately deep (≤1m) living fine roots were prevalent, may be due to the aeration problem during the major part of the growing period. Little or no rock fragments were visible in the profiles.

Table 6.1 Relief and some physical properties of the soil quality groups

Local soil name	Profile depth (cm)	Boundary distinctness	Local relief	Altitude (m)	Structure	Root size	Rooting depth (cm)
Carii	-40		Ridge	2452	SB	Very fine (< 1mm)	Moderately deep (80 cm)
	-80	Gradual			AB		
	-100	Diffuse			AB		
	-125	Gradual					
Abolse	-40		Middle slope	2430	SB	Very fine (< 1mm)	Moderately deep (100 cm)
	-70	Diffuse			AB		
	-100	Diffuse			AB		
	-125	Gradual					
Kooticha	-40		Foot slope	2411	SB	Medium (2-5 mm)	Moderately deep (70 cm)
	-80	Diffuse			AB		
	-120	Diffuse					
	-150	Diffuse					

According to Deckers *et al*. (2001) Vertisols are physically very heavy clayey (30-95%) soils, which become very hard and develop deep and wide cracks during the dry season. As revealed in the reference profiles, the texture of the soil in the study area was homogenously rich in clay (>70%) along the depth of the profiles (Table 6.2) corroborating Fisseha (1992) and Eylachew (2001) who reported similar results for the Vertisols in the Central Highlands. However, *Abolse* and *Kooticha* retained very high AWC (>20%), while *Carii* retained moderate to high (12-16%). Similarly, *Abolse* and *Kooticha* showed higher water aggregate stability as compared to *Carii*, which has showed least stability in water. Thus, *Abolse* is less susceptible to sealing of the surface pores during the rains as compared to *Carii*. Therefore, *Abolse* does not only store more plant available water, but also allows more water entry to the soil reducing surface runoff.

Table 6.2 Some physical characteristics of the soils

Local soil name	Depth (cm)	Soil texture (%)			Water holding Capacity (%)			Soil colour	
		Sand	Silt	Clay	FC	PWP	AWC	Moist chroma/ value	Description
Carii	-40	10	15	75	37	23	14	10YR 3/2	VDGB
	-80	12	13	75	42	26	16	10YR 2/1	Black
	-100	17	8	75	34	22	12	10YR 3/1	VDG
	-125	12	11	77	33	19	14	10YR 3/3	DB
Abolse	-40	8	17	75	44	24	20	7.5YR 2/0	Black
	-70	10	13	77	45	25	20	2.5Y 2/0	Black
	-100	12	13	75	47	29	18	2.5Y 2/0	Black
	-125	12	13	75	49	24	25	10 YR 3/2	VDGB
Kooticha	-40	8	19	73	46	24	22	10YR 3/1	VDG
	-80	12	13	75	45	25	20	10YR 3/1	VDG
	-120	10	15	75	40	22	18	10YR 3/1	VDG
	-150	8	17	75	38	20	18	10YR 3/1	VDG

DB = Dark brown, VDGB = Very dark grey brown, VDG = Very dark grey

6.1.2 Chemical and mineralogical characteristics

Regardless of the groupings, the soils had homogenous alkaline reaction with pH (H_2O) greater than eight with few exceptions (Table 6.3). This was attributed to the high calcium saturation and continues release of basic cations from the basaltic parent materials (Eylachew, 2001). The C_{org} and total nitrogen content were low consistent with the findings of Murphy (1959), who reported low OM (<2 percent) and low total nitrogen (<0.10%) for the same area and with similar reports elsewhere (Deckers *et al.*, 2001). Nevertheless, *Abolse* showed the highest C_{org} content (0.39-0.88%) in contrast to *Carii*, which contained the least (0.12-0.64%). Similar results have been reported for Vertisols in other parts of the highland areas (Murphy, 1959; Fisseha, 1992; Mesfin, 1998; Eylachew, 2001).

For all the groups, despite the annual application of 100kg DAP and 100kg Urea ha^{-1}, the plant available N and P were low, consistent with the previous findings (Fisseha, 1992; Mesfin, 1998; Eylachew, 2001). The low total and available N was associated with the low OM content (Fisseha, 1992; Deckers *et al.*, 2001). Eylachew (2001) attributes this partially to the inherent characteristics of the soils and the loss of N due to the removal of excess water, while Fisseha (1992) relates it to the small cereal cultivation which involves complete removal of crop residues. Denitrification due to the water logging may also contribute to the loss of nitrogen. The low available P is due to P-fixation, which is attributed mainly to the presence of Ca^{2+} and Mg^{2+} cations that can reach up to 75% of the applied phosphate in the highland Vertisols area (Eylachew, 1987; Eylachew and Moll, 1989).

In terms of mineralogy, only three minerals (smectite, illite and kaolinite) dominated the clay fraction (Table 6.4). Consistent with Fisseha (1992) who reported the dominance of smectite clay minerals (80-90%) for Vertisols in the central highland areas, smectite accounted for 90%, except for *Carii*, which had 70% smectite, 19% illite and 10% kaolinite (Table 6.4).The mineralogical difference along the depth remains minimal.

Table 6.3 Some chemical characteristics of the soils

Local soil name	Depth (cm)	pH (H_2O)	C_{org} (%)	Nt (%)	C: N	NH_4+ (mg. kg^{-1})	NO_3- (mg. kg^{-1})	Available P (mg.kg^{-1})
Carii	-40	8.1	0.64	0.03	22	5.6	7.0	0.80
	-80	8.1	0.18	0.01	16	7.7	4.2	0.80
	-100	7.8	0.18	0.02	12	6.3	5.6	0.80
	-125	8.1	0.12	0.01	11	8.4	7.0	0.90
Abolse	-40	7.7	0.74	0.03	22	8.4	9.1	1.10
	-70	8.1	0.88	0.03	27	7.7	6.3	1.00
	-100	8.1	0.86	0.03	27	7.0	9.1	0.70
	-125	8.2	0.39	0.02	22	7.7	7.0	0.60
Kooticha	-40	7.9	0.70	0.04	18	10.5	22.4	0.70
	-80	8.2	0.76	0.05	16	8.4	9.8	0.90
	-120	8.0	0.49	0.04	12	7.7	12.6	0.90
	-150	8.1	0.66	0.04	18	7.7	10.5	0.70

Owing to the abundance of smectitic clay, the cation exchange capacity (CEC) was very high with a slight decrease with depth, which is particularly true for *Kooticha* (Table 6.5). The OM content is too low to influence the CEC. The high CEC may result in relatively less nutrient loss by leaching, since only low percentage of cations might remain in the soil solution. This makes the soils inherently fertile with minor variation between the groups.

The base saturation was 100%, in which Ca^{2+} and Mg^{2+} occupied most of the exchange sites. This corroborates (Fisseha, 1992; Deckers *et al.*, 2001), who reported the dominance of Ca^{2+} and Mg^{2+} in the exchange solution for Vertisols. K^+ and Na^+ together represented less than two percent. The ratio of Ca^{2+} to Mg^{2+} is greater than one, except for the last horizon of *Abolse*, indicating little or no negative effect of excess Mg^{2+} on soil physical properties and crop production.

Table 6.4 Approximate mineralogical composition (percentage) of the clay fraction

Local soil name	Depth (cm)	Kaolinite	Illite	Smectite
Carii	-40	10	20	70
	-80	0	3	97
	-100	1	2	97
	-125	1	8	91
Abolse	-40	1	3	96
	-70	1	2	97
	-100	1	5	94
	-125	1	3	96
Kooticha	-40	1	3	96
	-80	1	2	97
	-120	1	8	91
	-150	1	3	96

6.2 Farmers fields

The results of the samples collected from the farmers' fields are consistent with those of the reference profiles (Tables 6.6-6.7). The soil texture was all clayey (>70%) < 2 µm. Similar to the profiles, *Abolse* showed the highest available water capacity (14-16%) while *Carii* retained the least (13-14%). The water aggregate stability was the highest for *Abolse* (3.84%) in contrast to *Kooticha*, which was the least stable in water (0.08%). The relative water stability of *Abolse* results in low surface sealing and reduced runoff and soil erosion as compared to *Kooticha* or *Carii* soils.

Table 6.5 Cation exchange capacity and exchangeable bases of the soils at Caffee Doonsa

Local soil name	Depth (cm)	$CaCO_3$ (%)	CEC (cmol. kg^{-1})		Exchangeable bases (cmol. kg^{-1})			
			Soil	Clay	Na^+	K^+	Ca^{2+}	Mg^{2+}
Carii	-40	6.5	94	140	0.2	1.3	69.4	37.4
	-80	6.6	83	123	0.2	1.2	61.5	50.3
	-100	2.5	61	91	0.3	1.1	46.4	32.7
	-125	4.8	82	120	0.2	1.2	61.0	43.3
Abolse	-40	2.1	85	125	0.3	1.4	48.9	25.8
	-70	4.1	75	109	0.3	1.3	55.7	23.0
	-100	4.1	80	118	0.6	1.2	59.7	46.9
	-125	6.3	82	122	0.8	1.1	63.6	70.8
Kooticha	-40	2.3	88	134	0.2	1.4	48.2	21.3
	-80	3.0	83	123	0.2	1.4	53.6	12.6
	-120	2.1	79	116	0.6	1.4	51.7	24.6
	-150	1.6	74	111	0.7	1.3	44.5	22.9

The difference in chemical characteristics and plant nutrient content (N_t, NH_4+, NO_3^-, Available P) between the SQ groups was not statistically significant (Table 6.7). The C_{org}, N_t as well as the available N and P contents were generally low. Indicating a negligible role of leaching, the content slightly decreased with depth. However, *Kooticha* has shown the highest available N (ammonia and nitrate) in the surface layer.

Table 6.6 Mean physical characteristics of the soil sampled from the farmers' fields

Local soil name	Depth (cm)	Texture (%)			FC (%)	PWP (%)	AWC (%)	AGG* (%)
		Sand	Silt	Clay				
Carii	-30	11	15	74	38	25	13	3.05
	-60	11	13	76	38	24	14	
	-90	10	13	77	38	25	13	
Abolse	-30	10	18	72	40	24	16	3.84
	-60	16	14	70	38	24	14	
	-90	13	14	73	39	25	15	
Kooticha	-30	10	16	74	39	24	15	0.08
	-60	10	16	74	38	24	14	
	-90	11	15	74	39	25	14	

*AGG= aggregate stability of surface soils (0-15 cm)

Table 6.7 Mean chemical characteristics of the soil sampled from the farmers' fields

Local soil name	Depth (cm)	C_{org} (%)	N_t (%)	C: N	NH_4^+ (mg. kg^{-1})	NO_3^-	Available P (mg. kg^{-1})	$CaCO_3$ (%)
Carii	-30	0.80	0.06	13.3	0.7	0.7	0.9	4.3
	-60	0.67	0.05	13.4	0.6	0.9	0.6	3.7
	-90	0.52	0.04	13.0	0.6	0.7	0.7	2.3
Abolse	-30	0.80	0.07	11.4	0.5	0.6	1.1	5.0
	-60	0.67	0.06	11.2	0.6	0.5	0.6	3.5
	-90	0.47	0.09	5.2	0.5	0.6	0.6	2.7
Kooticha	-30	0.76	0.17	4.5	0.9	1.3	1.1	5.0
	-60	0.65	0.06	10.8	0.7	0.9	0.6	3.8
	-90	0.68	0.04	17.0	0.9	0.8	0.6	3.3

This is attributed to the fact that legumes like chickpea are the major crops grown on *Kooticha* using residual moisture. The legumes do not only contribute to the nitrogen stock through biological fixation of the atmospheric nitrogen but also by consuming less nitrogen from the soil than cereals, which commonly grow on the other SQ groups. In addition, accumulation of nitrogen rich sediments is a possibility due to the location of soils within the landscape (Fig.6.1). The transect survey result was consistent with the reference profiles and the data from the farmers fields (Annex 1).

6.3 Analytical differences between the local soil groups

All the indicator parameters determined confirm that the soils belong to the Vertisols. Most soil properties were similar between ridge, shoulder positions and the bottomlands as represented by the farmers' SQ groups, *Abolse, Carii* and *Kooticha*. Despite the differences observed by farmers and confirmed through yield data, there was little difference in terms of physical, chemical or mineralogical properties between the SQ groups. However, with higher aggregate stability and water holding capacity *Abolse* was not only the best in terms of crop productivity as claimed by farmers and confirmed by the yield data, but also stable with respect to soil degradation due to surface crusting and soil erosion. The landscape, particularly slope gradient, which influences the surface drainage, might have contributed to the crop productivity difference. The potential micro nutrient deficiency was not addressed in this study. The minor differences such as clay mineralogy and CEC may also deserve consideration as they affect the production as well as the filtering role of soils.

7 Land preparation methods and crop productivity

Crop production in the highland Vertisols area of Ethiopia is highly constrained by the soil physical and hydrological properties. Land preparation is constrained by the hardness of the soils when dry and their stickiness when wet, and their very slow internal drainage with infiltration rates between 2.5 – 6.0cm day^{-1} (Teklu *et al.,* 2004). The problem is serious particularly for small farmers using handheld or animal-drawn implements (Kadu *et al.,* 2003).

Early planting is prohibited since most crops in the region are severely affected by water logging and fungal diseases. Traditionally, farmers start land preparation early using the short rains of April and May, keep the land bare 2-3 months with occasional tillage and plant at the end of the rainy season, such that the crops grow on residual moisture. In this region, five to nine cultivations before planting to prepare fine seed bed and control weed are common (Astatke and Jabbar, 2001; Teklu and Gezahegn, 2003). The tillage increases loss of SOM because of mixing of the soil and crop residues, disruption of aggregates, and increased aeration (Doran and Smith, 1987). Frequent tillage and delayed planting do not only exacerbate soil erosion, which is already among the devastating environmental problems of the Ethiopian highlands (Astatke *et al*., 2002; Teklu, 1998; Demeke, 1998), but also substantially reduce the growing period and crop productivity. Several attempts have been made to alleviate problems associated with water logging and to advance the planting date.

As already practiced by women farmers of the Inewari area in the Central Highlands of Ethiopia (Jutzi and Mesfin, 1987), surface drainage can be achieved by making BBF. Therefore, the BBF system that had been developed at the International Crops Research Institute for the Semi-arid Tropics (ICRISAT) (El-Swaify *et al*., 1985) was introduced into the Ethiopian highlands by the International Livestock Centre for Africa and was modified to fit to the smallholder system (ILCA, 1990; Astatke and Kelemu, 1993). Several authors reported increased yields of some crops grown on Vertisols due to the use of the BBF as compared to the flat seedbeds (Astatke *et al.,* 1995; Haque *et al.,* 1996; Saleem and Astatke, 1996). They suggested that the improvement in surface drainage and yield increase was spectacular during the excessive rain years.

Despite the yield advantage and concerted effort of popularization during the last decades, BBF is not well adopted. This was attributed to economic, environmental, socio-cultural, technical and policy constraints (Fassil *et al.,* 2001; Pankhurst, 2000). Weed infestation induced by early planting, shortage of time available for BBF preparation, difficulties in site selection, are among the technical constraints mentioned. To address these and other constraints, scarcity of feed, shortage of oxen for tillage, it was believed that alternatives should be sought. In this chapter BBF is compared to Green Manure (GM) and Reduced tillage (RT) as alternative to arrest some of the above problems in terms of crop productivity and economic profitability while the traditional practice Ridge and Furrows (RF) was included as a control.

7.1 Agronomic productivity and profitability

Among the several interdependent factors considered for the selection of appropriate land preparation methods include, agronomic performance and the economic benefits of the alternative practices were considered. However, as they are related to the economically important grain and straw yield of the crops, the agronomic characteristics were also discussed.

7.1.1 Effect on agronomic characters

The effects of the land preparation methods on the crop growth parameters depended on the crop types and year (Annex 5). In 1998, the effect was significant on plant height, days to heading and maturity of wheat. During this year, BBF resulted in the highest number of days to heading but lowest plant height as opposed to RF, which resulted in the lowest number of days to heading and highest plant height. This indicates that crop growth was retarded under BBF during the early stage in 1998.

In 1999, as opposed to the previous year, BBF caused the lowest number of days to heading and the highest number of days to maturity. It gave also the highest number of tillers per plant showing enhanced performance at early stage and hence more vegetative cover. The higher moisture availability due to early sowing explains the longer duration between heading and maturity. On the other hand, the poor vegetative performance of lentils under no drainage conditions is related to water logging, which caused poor aeration of the roots and poor nutrient uptake leading to weak growth and development and hence low crop yield. In addition, the crops on undrained plots were subjected to forced maturity due to the terminal moisture stress, induced by late sowing. The result is consistent with the previous findings, a better growth and yield of legumes like lentils under BBF due to enhanced drainage was reported (Abate and Saleem, 1992; DZARC, 1990 and ILCA, 1990).

In 2000, RF significantly increased the number of days to heading, while the residual effect of BBF and GM increased the number of tillers per plant. In 2001, RF resulted in the highest number of days to heading and the highest plant height of wheat, while the residual effect of BBF reduced the number of days to heading. Due to the heavy storm event, drought (Fig. 1) as well as associated disease and pests, the performance of lentils in 2002 was poor. Consequently, although it was significant on the days to maturity in that GM and RF delayed, the treatments effect was not fully manifested. Similar to the previous year, the treatments have significantly affected days to heading and height of the tef plant in 2003.

7.1.2 Effect on grain and straw yields

Similar to the other agronomic parameters discussed above, the effects of the land preparation methods on grain yields varied with the crops (Table 7.1 and 7.2). The mean grain and straw yields of wheat and lentil were significantly affected by the land preparation methods and their interaction with year. However, the effect of the land preparation methods on tef was not significant showing the insensitivity of the crop to physical manipulation of the land.

For lentils BBF significantly increased the grain yield (59% as compared to the control), corroborating the previous findings (Getachew, 2001) while the other alternatives were not different from the control. This is related to the advancement of the sowing date and the enhanced surface drainage, which resulted in earlier establishment of the crop so that it relatively tolerated the rainstorm and escaped the terminal moisture stress.

On the other hand, the highest mean grain yield of wheat was obtained due to RT (10% higher than the control). The straw yield was also significantly increased. While BBF significantly reduced the grain yield of wheat (35% less than the control), the effect of GM was not different from the control, both in terms of grain and straw yields. This does not corroborate the previous reports in which the use of BBF increased wheat grain and straw yields in other parts of the highlands of Ethiopia. However, the previous works often compared BBF against flat beds, unlike the current study, which compared it with RF and other alternatives (Efrem, 2001).

Table 7.1 Grain yield of the crops (kg.ha^{-1}) as affected by the tillage systems

Land preparation methods (L)	Wheat			Lentil			Tef		
	1998	2001	Mean	1999	2002	Mean	2000	2003	Mean
BBF	438	1763	1101^{b}	2732	532	1632^{a}	1260	1333	1296
GM	1940	1621	1780^{a}	1704	144	924^{b}	1194	1373	1284
RF	1209	2187	1698^{a}	1787	271	1029^{b}	1139	1409	1274
RT	1819	1904	1862^{a}	1482	212	847^{b}	1315	1443	1379
Mean	1352^{b}	1869^{a}		1926^{a}	290^{b}		1227	1389	
LSD (5%) L		217			193			NS	
Year		196			255			NS	
Year*L		307			273			NS	
CV (%)		10.73			13.85			9.50	

Means within the same column or same row are not significantly different at 95% confidence interval.

Although not significant, RT gave the highest grain and straw yield of tef resulting in 8% increase in grain yield, as compared to the control and the other alternatives. This confirms the previous reports of Aberra (1992) who suggested that ploughing more than once might not be necessary for tef, if non-selective herbicides are applied before ploughing. This indicates that tef is not sensitive to the type of seedbed or the changes in soil physical environment as wheat and lentil do. This challenges the hypothesis that tef requires well-pulverized and smooth seedbed (Ebba, 1969; National Research Council, 1996), a pre-text for high tillage frequency.

Table 7.2 Straw yield of the crops ($kg.ha^{-1}$) as affected by the tillage systems

Land preparation methods (L)	Wheat			Lentil			Tef		
	1998	2001	Mean	1999	2002	Mean	2000	2003	Mean
BBF	890	2679	1785[c]	2812	1572	2192	2579	3102	2841
GM	2565	2643	2604[b]	2342	1050	1696	2472	3317	2894
RF	2287	3265	2776[b]	2375	1567	1971	2613	3156	2884
RT	3148	3040	3094[a]	2287	1560	1924	2783	3178	2981
Mean	2222[b]	2907[a]		2454[a]	1437[b]		2612[b]	3188[a]	
LSD (5%) L		522			NS			NS	
Year		390			189			309	
Year*L		738			NS			NS	
CV (%)		16.18			17.43			8.53	

Means within the same column or row followed by the same letter are not significantly different at 95% confidence interval.

As the change of the yield from year to year was inconsistent (increase for wheat, decrease for lentil and a slight increase for tef) regardless of the treatments, it is not possible to predict if the SQ is aggrading or degrading with respect to productivity. This may require longer time and more data, including SQ indicators than the crop yield alone. The significant interaction between the land preparation methods and year is related to the performance of the effect of the land preparation methods and variation in the weather conditions. The land preparation methods seem to be sensitive to the rainfall with respect to wheat. The grain yield of wheat increased from the lower in 1998 to a higher in 2001 under all the land preparation methods, but GM in response to the increased total rainfall during the cropping season. On the other hand, BBF performed best both under favourable and unfavourable weather conditions. For instance, despite a poor performance of lentils in 2002 due to the unfavourable rainfall distribution, which started too late in June, followed by heavy storm events in August, and stopped earlier (Fig. 4.3) than normal years, the mean of the two years showed that BBF resulted in the highest grain and straw yields. As the weather in 2002 was particularly adverse for lentils, which suffered of hailstorms, various disease and pests, and terminal moisture stress, the effect of the land preparation methods was not sufficiently expressed. Nevertheless, similar to the previous year, BBF gave the highest grain and straw yields.

Considering the long-term (6 years) agronomic productivity, BBF gave the highest cumulative RPI followed by RT (Fig. 7.1). This is attributed mainly to the consistent highest yield of lentil under BBF. However, using BBF or RT for all the crops reduced the benefits that could be obtained by selecting the best practice for each crop by 22 % and 33%, respectively. In other words, considering BBF for lentil and RT for wheat and tef may result in the maximum agronomic productivity.

7.1.3 Economic and financial performance

Before recommending a sustainable practice for increased productivity and enhanced resource use efficiency, SQ parameters and economic analysis need to be conducted. In such analysis, the inputs, including the loss and gains in SQ need consideration. However, this is often limited by data availability or cost of its generation.

In order to realise the anticipated benefits, farmers have to invest financial and material resources. As these resources may limit the practicality of the options, economic evaluation is an essential aspect before implementing the alternatives. Yield comparison as conducted above can be one way. However as comparison of yield does not consider inputs, gross margin analysis has been conducted in this study. Gross margin is the difference between gross value of output and the total variable costs used in the production process. Although gross margin analysis is static, and does not take the time value of money into consideration, it is a useful tool, which can assist in improving the overall management of the farms as it addresses resource productivity in a given period (Senkondo *et al*., 2004).

The costs of inputs required for the production process under the different land preparation methods are variable (Table 7.3). GM and RT required the highest and the lowest total input cost, respectively. On the other hand, as compared to the control, an additional tillage cost of 90 Birr.ha^{-1} was required for BBF preparation except for tef, while RT saved 450 Birr.ha^{-1} on tillage. On the other hand, RT induced an additional herbicide cost of 480 Birr.ha^{-1} resulting in a marginal cost of 30 Birr.ha^{-1}. Similarly, GM required the highest additional cost of 120 Birr.ha^{-1}due to the extra labour for chopping the cover crop.

Table 7.3 Total variable costs (Birr. ha^{-1})$^{\$}$ of the inputs that are affected by the treatments

Land preparation methods	Cost item	Wheat	Lentil	Tef
BBF	Tillage*	600	600	600
	BBF preparation§	90	90	-
	Total	690	690	600
GM	Tillage	600	600	600
	Chopping of the green manure**	120	120	120
	Total	720	720	720
RF	Tillage	600	600	600
RT	Herbicide****	480	480	480
	Tillage	150	150	150
	Total	630	630	630

§ Tef requires no broad-bed and furrow, *Tillage costs at 30 Birr per oxen day, ** one man-day cost @ 10 Birr a day and ***Herbicide cost was considered at 120 Birr per litre, $^{\$}$ 8.65 Birr = one US$

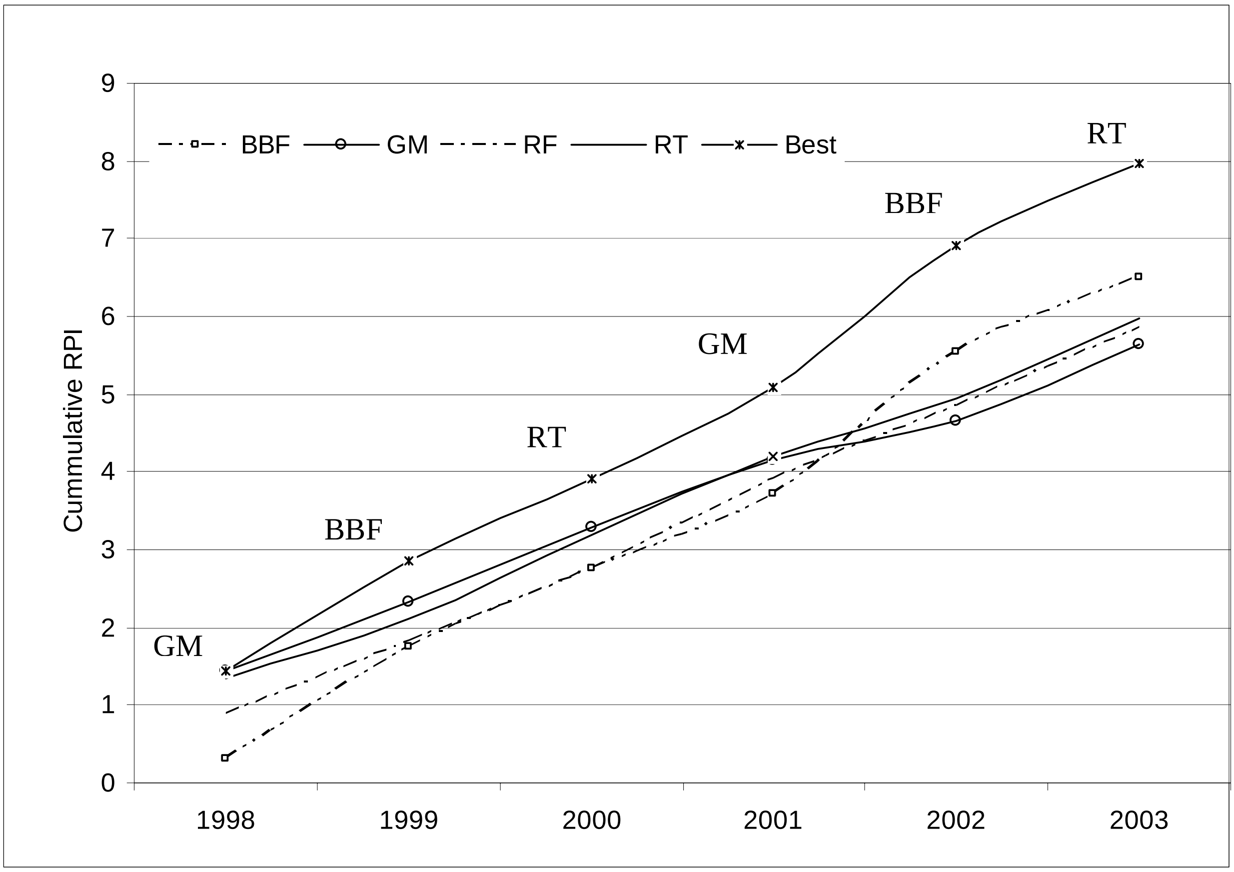

Fig. 7.1 Cumulative relative productivity index (RPI) of the alternative land preparation methods and that of the best option for each crop

Considering the values of the outputs (grain and straw), BBF and GM gave the highest and the lowest total gross return, respectively (Table 7.4). This was due to the considerable decreasing and increasing effect, respectively of BBF and GM on the productivity of lentil, which is the major cash crop in the area. Consequently, BBF gave the highest gross margin followed by RT while GM gave the least (Fig. 7.2). BBF increased the gross margin of lentil by 65% as compared to the control. This indicates that the different crops require different land preparation methods. Therefore, RT for wheat and tef, and BBF for lentil are the most profitable options.

Table 7.4 Gross values of outputs (Birr. ha^{-1})$^{\$}$ from grain and straw yields of the crops as affected by the land preparation methods$^{\&}$

Land preparation methods	Return item	Wheat	Lentil	Tef	Total
BBF	Grain	2202	4896	3240	10338
	Straw	357	219	710	1286
	Total	**2559**	**5115**	**3950**	**11624**
GM	Grain	3560	2772	3210	9542
	Straw	521	170	724	1414
	Total	**4081**	**2942**	**3934**	**10956**
RF	Grain	3396	3087	3185	9668
	Straw	555	197	721	1473
	Total	**3951**	**3284**	**3906**	**11141**
RT	Grain	3724	2541	3448	9713
	Straw	619	192	745	1556
	Total	**4343**	**2733**	**4193**	**11269**

&Grain price (Birr. kg^{-1}): 2, 3 and 2.5 for wheat, lentils and tef and straw: 0.2, 0.1 and 0.3, respectively; 10kg bale at 7Birr, Tef does not need Broad-bed and furrow, \$8.65 Birr = one US\$

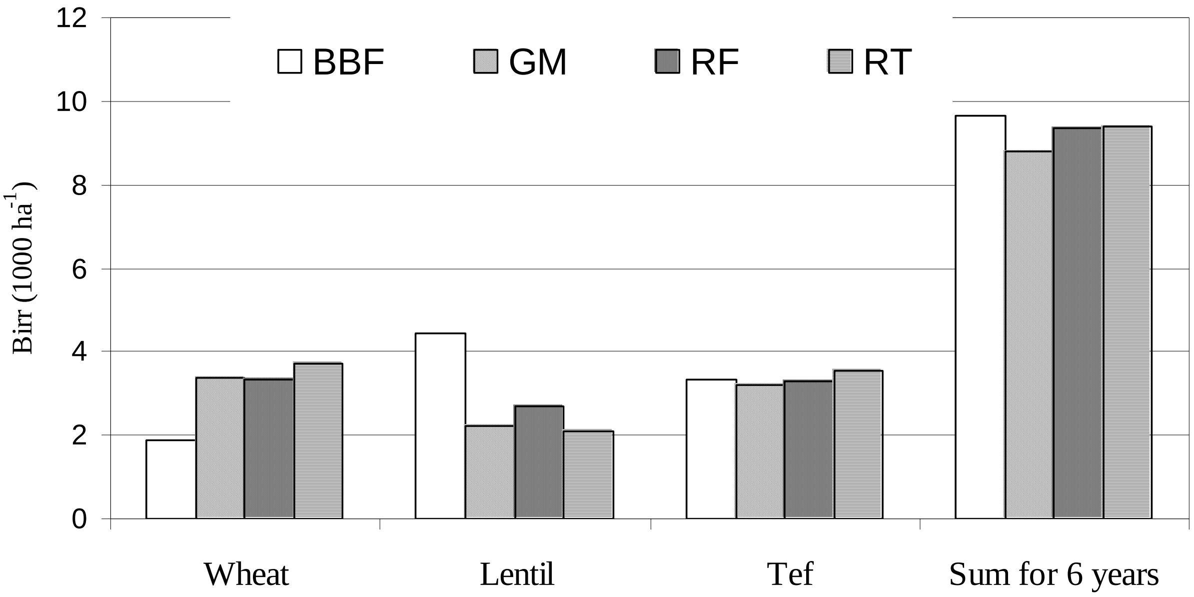

Fig. 7.2 Gross margin (1000 Birr. ha^{-1}) as affected by the land preparation methods for the individual crops and the sum over the 6 years

8 Land preparation methods and soil erosion

Vertisols are characterized by severe waterlogging during the rainy season due to its expansion, flaking and crust formation characteristics that reduces its percolation rate. With the exception of the hand made BBF in some pockets, the traditional management systems in Ethiopia do not allow early planting, because most crops in the region are severely affected by waterlogging and fungal diseases. Commonly, farmers prepare their land early and keep them bare for 2-3 months with occasional tillage, and plant at the end of the rainy season, so that the crops grow on residual moisture. This does not only reduce crop yield, but also exposes the bare fallow soils to high runoff and soil erosion during the intensive summer rainfall (Astatke *et al.*, 2002). Wani *et al.* (2003) reported a similar system involving rainy season bare fallow from a Vertisol around Hyderabad, India to have accelerated loss of C_{org} and to exacerbate soil quality degradation.
Their inherent properties make Vertisols among the most vulnerable soils to erosion (Deckers *et al.*, 2001). They slake under rapid wetting to form micro-aggregates in the fine sand to silt size range that are easily transported by water, because of their low density (Loch and Donnollan, 1983).Further, they form surface seals and crusts that close their cracks, slowing water infiltration rates (Mullins *et al*., 1987). These lead to high runoff and soil loss from Vertisols (Hussein *et al.*, 1992). Practices like, long fallow periods, frequent tillage, removal of crop residues, and cropping of shallow soils, especially on steep slopes exacerbates the problem (Mullins *et al*., 1987).
This entails the search for alternative systems that enhance surface drainage and allow early crop growth or systems that retain surface cover during the heavy rainy season to enhance productivity and reduce soil erosion. Such systems need to be evaluated both in terms of increasing crop productivity and economic benefits, and in terms of the onsite SQ and offsite soil and water quality to ensure environmental sustainability.

8.1 Runoff

The effect of different land preparation methods on runoff was not statistically significant during the first three years (1998-2000), although the magnitude of the difference was high. One possible explanation might be the high coefficient of variation, which is often the case in these kinds of studies. Nevertheless, as indicated in Table 8.1, BBF resulted in the highest runoff, draining 13, 30 and 16 percent of the total rainfall in 1998, 1999 and 2000, respectively. As tef does not need drainage, flat seedbed was used in 2000 instead of BBF. Yet, its residual effect resulted in the highest runoff, although it was reduced by half (from 30% to 16%), as compared to the previous year. In addition, BBF drained more proportion of water as the total rainfall increased, which makes it not only efficient but also dynamic with respect to surface drainage. On the other hand, in two out of the first three years, GM resulted in the second highest runoff while the difference between the RF and RT was negligible, except in 1999 when RT routed the second highest runoff.

Unlike the previous years, during the last two years (2001 and 2002), the effect of the land preparation methods on runoff was highly significant ($P \leq 0.01$). The runoff in 2001 ranged from 52% of rainfall for GM and RF to the all time high of 68% for BBF. Corresponding to the increased rainfall during the measurement period, the quantity of runoff routed was the highest in 2002 as compared to the previous years. This was despite the reduced annual rainfall (a severe drought year all over the country) as compared to the long-term average and to 2001 (Table 8.1). The increased total rainfall during the measurement period of 2002, which is believed to be more intensive, was responsible for such an increase in runoff volume. Although no data is available to substantiate, this has been depicted by a single storm event of 71mm occurred in less than two hours in August.

Table 8.1 Effect of land preparation methods on runoff

Land preparation methods	Runoff (mm)					
	1998	1999	2000	2001	2002	Mean
BBF	30	173	67	278[a]	286[a]	201
GM	44	63	40	212[c]	230[b]	136
RF	1.2	45	18	214[c]	237[b]	129
RT	nil	111	19	252[b]	281[a]	166
LSD (5%)	NS	NS	NS	15.6	38.2	
Seasonal rainfall (mm)*	236	572	407	411	531	
Annual rainfall (mm)	n.a	1052	908	1051	782	

Means within the same column, followed by the same letter are not significantly different at 95% confidence interval; *total for the measurement period, na= data of 1998 excluded from the mean

Alike the first three years, BBF routed the highest runoff in both years. On the other hand, RT resulted in the second highest runoff as opposed to the previous years. Of the total rainfall received during the experiment period, BBF drained 67% and 54 % as in 2001 and 2002, respectively, while RT routed 61% and 53% of the rainfall correspondingly. Despite the increased total runoff in 2002, there was a relative reduction in runoff coefficient (proportion of runoff to rainfall). This may be due to a substantial reduction of the short rain prior to the beginning of the measurement (Fig.4.1.3) to saturate the profile and seal the cracks, which holds true during the normal years.

8.2 Soil loss

Soil erosion by both wind and water is a major recognized cause of SQ decline. Soil erosion by water involves detachment, transport and deposition of soil particles. Soil detachment is caused by raindrop impact and runoff water (Gajri *et al.*, 2002). Soil surface cover and roughness reduce the raindrop and impact and hence soil loss. The amount and velocity of runoff also affects soil loss by water (Gajri *et al.*, 2002).

The effect of the treatments on soil loss was erratic (Fig.8.1). The data for 1998 are not presented, because the quantity was negligible as it was measured only for a short part of the season. The effect of the land preparation methods on soil loss was also not statistically significant. This may be due to poor accuracy of the measurement, especially with respect to some heavy storm events and low number of replications that resulted in uncontrolled experimental errors.

In 1999, RT resulted in the highest soil loss, despite its better vegetative cover to protect the soil from the heavy rain. Contradicting the plenty of evidences that reduced tillage helps soil erosion control (Gajri *et al.*, 2002) the soil loss from RT was increased three times as compared to the control and GM. There is no clear explanation for this, but it may be partially attributed to the higher runoff volume (Table 8.1). Corresponding to its highest runoff (30% of the total rainfall), BBF resulted in the second highest soil loss. This was despite the best performance of lentil under BBF conditions, which gave a better surface cover. Similarly, the residual effect of BBF caused the highest soil loss in 2000. This corresponds to its highest runoff, while there was a slight increase in soil loss from the other treatments as compared to the control. However, as opposed to the previous year, soil loss from RT was substantially reduced.

During the last two years of the study (2001 and 2002), soil loss was substantially reduced as opposed to the runoff (Fig.2). However, regardless of the treatments there was a slight increase in soil loss in 2002 as compared to 2001. This may be related to the slight increase in runoff during 2002. Consequently, similar to 2000, BBF resulted in the highest soil loss in 2001 and 2002 as well. Regardless of the treatments and years, the soil loss was low for the Central Highland Vertisols compared to the previous reports (Teklu, 1997), where losses of 10.4 t ha^{-1} and 9.9 t ha^{-1} under RF and BBF (at Ginchi, about 150 km away to the west) planted to wheat, respectively, were reported.

Soil erosion is a function of erodibility (soil factor) and erosivity (rainfall factor). Soil erodibility depends on soil texture, among other factors. Soils with higher silt content are more vulnerable to erosion. Therefore, one possible explanation for lower soil loss from Caffee Doonsaa is the lower silt content of the Vertisols (13%) as compared to the Vertisols at Ginchi (20%). In addition, higher rainfall intensity had been observed at Ginchi than at Caffee Doonsa, leading to higher erosivity. However, there is no quantitative data to substantiate this claim, although there is a general trend of increase in rainfall intensity and amount from the northeast to the southwest.

Although there is still a controversy regarding the estimates of soil loss from the highlands of Ethiopia; irrespective of the treatments, the quantity of soil loss observed is much less than the previous estimates (FAO, 1984; SCRP, 1987; Hurni, 1988; Hawando, 1995). The Soil Conservation Research Project (Hurni, 1988) and National Conservation Secretariat (1992) claim that soil losses may have been over-estimated by FAO (1984). However, Hawando (2000) suggests that the soil loss reported by FAO (1984) was reasonable, while the estimate by National Conservation Secretariat and the Soil Conservation Research Project can be considered to grossly underestimate the magnitude of land degradation in Ethiopia. The underestimation was mainly related to low land area data used in the calculations.

Nevertheless, this study also seems to underestimate the total soil loss. This may be attributed to the very high clay content of the soil (about 70%), the gentle slope of the site (2-3%) and the plot size used. Although gully erosion which operates as rotational slumping on slickensides and subsurface piping through the cracks, is a major problem in Vertisols (Deckers *et al.*, 2001) only sheet erosion was measured due to the plot size used. Thus, a more realistic estimate of soil loss from Vertisols may be at watershed level.

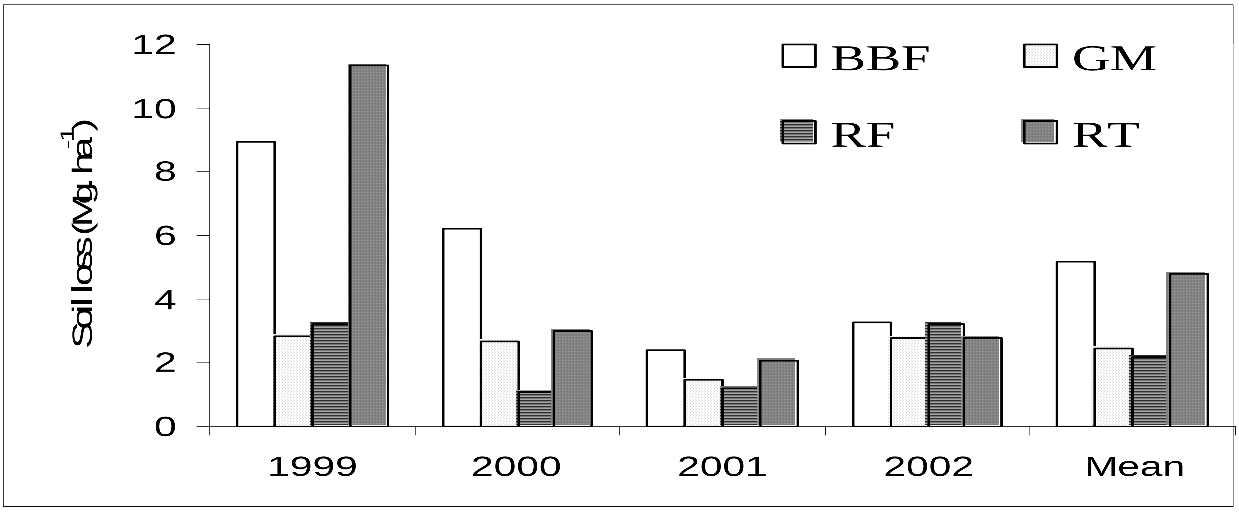

Fig.8.1 Effect of land preparation methods on soil loss

Considering the overall performance of the treatments with respect to soil erosion, BBF resulted in the highest mean soil loss followed by RT (Fig. 8.1). The increase in soil erosion at plot level may be exacerbated in larger areas (watershed) as the quantity of water drained increases and concentrate to gain more energy. In addition, the other forms of erosion such as rill and gully start to operate. In the face of the above, it may not be judicious to promote BBF only looking at the yield increase that may be realized for some years and crops, when environmental and sustainability considerations are at stake. Therefore, a longer-term experiment that considers all physical, chemical, biological and economic variables needs to be carried out at larger scales, like watershed, before the fate of such practices as BBF are judged.

8.3 Nutrient loss

Associated with the runoff and soil loss is the loss of OM, nitrogen, phosphorus and other essential plant nutrients. Similar to runoff and soil loss, the effect of the land preparation methods on the nutrients lost with the eroded sediments was not statistically significant (Table 8.2). However, corresponding to its highest runoff and soil loss, BBF resulted in the highest loss of C_{org} and nutrients, except for C_{org} in 2001, in which RT exceeded it.

Table 8.2 Effect of land preparation methods on nutrient and C_{org} loss with eroded sediments

Year	Land preparation methods	Nutrient loss with sediments		
		C_{org} (kg.ha^{-1})	N_t (kg.ha^{-1})	Available P (g.ha^{-1})
2001	BBF	25.5	1.2	12.9
	GM	17.2	0.6	6.6
	RF	14.6	0.7	6.3
	RT	26.1	0.9	11.0
	CV (%)	16.48	13.63	24.3
2002	BBF	34.9	2.0	2.4
	GM	26.8	1.5	1.6
	RF	29.9	1.7	1.9
	RT	25.6	1.5	2.1
	CV (%)	13.59	14.26	23.14

Generally, there was a strong relationship between the nutrient content of the eroded sediment and that of the surface soil, except for BBF. There was a strong correlation between the concentration of C_{org}, N_t and available P in the surface soil and that of the sediment for RT. In addition, correlation was strong for the concentration of N_t and available P of sediments from GM and its original surface soil. The same was true for the available P under RF conditions. Therefore, the higher the concentration of the surface soil, the more the nutrient loss with the sediment.

A paired sample t-test showed that regardless of the treatments, the C_{org} and available P contents of the eroded sediment was significantly higher ($P \leq 0.05$) than that of the surface soil sampled during the active growing stage of the crop in 2002 (data not shown), while the N_t content was nearly the same. This indicates that runoff does not only remove the surface soil with its sediments, but also washes the nutrients and C_{org} out of the remaining soil, leading to SQ deterioration.

The enrichment ratio (ER), the ratio of the C_{org} and nutrients content of the eroded sediment (Table 8.3), to that of the original surface soil (Table 8.4) was the highest for C_{org} and available P under RF and RT, respectively (Fig.8.2). According to Chongfa *et al.* (1999), ER is correlated with the content of the fine aggregates and particle size distribution of the eroded sediment, such that eroded sediments contain more fine particles than the surface soils from which they come, and thus contain more nutrients.

Table 8.3 Mean nutrient and C_{org} content of the eroded sediment (2002)

Land preparation methods	C_{org} (%)	N_{org} (%)	C:N	Available P (g. ha^{-1})
BBF	1.25	0.07	17.86	0.88
GM	1.31	0.07	18.71	0.78
RF	1.32	0.07	18.86	0.84
RT	1.27	0.07	18.14	1.04

Table 8.4 Mean nutrient and $\mathbf{C_{org}}$ content of the original surface soil (0-15 cm) at active growth stage (2002)

Land preparation methods	C_{org} (%)	N_{org} (%)	C:N	Available P (g. ha^{-1})
BBF	0.85	0.07	12.14	0.68
GM	0.97	0.08	12.13	0.43
RF	0.86	0.07	9.29	0.55
RT	0.99	0.09	11.00	0.50

There was reduced enrichment ratio (less than one) for N_t under GM and RT. As only part of nitrogen lost with the sediments (not the part that was dissolved in runoff), were considered the loss of nitrogen was under estimated. Therefore, the fact that nearly equal or less concentration of N_t exists in the sediments as compared to the surface soil does not show the tendency of nitrogen to stay behind, when the sediment is eroded.

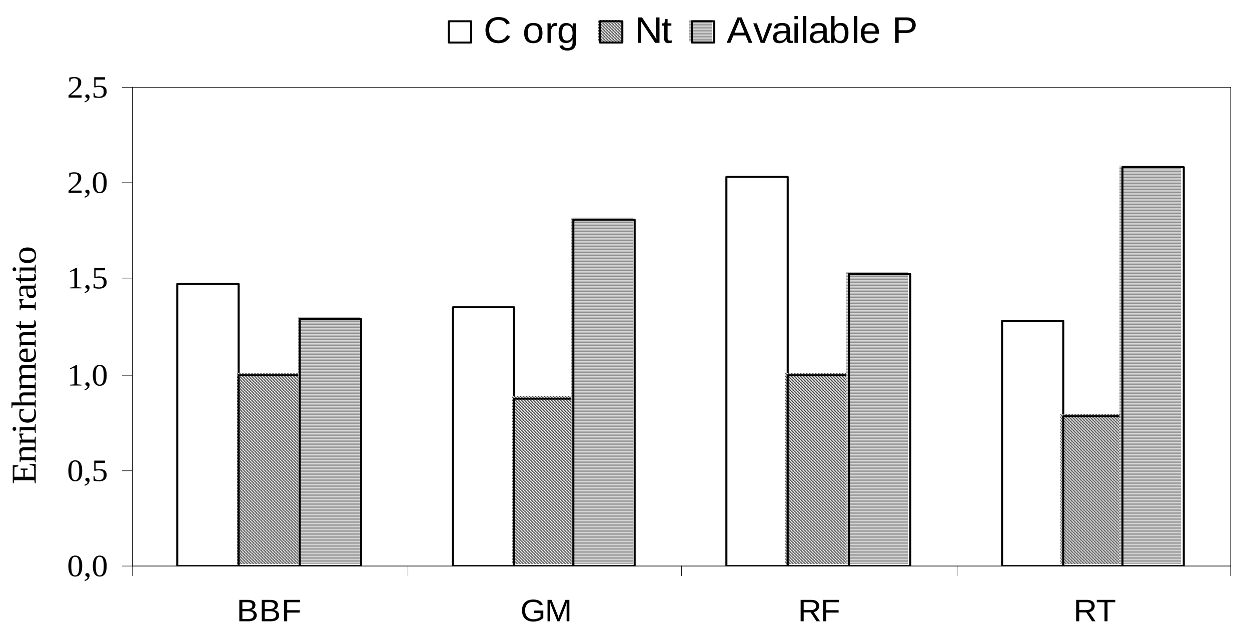

Fig.8.2 Effect of land preparation methods on nutrient enrichment ratio (ER) of eroded sediment (2002)

8.4 Management implications of runoff and soil loss

The study indicated that BBF and RT routed more excess rainfall than RF and GM, indicating their relative efficiency in terms of enhancing surface drainage. BBF was designed for draining excess water (Jutzi *et al*., 1986; El-Swaify *et al*., 1985) such that the excess water goes from seedbeds to furrows through which it proceeds to sub drains. Therefore, the result confirmed the expectations and previous reports (Teklu, 1997), in which BBF induced the highest surface runoff as compared to RF and flat seedbeds for Vertisols at Ginchi (in the highlands of Ethiopia). Runoff from RT increased because of the reduced surface storage capacity since the soil surface was relatively smooth as opposed to the traditional systems where surface roughness is created through tillage operations, which form micro depressions in which the excess water is detained. Similarly, GM and RF drained lower runoff in both years due to their increased surface storage capacity formed by the irregular furrows created by the tillage operations. As crops grow on ridges in both cases (except for tef), the furrows detain more water, which would be evaporated or slowly percolated.

Irrespective of the treatments, runoff coefficient was substantially increased in 2001 and 2002. In 2001, BBF and RT routed 68% and 61%, respectively, of the rainfall. Even during the severe dry year of 2002, BBF and RT removed 54% and 53% of the rainfall, respectively. Evidently, a suitable system of harvesting the excess water for supplementary irrigation and other purposes can be used to effectively deal with the problem of moisture stress, and to avoid soil and nutrient loss.

The highest soil loss from BBF is partially attributed to increased runoff. In addition, bare walls and bottoms of the furrows that are exposed to both the rainfall impacts and the scoring effects of the concentrated runoff leave the soil vulnerable (Teklu, 1997). Despite its better vegetative cover before planting, RT increased soil loss as compared to RF. This is related mainly to the increased runoff volume. This is against the expectations that RT may improve both physico-chemical, biological conditions of the soil, which positively contribute to soil conservation. Therefore, a longer time may be required for its positive effects with respect to soil conservation to be realized. The increased soil loss due to RF in 2002 compared to GM, RT was explained by the occasional tillage before, and during the main rainy season, which buries any emerging weed and leave the bare loose soil.

Soil quality degradation is caused not only due to the quantity of physical soil loss, but also due to the relative quality of the sediment lost. The quality of the sediment is, in part characterized by its chemical composition. To policy makers and land managers, the amount of fertilizer lost with the sediment and its financial implications or the degree of water pollution and the effects on human health may be more meaningful for urgent actions. The enrichment ratio (ER) may be used in calculating or modelling the onsite and offsite effects of runoff and soil erosion. In addition, in investigating or modelling the nutrient enrichment of surface water bodies and the danger of pollution, ER may be used instead of total sediment load and nutrient content of the original surface soil (Chongfa *et al*., 1999).

9 Land preparation methods and soil quality indicators

9.1 Physical soil quality indicators

Land preparation for crop production often involves tillage with various frequencies. Tillage eliminates weeds, achieves favourable conditions for sowing, attains emergence and good development of plant, preserves SOM and avoids erosion, and eliminates hardpans or compacted layers to increase water infiltration. It also incorporates agro-chemicals and agricultural residues into the soil (Mazuchowski and Derpsch, 1984).

Ranges of tools from sharp stone and wooden plough to tractors and heavy tillage implements depending on the societal development level and feasibility under the prevailing environment are used for land preparation. In Ethiopia, 90% of the land preparations for crop production are carried out with a traditional wooden plough, pulled by a pair of oxen (Astatke *et al.,* 2002).

In the highlands, the frequency, and feature of the final tillage that affects drainage, soil erosion, moisture conservation, weeding and harvesting is dictated by crop type, soil type, landscape position, and climate and farmers tradition. Five to nine cultivation passes before sowing is common (Astatke *et al*., 2002; Teklu and Gezahegn, 2003). Such a frequent tillage increases the loss of SOM because of mixing of the soil and crop residues, disruption of aggregates, and increased aeration (Doran and Smith, 1987). In this connection, Gajri *et al.* (2002) state that tillage disrupts and compacts soil, and changes volume-mass relations in the disturbed zone, thereby changing soil physical environment. Thus, it is believed that reducing tillage frequency, incorporating cover crops as green manures, and enhanced surface drainage improve physical SQ indicators as compared to the traditional method of intensive tillage and late planting.

9.1.1 Soil texture

Although soil erosion is often selective with respect to texture, in this study, the difference in runoff and soil loss caused by the land preparation methods (Chapter 8) did not affect the textural composition of the surface soil (Table 9.1). This is because of the homogenously high clay content and the self-mulching properties of the soil (Mesfin, 1998). Thus, the selective nature of soil erosion was not reflected in topsoil texture. Consequently, soil texture is not a good indicator of dynamic SQ at least when soils with homogenous texture profile are compared.

Table 9.1 Effect of the land preparation methods on soil texture (%)

Depth (cm)	Texture	BBF	GM	RF	RT
0-15	Sand	6	7	7	6
	Silt	22	21	21	21
	Clay	72	72	72	72
15-30	Sand	10	5	7	6
	Silt	17	21	21	22
	Clay	73	74	72	72

9.1.2 Aggregate stability and crusting

Although many Vertisols are well structured, they flake under rapid wetting to form micro-aggregates with sand to silt size range that are easily transported by runoff because of their low density (Loch and Donnollan, 1983). Repeated tillage breaks soil aggregates into finer sizes and loss of OM. As the loss of OM exacerbates aggregate stability, RT increases stability (Havlin *et al*., 1990). Nevertheless, the slightly increased SOM content in this study did not improve aggregate stability under RT. On the contrary, GM increased water aggregate stability (WAS) (Table 9.2) and lowered crusting due to its enhanced OM content. While this can be related to USDA-NRCS (1998), which reported improved soil physical properties following legume cropping in both the United States and Canada on non Vertisols, the inconsistent relationship between the OM level and aggregate stability is related to the high clay content of the Vertisols, which undermines the role of SOM.

Table 9.2 Effect of land preparation methods on water aggregate stability (WAS) and crust formation (2002)

Land preparation methods	WAS (%)	Std	Crusting			
			Thickness (mm)	Std	Strength (kg. cm^{-2})	Std
BBF	7.4	7.2	7.4	0.00	1.40	0.38
GM	10.9	7.2	7.0	0.64	0.97	0.52
RF	9.4	3.6	6.7	0.81	1.35	0.48
RT	8.7	5.7	7.5	0.47	1.40	0.53

Increased aggregate stability reduces soil erodibility and crusting. Surface crust strength was reduced under GM, although the thickness was slightly increased. This may explain the higher final infiltration rate under GM despite its lowest initial rate. Valentin and Casenave (1992) explain that heavy textured soils form surface crusts of coalescing loamy clayey aggregates with infiltration capacity of below 10mm.h^{-1}. Due to their high smectite content, the Vertisols in the area are prone to crusting, especially under repeated tillage. As crusts affect runoff, soil moisture distribution, germination and development of plants (Graef, 1999), and as stable aggregates resist the splashing and scoring effects of raindrops and runoff or the effects of slaking and structural explosion, the use of GM showed a promising trend of enhancing soil quality.

9.1.3 Penetration resistance and bulk density

When soil particles are pressed together, reducing the overall pore space, they become dense and hard to penetrate (USDA-NRCS, 1996). This can be caused by tilling when the soils are wet. Measurement of penetration resistance is relatively easy and thus useful for rapid evaluation of strength and structural changes (Lowery and Morrison, 2002). Soil OM reduces compaction by promoting soil aggregation and increasing porosity. AS it involved a primary tillage when the soil was dry, followed by four tillage operations at about field capacity moisture content, BBF significantly increased penetration resistance (Fig.9.1), both under moist and dry soil conditions.

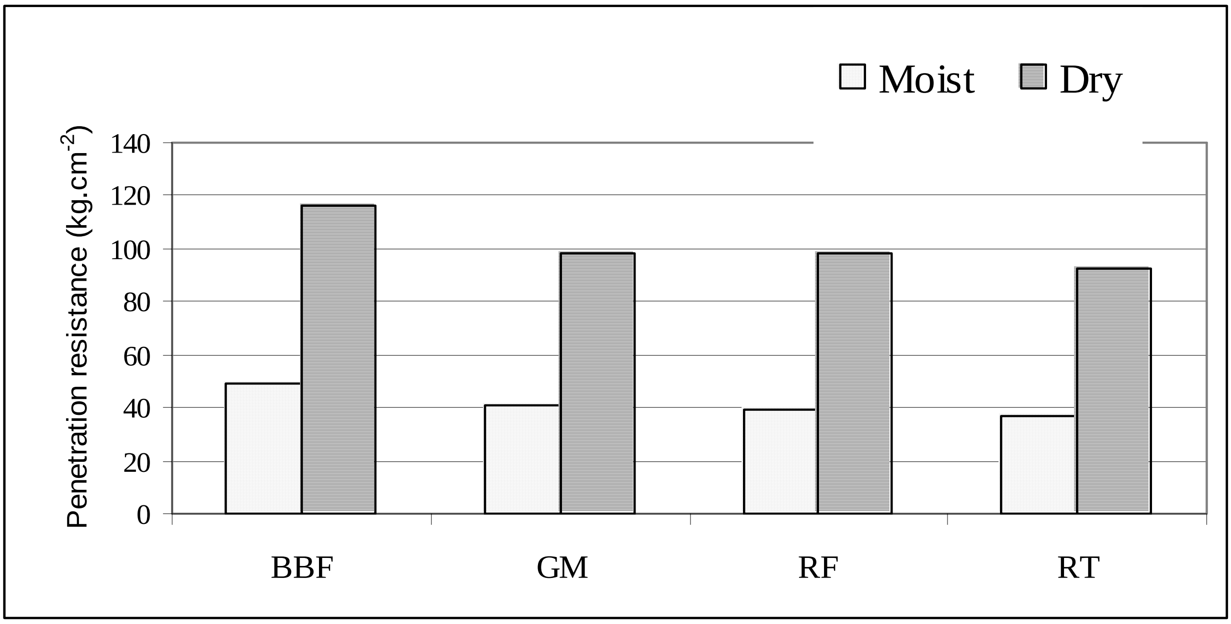

Fig.9.1 Effect of the land preparation methods on soil's penetration resistance at moist and dry conditions

Contrastingly, RT tended to reduced penetration resistance despite its higher crust thickness and strength. This is because; penetration resistance was measured up to the depth of 15 cm while surface crust is limited to the upper few millimetres. Thus reducing the frequency of tillage may reduce soil compaction, improve aeration, and enhance root growth and access to nutrients and water (Thompson *et al*., 1987). In accordance with Vazquez *et al.* (1991), who found that resistance to penetration to be tenfold more sensitive than BD as indictor of soil compaction, bulk density and porosity were not affected by the treatments and all lie in an acceptable range (Table 9.3) for clayey soils.

Table 9.3 Effect of land preparation methods on bulk density and soil porosity during the growth stage (2002)

Land preparation methods	Bulk density ($g.cm^{-3}$)		Total porosity vol. (%)	
	0-30 cm	30-60 cm	0-30 cm	30-60 cm
BBF	1.11	1.07	58	60
GM	1.11	1.06	58	60
RF	1.11	1.06	58	60
RT	1.09	1.06	59	60

9.1.4 Soil water storage

Despite a significant effect of the treatments on surface drainage in which BBF routed the highest runoff (Teklu *et al.*, 2004), the soil moisture content during the growing periods was not significantly affected, confirming the previous findings of Teklu (1998). However, the difference between the treatments tended to gradually increase from 1999 to 2002 (Fig. 9. 2 a and b). In 2002 (a dry year), reduction of soil moisture under BBF was pronounced as of September. This is related to the enhanced drainage and the consequent improved crop performance, leading to higher evapotranspiration. The lacking difference in soil moisture content especially during the high rainfall years, despite the significant difference in runoff may indicate the existence of additional input to the system other than rainfall. Thus, it is suspected that the profiles might be recharged from the bottom through capillary rise, lateral flow derived by head difference created due to surface drainage.

9.1.5 Water holding capacity

Regardless of the treatments, the soil retained high proportion of water (>23%) at permanent wilting point (PWP) due to the high smectitic clay content. Like the other physical indicators, available water holding capacity (AWC) was not significantly affected, although GM tended to increase it in the upper 30 cm (20.4%) as opposed to BBF, which slightly reduced (Table 9.4). The relative increased due to GM is consistent with its influence on the OM content and aggregate stability. This minor increase in the upper layer is important for shallow rooting crops like tef.

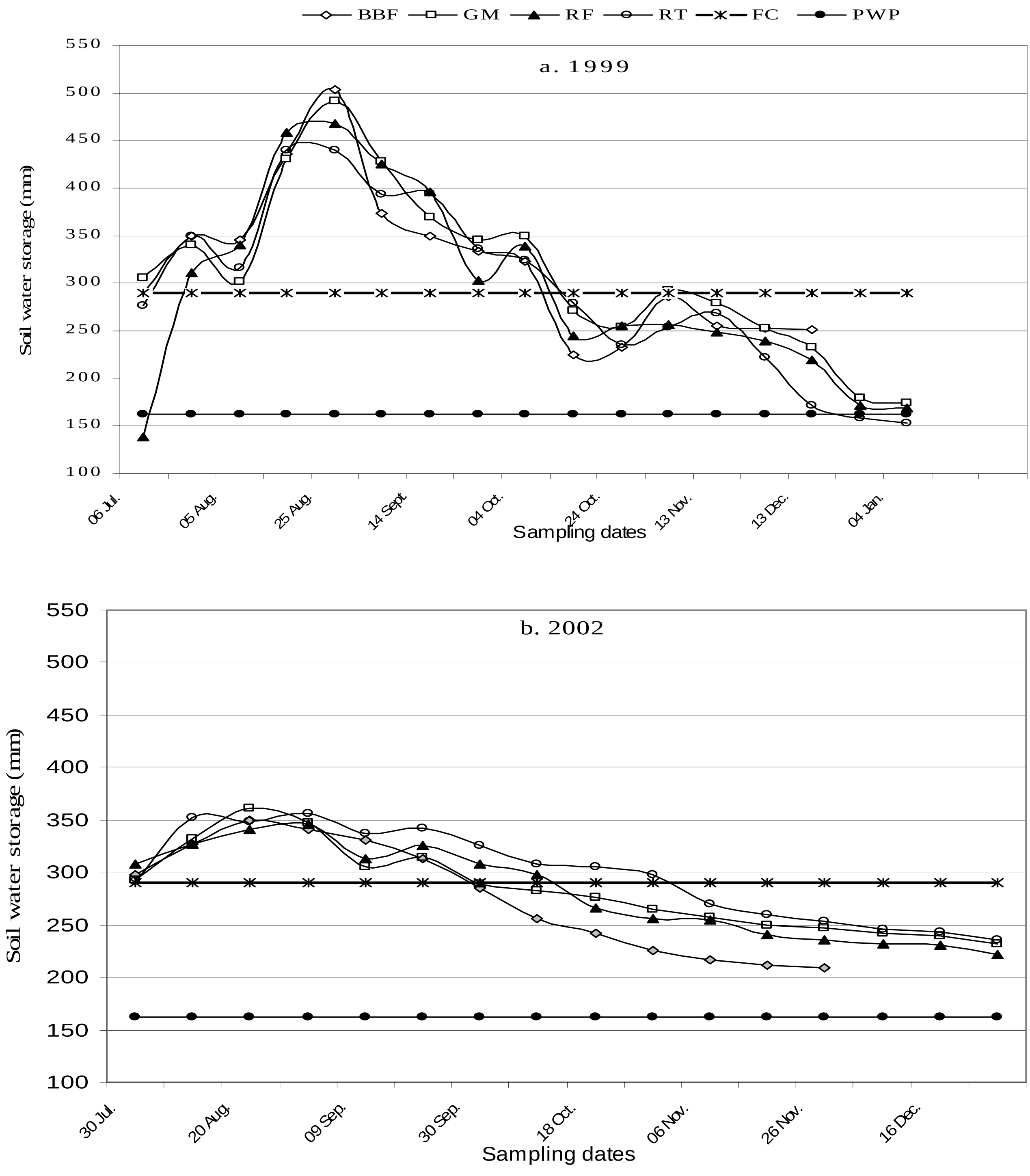

Fig.9. 2 a & b Effect of the land preparation methods on soil water storage (0-60 cm depth) under lentil crops during the growing periods

Table 9.4 Effect of land preparation methods on soil water holding capacity

Land preparation methods	Depth (cm)	FC (Vol.%)	PWP (Vol.%)	AWC (Vol.%)	AWC over the whole depth (90 cm)
BBF	0-30	42.9	24.6	18.3	198 mm
	30-60	43.8	23.9	19.9	
	60-90	44.2	23.2	21.0	
GM	0-30	44.0	23.6	20.4	193 mm
	30-60	43.5	24.2	19.3	
	60-90	42.8	24.5	18.3	
RF	0-30	44.2	24.7	19.5	197 mm
	30-60	45.2	25.3	19.9	
	60-90	45.7	26.1	19.7	
RT	0-30	46.0	26.5	19.5	198 mm
	30-60	45.9	26.6	19.3	
	60-90	47.2	26.6	20.6	

9.1.6 Infiltration

Saturated hydraulic conductivity and water infiltration indicates effect compaction on water flow (Young and Voorhees, 1982). Soil under good condition has a stable structure and continuous pores to the surface. Surface crusting resulting from weak soil structure and non-existing macro pores produce a low infiltration rate.

The minimum infiltration rate, which is important with respect to runoff and soil erosion, was not more than 3 mm h^{-1} (much less than rainfall intensity) regardless of the treatments (Table 9.5). This is despite the high initial infiltration rate which could go as high as 60 mm h^{-1}. The low final infiltration rate was related to the inherent property of the soil. This often causes water logging on level lands; and flooding on graded landscapes, a common event in Awash River basin, which emerges and is fed by the rainfall in the central highlands.

The infiltration rates decreased in 2002 compared to 2001 (Table 9.5). The mean of the two years showed that the alternative treatments improved the final infiltration rate as compared to RF. Despite its higher compaction, BBF tended to increase infiltration rates in both years. This is may be due to the longer time between the last tillage and the time of infiltration measurement. BBF, which involves early planting, received the last tillage early July, while the others were tilled until the end of August. Corroborating its effects on aggregate stability and crusting, GM resulted in the highest final infiltration rate following BBF in both years. This confirms the findings of Thierfelder *et al.* (2003), who reported improved final infiltration rates due to legumes and improved fallow rotations on non Vertisols. As Vertisols are severely limited by their final infiltration capacity, a little improvement may be considerable for better productivity and resource conservation.

Table 9.5 Initial and final infiltration rates (mm h^{-1}) as affected by land preparation methods

Land preparation methods	2001		2002		Mean	
	Initial	Finale	Initial	Final	Initial	Finale
BBF	60	2.8	55	2.9	58	2.9
GM	33	2.8	29	2.5	31	2.7
RF	57	1.8	17	1.1	37	1.5
RT	42	2.4	12	2.1	27	2.3

9.2 Chemical soil quality indicators

Vertisols are the most fertile soils of the seasonally dry tropics (Duchaufour, 1998). However, management practices affect their chemical characteristics. Tillage affects soil pH, through its effects on the distribution of nutrients and OM. Studies have shown lower surface soil pH under zero-tillage and stubble mulch than ploughed treatments (Follett and Peterson, 1988). Lower pH was reported under zero tillage and reduced tillage than under conventional tillage. Reduced tillage decreases soil mixing, which may lead to concentration of immobile nutrients such as P and K in the upper soil layers (Follett and Peterson, 1988; Robbins and Voss, 1991; Weil, *et al*., 1988). The effects of tillage on soil mixing, soil water content, soil porosity and OM breakdown influences the distribution of the mobile nutrients such as nitrogen (Doran and Smith, 1987).

The effects of tillage systems on soil chemical characteristics depend on soil type. Grant and Bailey (1995) reported a higher concentration of nitrate under zero tillage than under conventional tillage in the surface 7.5 cm of fine sandy soils, presumably due to N mineralization of organic residues or residual N build-up from reduced downward movement of fertilizer. They reported that NO_3^- was uniformly distributed through the surface 15 cm depth under conventional tillage in the silty-clay soils, while there was higher concentration in the surface 7.5 cm under zero tillage. In the same study, higher NO_3^- was observed under conventional tillage than under zero tillage. Similarly, higher P concentration in the surface 15 cm depth, with a peak occurring at the depth of fertilizer placement under both conventional and zero tillage was reported (Grant and Bailey, 1995). This was linked to the relative immobility of phosphorus.

9.2.1 Soil reaction (pH)

The soil reaction is slightly alkaline regardless of the treatments and the time of sampling with a tendency of increase with depth (Table 9.6). The treatment effect was not statistically significant at tillering stage of the crop while at harvest the treatments significantly affected soil pH at the 30-60 and 60-90 cm depths. However, the highest pH was recorded for BBF and RT in the top and lower layers, respectively. Nitrogen fertilizers have an acidifying effect on soil (Gajri, 2002).

Thus, the higher pH under BBF at the surface may be related to its highest infiltration rate (Chapter 9.1) which leads to leaching of N from the surface to the lower profile and the higher runoff rate that may wash the nitrogen away. As compared to the tillering stage, BBF and RT tended to have increased pH in upper layer (0-30 cm). This may also be related to the differential loss of N from the surface layer due to crop uptake, leaching and runoff (Chapter 8).

Table 9.6 Effect of the land preparation methods on soil pH

Land preparation methods	At tillering		After harvest		
	Depth (cm)				
	0-15	15-30	0-30	30-60	60-90
BBF	7.5	7.5	7.7	7.7 AB	7.7 B
GM	7.4	7.5	7.4	7.6 B	7.8 AB
RF	7.5	7.5	7.5	7.7 AB	7.7 B
RT	7.5	7.6	7.6	7.8 A	7.9 A
LSD (5%)	NS	NS	NS	0.14	0.19
CV (%)	2.20	1.89	1.62	0.94	1.33

Means within the same column followed by the same letter are not significantly different at 95% confidence interval.

9.2.2 Organic matter

Soil OM is an important parameter determining SQ as it influences the structural stability, moisture retention, nutritional status, and biological activity of the soil (Gajri, 2002). The effect of the treatments on OM was not statistically significant. However, RT and GM slightly increased the C_{org} content in the upper horizons (Table 9.7). Due to the annual incorporation of the freshly chopped cover crops through tillage, GM increased C_{org} content in the lower layer (15-30 cm). While part of the organic materials left in the top layer were mineralised quickly, the parts that were incorporated deeper might have taken longer time to decay due to limited aeration. This, however, needs to be confirmed by further research. Presumably, the increase in case of RT is ascribed to the limited disturbance of the soil and hence to the reduced mineralization rate of the OM and accumulation of weeds and crop stubbles in the surface soil.

9.2.3 Cation exchange capacity

The OM and clay content and the nature of clay minerals determine the cation exchange capacity (CEC) of a soil. Since the mineralogical composition of clay does not change over a short period, the two factors contributing to CEC are OM and clay content; and changes in CEC often follow those in SOM (Gajri *et al.*, 2002).

Table 9.7 Effect of the land preparation methods on soil organic carbon content (%)

Land preparation methods	At tillering		After harvest		
	Depth (cm)				
	0-15	15-30	0-30	30-60	60-90
BBF	0.85	0.72	0.90	0.77BC	0.67
GM	0.97	0.99	0.94	0.95A	0.78
RF	0.86	0.69	0.85	0.66C	0.73
RT	0.99	0.84	0.86	0.85AB	0.70
LSD (5%)	NS	NS	NS	0.35	NS
CV (%)	33.45	29.44	25.77	8.96	25.80

Means within the same column followed by the same letter are not significantly different at 95% confidence interval.

The treatments did not significantly affect the CEC of the soil (Table 9.8). This is because of the very high clay content and the abundance of smectitic clay mineral, which suppressed the minor change in C_{org} to play a considerable role. Similarly, the treatments did not affect the exchangeable bases (Table 9.9). As indicated in characterization of the soil in the area (chapter 6), Ca^{2+} is the dominant base followed by Mg^{2+} and K^{+}. Regardless of the treatments and depths considered, the concentration of Mg^{2+} is much lower as compared to those from the profiles while the other cations are comparable.

Table 9.8 Effect of the land preparation methods on the cation exchange capacity and carbonate concentration of the soil

Land preparation methods	CEC (cmol. kg^{-1}soil)			CaCO3 (%)		
	Depth (cm)					
	0-30	30-60	60-90	0-30	30-60	60-90
BBF	81	94	103	4.9	5.2	4.2
GM	104	105	103	5.8	5.3	4.7
RF	103	99	103	5.6	4.4	5.4
RT	98	102	101	5.2	5.2	3.7
LSD (5%)	NS	NS	NS	NS	NS	NS
CV (%)	17.22	7.96	3.56	14.6	14.6	25.8

Table 9.9 Effect of land preparation methods on the exchangeable bases (cmol.kg^{-1}) of the soil

Land preparation methods	Depth (cm)	Na^+	K^+	Ca^{2+}	Mg^{2+}
BBF	0-30	0.1	2.1	49.8	7.5
	30-60	0.1	2.1	50.9	7.3
	60-90	0.1	2.1	50.2	7.2
GM	0-30	0.1	2.1	50.1	7.3
	30-60	0.1	2.1	49.5	7.5
	60-90	0.1	2.1	49.8	7.6
RF	0-30	0.1	2.2	51.3	7.5
	30-60	0.1	2.1	51.9	7.4
	60-90	0.1	2.1	51.4	7.7
RT	0-30	0.1	2.1	51.1	7.6
	30-60	0.1	2.1	51.2	7.3
	60-90	0.2	2.2	51.5	6.7

9.2.4 Nitrogen

The effect of the treatments on total N at tillering stage was not significant at both depths (Table 9.10). At harvest, it was significantly affected by the treatments at the lower layer (60-90 cm). The total mineral N (nitrate plus ammonia) content in the top layer (0-30 cm) was considerably reduced from tillering stage to harvest, irrespective of the treatments. This is accounted for by the crop uptake as well as the losses due to runoff, leaching, volatilization and denitrification processes.

Table 9.10 Effect of the land preparation methods on N_{org} (g.kg^{-1})

Land preparation methods	At tillering		After harvest		
	Depth (cm)				
	0-15	15-30	0-30	30-60	60-90
BBF	0.7	0.7	0.47	0.67	0.3^B
GM	0.8	0.8	0.50	0.40	0.4^A
RF	0.7	0.6	0.50	0.43	0.4^A
RT	0.9	0.7	0.50	0.43	0.3^B
LSD (5%)	NS	NS	NS	NS	0.1
CV (%)	31.88	18.88	11.74	16.32	13.33

Means with in the same column followed by the same letter are not significantly different at 95% confidence interval.

The difference in the concentration of nitrate due to the treatments was not significant both at tillering stage and at harvest, while that of ammonia was significant only at the surface layer (0-30 cm) after harvest (Table 9. 11-12). This significant difference in the surface layer may be attributed to the differential uptake of the crops which performed differently. However, the difference in the concentration of ammonia and nitrate under the different treatments and the depths considered is remarkable. Ammonium N ranged from 33 mg. kg^{-1} for RT at the surface to 60 mg. kg^{-1} for GM at the lower layer while nitrate ranged between 29 mg. kg^{-1} for BBF at the surface and 52 mg. kg^{-1} for RT at the lower layer. The general decrease of ammonium and nitrate N with depth is natural because of the higher biological activities near the surface. On the other hand, RF has shown both the minimum and maximum C: N ratio for the surface (0-15 cm) and the lower layer (15–30 cm), respectively (Table 9.13).

Table 9.11 Effect of the land preparation methods on the total inorganic nitrogen (ammonia and nitrate content, mg. kg^{-1}) of the soil

Land preparation methods	At tillering stage				After harvest					
	NH_4^+		NO_3^-		NH_4^+			NO_3^-		
	Depth (cm)									
	0-15	15-30	0-15	15-30	0-30	30-60	60-90	0-30	30-60	60-90
BBF	41	56	29	49	0.91 ^{AB}	0.89	1.24	0.86	1.03	0.96
GM	37	61	41	47	0.65 ^{AB}	1.03	0.68	0.79	0.98	0.82
RF	46	58	33	46	0.56 ^{B}	0.93	0.75	0.65	0.72	0.72
RT	33	44	46	52	1.10 ^{A}	0.93	0.79	1.03	0.68	0.84
LSD (5%)	NS	NS	NS	NS	0.46	NS	NS	NS	NS	NS
CV (%)	35.12	21.21	40.89	21.39	30.33	31.50	42.44	50.59	31.29	20.12

Means within the same column followed by the same letter are not significantly different at 95% confidence interval.

Table 9.12 Effect of the land preparation methods on mineral N (mg. kg^{-1}) content of the soil

Land preparation methods	At tillering		After harvest		
	Depth (cm)				
	0-15	15-30	0-30	30-60	60-90
BBF	6.8	10.3	1.80	1.90	1.00
GM	7.6	10.7	1.50	2.00	1.50
RF	7.9	10.4	1.30	1.60	1.50
RT	7.9	9.5	2.10	1.60	1.60

Table 9.13 Effect of the land preparation methods on C: N ratio of the soil at tillering

Land preparation methods	0-15 cm	15-30 cm
BBF	11.0	8.0
GM	10.4	8.9
RF	7.0	8.7
RT	9.1	8.7
CV (%)	30.0	17.3

9.2.5 Available Phosphorus

Although the concentration was generally very low, more available P was observed in the surface layer under BBF and RF. This may be due to the poor performance of the previous crops (Chapter 7) on the two seedbeds, which might have retarded utilization of applied P leading to increased residual phosphorus. Despite the high coefficient of variation, available P after harvest was significantly affected at 30-60 and 60-90 cm depths (Table 9.14).

Table 9.14 Effect of the land preparation methods on the available P (mg. kg^{-1}) content of the soil

Land preparation methods	At tillering		After harvest		
	Depth (cm)				
	0-15	15-30	0-30	30-60	60-90
BBF	0.68	0.55	0.77	0.80^{A}	0.53^{AB}
GM	0.43	0.52	0.43	0.10^{B}	0.13^{B}
RF	0.55	0.43	0.57	0.63^{A}	0.83^{A}
RT	0.50	0.55	0.20	0.33^{AB}	0.47^{AB}
LSD (5%)	NS	NS	NS	0.49	0.41
CV (%)	38.80	25.19	68.97	55.33	44.71

Means within the same column followed by the same letter are not significantly different at 95% confidence interval.

9.3 Microbial biomass

In addition to affecting physical and chemical characteristics of soil, tillage practices also affect its biological properties including crop growth and the growth of microorganisms and soil fauna (Gajri *et al.*, 2002). Soil microbial biomass (SMB) is the living component of SOM (Jenkinson and Ladd, 1981) excluding macro fauna and plant roots. It is part of the active pool of SOM. It plays focal roles in decomposition of organic materials, nutrient cycling, and biophysical manipulation of soil structure (Franzluebbers *et al.*, 1999). The amount of microbial biomass in a soil reflects the total OM content, with the living microbial component forming a low proportion of the total (Sparling, 1997).The SMB is both a source and sink of the nutrients like carbon, nitrogen, phosphorus and sulphur contained in the OM. It

comprises approximately two percent of the total OM in soil and as a result, may easily be dismissed as of minor importance in the soil (Franzluebbers *et al.*, 1999).
The SMB is a sensitive indicator of changes in soil processes since it has a much faster rate of turnover than the total SOM (Jenkinson and Ladd, 1981; Paul, 1984). Changes induced by management systems like tillage can be recognized early, through monitoring of SMB because of its rapid turnover (Lynch and Panting, 1980; Carter, 1991). Thus, it is essential for earlier prediction of management effects and long-term trends on sustainable utilization of the resource base. Larson and Pierce (1994) suggest that the rates of change in soil parameters (including the SMB), rather than the absolute values, can provide an assessment of long-term SQ and health. This implies the need for monitoring of changes over time through repeated sampling at certain intervals including critical times like at the tillering stage of the crop and before and after certain management interventions.
Tillage is increases loss of OM because of aggregate break down and increased aeration. However, the effects of tillage depend, among others, on the frequency and time of the operation and the type of the implement used. Reducing tillage frequency, intensity and use of conservation tillage systems increase input of organic materials and hence improve microbial activity in the upper layer of the soil (Doran, 1987).
The SIR is a method where the maximum respiration rate in a soil upon addition of an easily degraded carbon source such as glucose (Schinner *et al.*, 1996) is measured and converted to MBC. The maximum initial respiratory response after amendment with glucose is proportional to the amount of microbial carbon present in the soil sample (Schinner *et al.*, 1996). Applying a conversion factor derived from the calibration of SIR to the chloroform-fumigation incubation technique, values can be converted to biomass carbon (Anderson and Domsch, 1978).
Although microbial indices can be sensitive measures of changing soil processes, there are no reference values for healthy or high quality soil (Sparling, 1997). Thus, interpretation can be hampered by the natural range in microbial biomass contents in different soil types and eco-systems, seasonal fluctuations and inconsistent trends in relation to soil fertility and plant production. In evaluating the effects of different management alternatives on SQ, results should be interpreted with respect to the soil functions and as related to other SQ indicators at a certain time.

9.3.1 Microbial biomass carbon

When soil temperature and moisture are favourable, the availability of organic materials is the primary factor that determines how much microbial activity occurs in the soil. The treatments considerably affected the total C_{org} content of the soils (Table 9.6) in five years more than they affected SMB. This is against the previous reports, which indicated a slow response of C_{org} to management interventions (Jenkinson and Ladd, 1981) as compared to microbial biomass. However, the treatment effects on the biomass C depended on the depths considered. The effect of

the treatment on SMB was statistically significant ($p \leq 0.05$) in the lower layer (15-30) where its concentration was lower as compared to the surface samples. The highest MBC was obtained due to GM at both depths followed by RT consistent with Doran (1987), who stated that conservation tillage systems improve microbial activity, while the lowest was from BBF and RF at the upper and lower layers, respectively (Fig. 9.3). The improvement in MBC corresponded to the relative enhancement in total C_{org} content due to the treatments (GM and RT). There was a strong correlation (r= 0.9) between the mean C_{org} content and soil microbial biomass carbon (SMBC) in the lower layer while the correlation in the upper layer was weak (r = 0.4).
Regardless of the treatments and despite a minor decrease in total C_{org} content, the MBC was considerably reduced to less than half from the upper 0-15 to 15-30 cm depth. Thus, MBC may show SQ differences, which could have been ignored using other indicators like C_{org}. However, the difference may also be due to a possible variation in the prevailing soil temperature and moisture when measurement was carried out rather than the bio-chemical or physical variation of the soil. Thus, interpretation of the results should consider other related soil parameters.

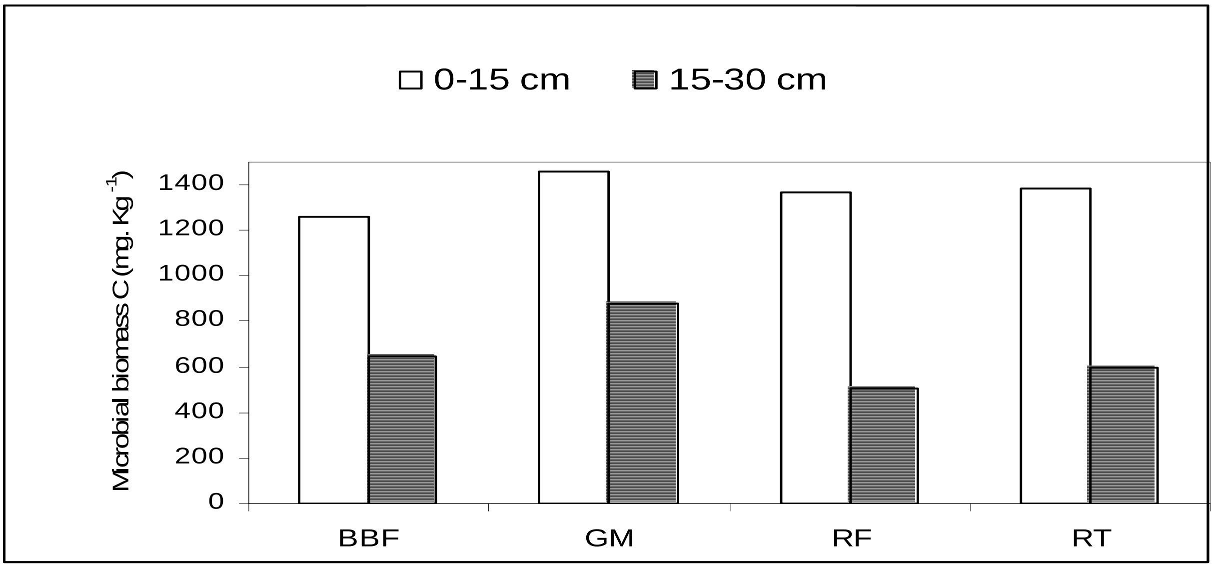

Fig.9.3 Microbial biomass carbon of the soil as affected by the land preparation methods

Higher MBC may indicate higher amount of potentially available N (Hart *et al.*, 1986; Stockdale and Rees, 1994). Looking only at the quantity of MBC, GM was found to be most conducive for the microbial activities. This may be attributed to the quantity and quality of the organic material input through the nitrogen rich legumes, which have been supplied every year compared to the clean tillage under BBF and RF.

Microbial quotient (MQ), the ratio of Soil Microbial Biomass (MC) to total C_{org} (**Eq. 9.1**), may tell whether SOM is degrading due to mineralization or aggrading. Sparling (1997) showed that higher MQ indicates aggradations while lower ratio shows the opposite. However, it may not be possible to describe a system as aggrading or degrading based on a sample at one point in time (Sparling, 1997; Rice *et al.*, 1996). Hence, long term monitoring is required to see the tendency. This is partially due to the high variation in the SMBC caused by factors other than the treatments.

$$MQ = \frac{MC}{C_{org}} \qquad 9.1$$

where MQ= microbial quotient
MC =Microbial Carbon and
C_{org} = Total organic Carbon

In this study, RF gave the highest MQ in the upper layer (Fig.9.4), which according to Sparling (1997) indicates aggradations. However, the absolute value of C_{org} did not support the theory. Although higher SMBC, which may correspond to higher microbial respiration and N mineralization, can be considered positive with regard to nutrient supply to the crops, sustainability of the RF system can be questioned, as the OM pool of the soil is relatively low. On the other hand, the higher SMBC may indicate a response of the microorganisms to stress induced by water logging. Contrastingly, RT resulted in the lowest MQ, followed by GM indicating degradations. However, the higher total C_{org} content indicates aggradations. Thus, the results contradict with that of Sparling (1997). Therefore, whether the measured values of SMBC and its ratio to total C_{org} indicate aggrading or degrading SQ depends still on other factors, like the nutrient supply capacity of the soil at the tillering stage of the crops. In this study, the carbon to nitrogen ratio (C: N) of the soil indicated modest availability of nitrogen to plants under all the treatments. The supply of NO_3^- is relatively higher under GM and RT despite their lower MQ, corresponding to their MBC and total C_{org} content. Thus, in this study, the MBC seem to have depicted the situation better than the MQ. The effect of the treatments on plant available P was minimal although BBF tended to be better, may be due to its effect on soil moisture.

Although the total C_{org} content and the MBC of the soil were improved due to the use of RT and GM, the increment on MBC was not proportional to that of the total C_{org} content leading to low microbial quotient. The low MQ under RT and GM systems, despite the increased MBC may indicate aggradations of the SOM with a long-term SQ improvement. However, the SQ for the current use may not be necessarily higher. The higher MQ under ridge and furrow with relatively low total C_{org} may indicate degradation of SOM and hence deterioration of SQ in the long term. However, since this study compared the treatment effects based on a sample at one point in time, temporal comparison of each alternative through repeated sampling might be necessary to see the trend.

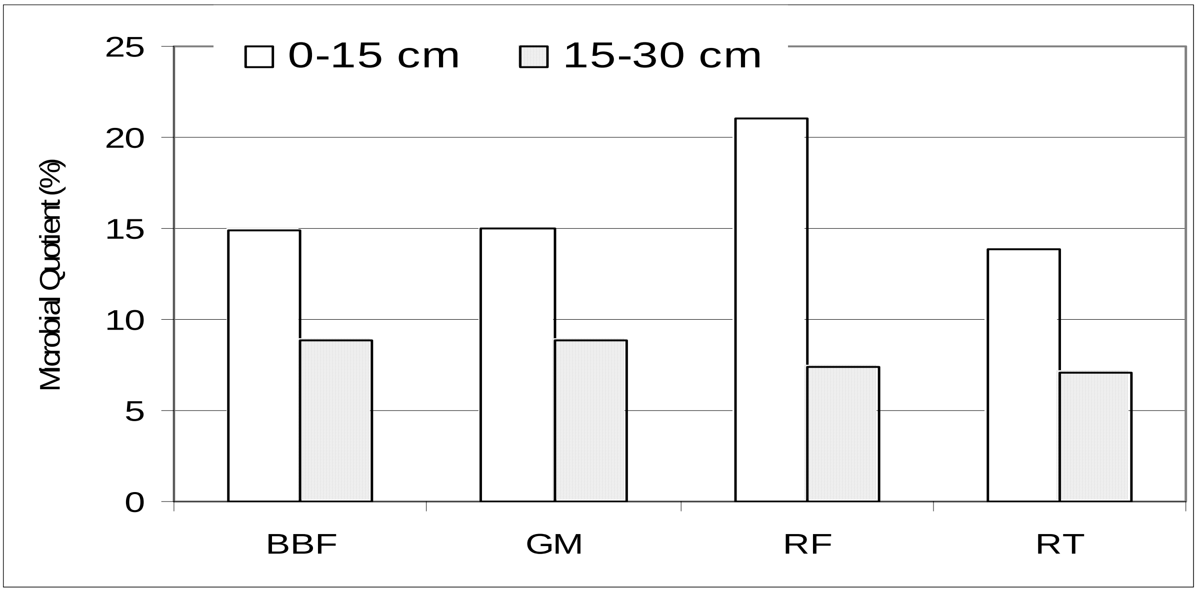

Fig. 9.4 Effect of the tillage systems on microbial quotient as indicator of soil quality

10 Soil quality index

Soil quality assessment is a system of monitoring effects of management systems on the capacity of soils to function. Relevant and reliable indicators for specific functions under a given agro-climatic and socio-economic circumstances is essential for SQ assessment. Comparison of individual physical, chemical and biological indicators is one way of assessing soil quality (Bucher, 2002). However, these indicators are interdependent and may respond to different management systems differently. As this confounds the effects of management systems on the overall soil quality (Weil *et al.*, 1996), individual indicators are not adequate measures (Skujins, 1978; Elliott *et al.*, 1994). Consequently, combining them in a meaningful way to a single index may enhance the assessment (Bucher, 2002).
As the idea of SQ indexing is new, there is no universally accepted approach to carry out. Therefore, the procedures of selecting, scoring and integrating of the indicators are under continued discussion (Andrews *et al.*, 2004). Accordingly, expert opinion or using statistical procedures have been suggested and used for selection of indicators (Doran and Perkin, 1994; Doran and Perkin, 1994). Andrews *et al.* (2002a) have shown that both approaches produced similar results.
Before integration, the values of the selected indicators need to be converted into scores (0 to 1). This requires establishment of functional relationship between the soil function in question and the SQ indictors. The functional relationship could be linear or non-linear (Herrick *et al.*, 2002). Linear scoring functions may be desirable for indicators that change gradually along a continuum, while non-linear functions accommodate threshold and optimum values as well as transition areas, where small changes in indicator values represent large changes in soil function. In line with this, Andrews *et al.* (2002a) have shown that non-linear functions reflected soil functions more accurately than the linear ones.
Although several alternatives have been proposed to integrate the scored indicators into SQI, there is no universally accepted quantitative functional relationship between the overall SQ and the individual indicators (qi) values and their interactions. Yet, Larson and Pierce (1991) suggested that soil quality should be expressed as a function of attributes of soil quality (**Eq. 10.1**).

$$Q = f\left(q_i \dots n\right) \qquad 10.1$$

q_i represents individual SQ indicators such as C_{org}, texture, structure, pH etc. (Letey *et al.*, 2003) and Q is the collective contribution of all q_i.

Andrews *et al.* (2002a) found few differences among the integration methods including additive (Andrews and Carroll, 2001), weighted (Harris *et al.*, 1996), and max-min objective functions (Yakowitz *et al.*, 1993), when used for non-linearly scored indicator values. Weil *et al.* (1996) suggested multiplicative models, though they exaggerate the importance of parameters with score values near zero. However, Andrews *et al.* (2002a) have shown that additive models (**Eq. 10. 2**) may be more useful in assessing SQ despite their sensitivity to the units of parameters.

$$SQI = \left(\frac{\sum_{i=1}^{n} Si}{n} \right) * 10 \qquad 10.\ 2$$

S_i represents the scored indicator values and, n is the number of indicators in the Minimum Data Set (MDS).

Using the number of indicators (n) in the MDS as a divisor corrects for any missing data in the data set. The index value is multiplied by 10 so that it ranges from 1 to 10 rather than 0 to 1 to make it more amendable for the users (Andrews *et al.*, 2003). (Andrews *et al.*, 2004) designed a framework known as Soil Management Assessment Framework (SMAF) to follow the three basic steps: indicator selection, indicator interpretation, and integration of score values into an index (Andrews, 1998). This framework was applied in this study.

10.1 Indicator selection

Indicators were identified for the management goal of crop productivity and taking some site-specific factors (Andrews *et al*., 2004). Using **Fig. 10.1** as a guide, nutrient cycling, physical stability and support, resistance and resilience, and water relations were selected as critical soil functions.
Corresponding to the critical soil functions, indicators were selected based on several additional criteria (Table 10.1) including climate, crop type or rotation, tillage practice(s), assessment purpose, and inherent soil properties (such as OM class, texture, slope, degree of weathering and pH) (Andrews *et al*., 2004).

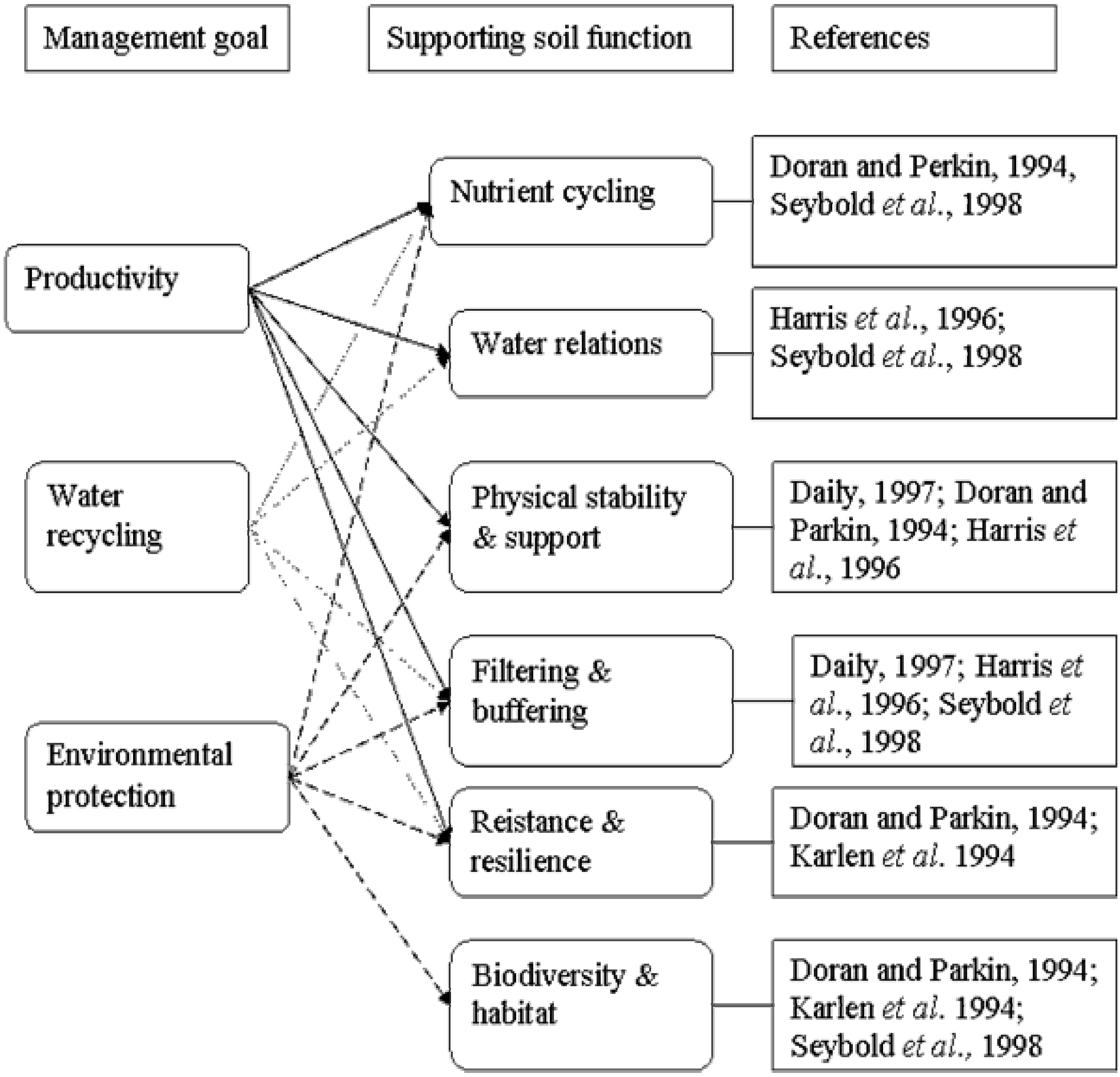

Fig.10.1 Potential management goals and associated soil functions used to select appropriate SQ indicators (Adapted from Andrews *et al*., 2004)

Table 10.1 Selection rules for some potential indicators of the supporting soil functions (Adapted from Andrews *et al*., 2004)

Soil function	Indicator	Criteria for Selection	Reference for use as indicator
Nutrient cycling	• Soil pH • PMN • MBC	• always selected under this function • always selected under this function • alternative to PMN (Sparling, 1997)	• Doran and Parkin, 1994; Smith and Doran, 1996; Karlen *et al*., 1996 • Doran and Parkin, 1994; Needelman *et al*., 1999 • Turco *et al.,* 1994; Gregorich *et al*., 1994; Rice *et al*., 1996
Physical stability and support	• BD • AGG	• clayey soil texture & tillage comparison • always selected under this function	• Larson and Pierce, 1991; Doran and Parkin, 1994; Arshad *et al.,* 1996 • Harris *et al* 1996; Arshad *et al.,* 1996; Karlen *et al*.,1996
Resistance and resilience	• Soil depth • C_{org}	• environment or productivity mgt. goal • comparisons over time or organic amendment comparison	• Arshad *et al*., 1996; USDA-NRCS, 2001; Grossman *et al*., 2001b • Larson and Pierce, 1991; Doran and Parkin, 1994; Elliot *et al*., 1994; Sikora and Stott, 1996
Water relations	• AWC • EC • SAR	• always selected under this function • arid regions or manure mgt. goal • selected in arid regions	• Larson and Pierce, 1991; Lowery *et al.,* 1996 • Smith and Doran, 1996 • Andrews *et al*., 2002a,b

PMN = potentially mineralisable nitrogen, MBC= microbial biomass carbon, AGG = Aggregate stability, BD= Bulk density, AWC= Available water capacity, EC = Electrical conductivity, SAR = Sodium absorption ratio

10.2 Indicator scoring

Indicator interpretation is the conversion of the measured values of the indicators into score values. The measured values were transformed into 0 to 1 using the conversion algorithms developed based on non-linear scoring curves (Table 10.2) (Karlen and Stott, 1994; Andrews *et al*., 2002a) and factor classes (Table 10.3). The factor classes were used to estimate parameters (a, b, c, d) in the conversion algorithms. A score value of 1 represents the highest potential function for that system, which means that the indicator is non-limiting to the soil functions and processes considered.

Ascending logistic or “more-is-better” functions were used for SOM and aggregate stability (AGG) (Tiessen *et al*., 1994; Herrick and Wander, 1998), plant available water-holding capacity (AWC) (Gregory *et al.,* 2000) and MBC (Elliott and Coleman, 1988). On the other hand, a “less-is-better” function was used for bulk density (BD) (Grossman *et al.*, 2001b). Based on crop response and environmental risks (Pierzynski *et al*., 1994; Maynard, 1997), variations of mid-point optimum or

Gaussian functions were used for soil pH (Whittaker *et al.*, 1959; Smith and Doran, 1996) and available phosphorus (P).

Table 10.2 Scoring function for the selected indicators

Indicator	Scoring functions§	Values of the fixed parameters	Reference
C_{org}	Y = a / 1+b * exp –c * C_{org}	a = 1 b = 50.1	USDA, 1966
AGG	Y = a+b*cos(cx-d)	a = -0.8 b = 1.7993 c = 0.0196	USDA, 1966
MBC	Y = a / 1 + b * exp(-cx)	a = 1 b = 40.748	Franzluebbers *et al*., 1996
pH	y = a * exp((-(x-b)2) / 2*c2)	a = 1	Whittaker, 1955
BD	Y =a- b*exp(-c xd)	a = 0.994	Grossman *et al*., 2001
AWC	Y = a+b*cos(cx+d)	a = 0.4772 b = 0.52675 c = 6.87765	Andrews *et al*., 2004

§ Y is interpretation score; x is the measured value of the respective indicator, while parameters in block are site-specific and were determined based on other factors

10.3 Integration of score values

Additive method (Andrews *et al*., 2004) was used in integrating the score values into soil quality indices (SQI). This was accomplished by adding up the score values of each indicator under a treatment and the replicates and dividing by the total number of indicators, and then multiplying by 10 (**Eq. 10.2**). Analysis of variance was carried out to test the significance of the land preparation methods effect on the index values. In addition, correlation test was conducted between the index values and the grain yield of tef planted in 2003.

10.4 Selected indicators

Similar to Andrews *et al.* (2004), the minimum data set (MDS) selected included soil biological, chemical and physical quality indicators as suggested by several authors (Larson and Pierce, 1991; Doran and Parkin, 1994; Seybold *et al.*, 1998). Using the decision rule for indicator selection of the SMAF (Table 10.1), seven SQ indicators including MBC, BD, AGG, C_{org}, pH, AWC and available P were selected as a MDS (Table 5) for crop production. Nevertheless, the plant available P content of the soil was not only very low but also insensitive to the treatments. Consequently, its score value was nil, irrespective of the treatments, confirming the previous reports (Asnakew *et al*. 1991; Tekalign *et al*. 1988). Thus, it was dropped from further analysis. Similarly, soil crusting, which was significantly affected by the land preparation methods (Chapter 7), was not included in the MDS since its direct effect on the productivity is not established.

Table 10.3 Site-specific factors selected and their interpretation criteria for determination of site-specific parameters

Parameter	Factor class selected	Factor interpretation (criteria)	Reference
Texture	5	Clay > 60%	Quisenberry *et al.*, 1993
Fe_2O_3	2	All soils except ultisols	USDA-NRCS, 1998
Season	2,3	Mid growing season, just after harvest	USDA-SCS, 1981; Grant and Bailey, 1995
Mineral	1	Smectitic	USDA-NRCS, 1998
Region	2	Humid	-
Crop	7	Wheat	-
Slope	2	2-5	-
P method	4	Olsen	Wolf and Baker, 1985
Weathering	3	Slightly	Sharpley 1991 SSSAJ 55:1038
Climate	3	Degree days <170; average precipitation > 550 mm	USDA-SCS, 1981; Grant and Bailey, 1995

10.5 The score values

Among the indicators selected, the score values of C_{org} and MBC increased under the alternative land preparation methods as compared to the control (Table 10.4) while that of soil pH increased due to the use of BBF and GM only. In addition, BBF and GM increased the score values of AWC and AGG, respectively, while that of BD was depressed due to all the alternative land preparation methods. In other words, GM increased the score values of C_{org}, AGG and MBC, while BBF increased those of C_{org}, MBC, pH and AWC.

Table 10.4 Score values of soil quality indicators and additive soil quality index as affected by the land preparation methods

Land preparation methods	Corg	AGG	MBC	PH	Bd	AWC	Additive SQI	Std.
BBF	0.49	0.21	0.37	0.97	0.73	0.70	3.46	0.39
GM	0.56	0.30	0.39	0.95	0.71	0.64	3.55	0.35
RF	0.33	0.26	0.23	0.90	0.75	0.68	3.15	0.45
RT	0.46	0.24	0.31	0.89	0.71	0.62	3.24	0.74

10.6 Soil quality index

The land preparation methods did not significantly affect the overall soil quality. However, the study suggested that GM and BBF tended to increase SQI (Table 10.4). Consequently, the land preparation methods may be preferred for SQ in a decreasing order as ***GM≥ BBF≥ RT≥ RF***. The relative enhancement of SQ due to GM is linked mainly to its increased C_{org} content, which improved soil chemical, physical and biological quality (Chapter 9). Although it corresponds to the enhanced stability of the soil against soil erosion as portrayed by its reduced soil loss, this was not reflected in crop productivity in which GM gave the lowest cumulative relative productivity index (RPI) (Fig. 10.2). Generally there was a weak correlation between the SQI and the crop yield of 2003.

Corresponding to its highest RPI and economic performance, BBF showed the second highest SQI, while RT with its second highest RPI and economic benefit has increased SQI only slightly. The relative improvement in SQ under BBF despite its higher soil loss is linked to the superior performance of the lentils that increased the C_{org} content.

The weak correlation between the SQI and RPI is related, in part to the fact that SQI was developed based on the requirements of one crop (wheat), while RPI was based on three crops grown in rotation over six years. In addition, as crop performance is a function of multiple factors (like weather) in addition to SQ, the temporal and spatial variability and their interaction affected the relationship. Similarly, the correlation between the individual indicator scores and the SQI (determined during the cropping season of 2002) on the one hand, and crop yield of 2003 (tef) on the other was poor. The high SQI due to BBF contradicted its highest soil loss rate. This is because SQI was developed for crop productivity and not for resistance against soil erosion.

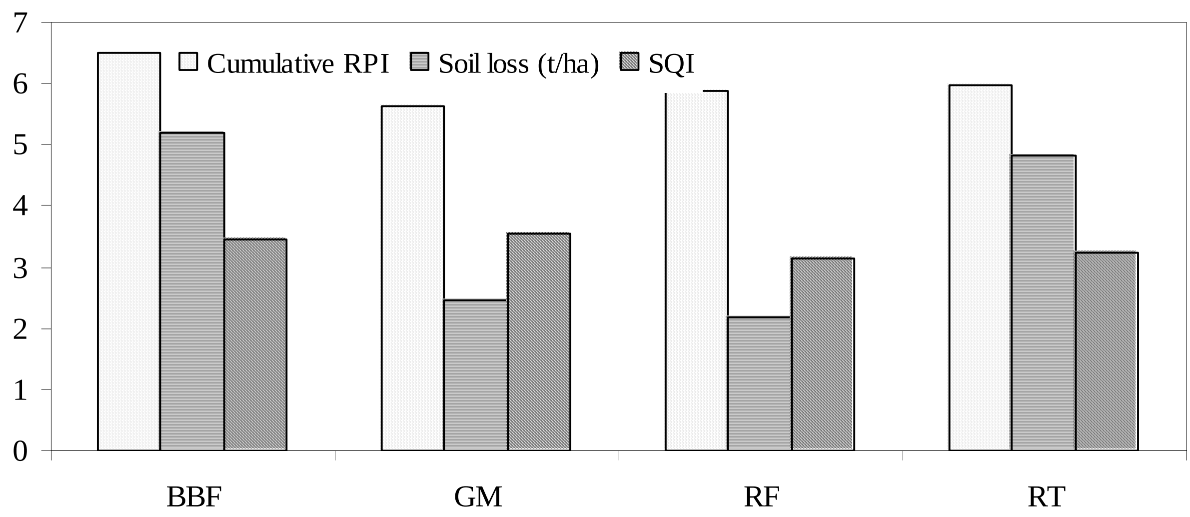

Fig. 10.2 Effect of the land preparation methods on crop productivity (RPI), soil loss and soil quality index

Considering the overall performance of the land preparation methods, the order of preference is **BBF≥RT≥RF=GM** (Table 10.5). However, as SQI was based on one-year data as opposed to the other performance indicators, which were based on several years' data, the trend needs to be confirmed through repeated measurement of SQI accommodating weather variations.

Table 10.5 Performance ranking of the land preparation methods with respect to some management goals (1 is good and 4 is bad)

Performance indicators	Rank in order of preference			
	BBF	GM	RF	RT
Crop productivity (RPI)	1	4	3	2
Profitability (Gross margin)	1	4	3	2
Soil quality index	2	1	4	3
Soil erosion	4	2	1	3
Overall	1	3	3	2

11 General discussion

11.1 The rationale of soil quality research

The rudimentary concept of SQ has been intuitively understood and used worldwide to improve soil management practices (Karlen *et al*., 2003), may be since antiquity. In its modern approach, however, research on SQ was initiated to address the multiple issues of environmental protection and food quality in industrialized countries and to increase agricultural productivity to tackle poverty and ensure food security and reduce land degradation in developing countries (Schjonning *et al.*, 2004). During the past decade, research and education programs on SQ have increased exponentially (Karlen *et al*., 2003).

Soil quality is the capacity of soil to function (Karlen *et al*., 1997). The capacity to function depends on the inherent properties, which is based on its genesis and the management driven dynamic changes occurring in these properties (Gajri *et al*., 2002). Soil quality assessment is aimed at monitoring the impacts of the management alternatives on the sustainable productivity of the resource and to support soil management decision systems. The existing methodologies for SQ assessment can be used to compare the effect of management systems on the same soil in space and time. Despite the gravity of environmental problems in developing countries, the awareness, concerns and efforts related to SQ issues is rather stronger in industrialised countries. Yet, it is believed especially important for the two billion people, who are malnourished, and for an equal number, who live below the poverty level in developing countries (Eswaran *et al*., 1999). For Ethiopia, which is characterized by abject poverty, land degradation and desertification, research and development efforts related to SQ and natural resources management need to be strengthened.

11.2 Land and soil quality issues in Ethiopia

The high and ever increasing human and livestock population in Ethiopia, especially in the highlands are escalating the environmental degradation. The human population which is currently estimated at 72 million and the livestock, which numbers the highest in Africa, depend on the natural resources for their basic needs. About 99% of the household energy in the country comes from biomass burning (World Bank, 1984; Cesen, 1986). Out of the 22.5 million tones of cattle manure and 21.2 million tones of crop residues produced annually, 38% and 24%, respectively, are used as fuel, while the remaining crop residue is used as feed. Deforestation is estimated at 150,000 to 200,000 ha per year for fuel, construction and expansion of crop land, posing a serious threat to the ecosystems (Zinabu, 1998).

Coupled with the rugged topography and high intensity rainfall, this poor management accelerates the rate of soil erosion. Studies indicate that, soil erosion affected 27 million ha of the highland areas, out of which 14 million ha are seriously eroded, with

2 million ha having reached a point of no return (FAO, 1984a). Moisture and plant nutrients storage capacity diminished due to decreased soil depth. Since access to agricultural inputs to substitute the nutrient loss is limited, and due to the soils physical, chemical and biological degradation, productivity of the land declines continuously (NCS, 1992, FAO, 1984a). The increased frequency of flooding and water quality deterioration, and failure to tolerate dry spells are manifestations of the reduced infiltration and storage capacity of the soil. Exasperated by the recurrent drought, the traditional balance between people, livestock and their habitat and the socioeconomic systems is fast crumbling.

11.3 Soil quality management and productivity

The primary objectives of SQ management vary depending on ecological and socio-economic circumstances. Soil quality management involves enhancement of soils productivity, while reducing the negative effects on the environment (Schjonning *et al*., 2004). This study evaluated alternative land preparation methods with respect to crop productivity, which is the priority soil function for the farmers in the area. In addition, the onsite and concomitant offsite environmental effects were considered. Soil quality can be assessed at various scales: plot, field, farm, watershed or regional levels. In this study a participatory on farm assessment at watershed level augmented the on station plot based experiment.

11.3.1 Participatory assessment

Regardless of the level of their operation, farmers are the ultimate decision makers regarding their land, at least in Ethiopia. Regrettably, their choices are often irrespective of the consequences. This calls for development of appropriate technologies which attract the farmers in favour of sustainable management. As farmers often take on technologies that fit into their aspiration, tradition and socio-cultural values, the development of appealing technologies can be achieved through their participation. This does not only make them generators of technologies which appropriately address their concerns, but also encourages researchers to learn from traditional knowledge and practices, which can be blended with scientific facts to yield robust technologies.

The study suggested that farmers in the area depend more on the inherent characteristics, although they recognize the role of management systems. Using these characteristics as indicators, they could not only classify their soils into quality groups, but also estimated their potential productivity, which was later confirmed by the yield data. Such expertises have been used for generations in land related decisions.

11.3.2 On station research

The dynamic SQ as affected by land preparation methods was considered in the on station experiment. Compared were three alternatives: Broad Bed and Furrows (BBF), Green Manure (GM) and Reduced Tillage (RT) with the traditional Ridge and Furrows (RF) as a control; setting crop productivity, economic profitability, and soil erosion and SQ as performance indicators.

11.3.2.1 Crop productivity and economic benefit

While undisputed conclusion requires longer time, the study showed a clear tendency. Accordingly, BBF enhanced the productivity of lentil both under the adverse and favourable conditions. Despite a reduced grain yield of wheat by 35%, the use of BBF for all the crops in the rotation increased profitability by 10%. This is attributed to the 59% increase of lentils grain yield, corroborating the previous reports in which BBF was recommended for lentil in the area (Abate and Saleem, 1992; DZARC, 1990). As lentil is the major protein source and cash crop in the area, this is quite substantial. For the 8 million ha of the highland Vertisols, this does not only increase crop yield but also enhances SQ due to the N-fixation, leading to reduced input cost.

The second highest grain yield for the six years was due to RT, which increased the yield of wheat and tef by 10% and 8%, respectively. This corroborates the report of Aberra (1992) who suggested that ploughing more than once might not be necessary for tef, if non-selective herbicides are applied. Apparently, tef is insensitive not only to surface drainage, but also to the type of seedbed or the changes in soil physical environment unlike wheat and lentils. This challenges the premise that tef requires well-pulverized and smooth seedbed (Ebba, 1969; National Research Council, 1996), a pre-text for high tillage frequency. Given the continued expansion of the area under tef (Seifu, 2000), in response to the huge local and emerging international demands, and the detrimental effects of traditional tef culture on SQ (Ebba, 1969; NRC, 1996; Teklu and Gezahegn, 2003), this has tremendous implications.

The number of oxen owned for tillage is a major indicator of farm households' wealth in the area, as it affects the plot size to be operated and thereby the households' income. Besides, as tillage is traditionally men's job, female farmers should either hire male, or resort to arrangements like share cropping or leasing out their plots to get lower benefit. Therefore, adopting RT does not only enhance agricultural sustainability due to reduced SQ degradation, but also narrows the disparity due to oxen ownership and gender status.

11.3.2.2 Runoff and soil erosion

Runoff was significantly affected such that, BBF and RT routed more water that is excess and thus enhanced the surface drainage. This explains the highest grain yield of lentils grown on BBF. However, the runoff under all the treatments accounted for more than 50% of the seasonal rainfall showing the potential of water harvesting for agriculture and domestic use.

Corresponding to the runoff, there was a non-significant tendency of increased soil and nutrient loss due to BBF. This is related to the alternate drying and wetting of the soil to produce crumbles of soil ready to be transported by runoff that follows the heavy rain storms that occur in the afternoons (Teklu *et al*., 1999). The effect may further soar with increased catchments size to initiate gulley, which is a major erosion process in Vertisols (Teklu and Selamyihun, 2001). The high nutrient and C_{org} enrichment of the sediments regardless of the treatments indicates SQ deterioration. This drawback is especially significant for the poor farmers who cannot afford substituting the nutrients through purchased inputs.

11.3.2.3 Soil quality indicators

The land preparation methods affected most of the soil physical quality indicators, but not statistically significant. Aggregate stability, compaction, crusting and infiltration were strongly affected; hence they are sensitive indicators in a short term. GM and RT enhanced the soil physical quality indicators; mainly due to their increased C_{org} contents. As they were not sensitive to the treatments, texture, bulk density and porosity were not good indicators. The effect on soil chemical attributes was not significant ($p \leq 0.05$), during the growing period. However, it was significant on several parameters after harvest, but inconsistent. This erratic response indicates the need of longer time experiment. Therefore, continued monitoring is necessary to trace the dynamics both over the growing and fallow periods.

Although the C_{org} and the MBC content of the soil were enhanced due to RT and GM, the increment of MBC was not proportional to that of the C_{org} content leading to low microbial quotient. The low microbial quotient despite the increased MBC may indicate aggradations of the SOM leading to a long term SQ improvement, although the SQ for the current use may not be necessarily higher. Contrastingly, the higher microbial quotient under RF despite its lower C_{org} may indicate long term SQ degradation. However, temporal comparison of the alternatives through repeated sampling is necessary to see the trends.

11.4 Scenarios analysis

The management goals should be prioritized before deciding which method to implement. Priority setting may assume various scenarios, ranging from the actual situation where multitudes of factors limit their implementation to a situation with reduced limitations and to conditions with no limitation, where all the alternatives can be optimally realized. On the other hand, the thread offs can be offset by combining the methods.

For their poverty status and the gloomy policy environment, the farmers are interested in practices with short term benefits. As none of the methods simultaneously maximized all the management goals, the sustainability goals should be combined with productivity. As none of the methods was essentially superior for all the crops due to the variability in the requirements of different crops, choosing a suitable method for each, instead of one method for all the crops may maximize the benefits.

Because of its highest lentils productivity, BBF gave the highest RPI and economic profitability. Despite its highest soil erosion rate, it resulted in the modest soil quality improvement. Therefore, the balance between the benefit due to increased productivity of lentils and the penalties incurred in terms of land degradation due to soil erosion needs further investigation.

Provided that SQ and erosion control are considered priority, GM with its highest SQI can be recommended, although its productivity and profitability was the poorest. Better methods of chopping and incorporating the green manure crops to reduce cost and to ensure faster decomposition may improve the performance of GM with respect to economic benefits.

Despite its lowest soil erosion rate, the performance of RF was the worst in terms of SQ, while its economic profitability was as poor as GM. Normally, accelerated soil erosion is a common phenomenon under RF on steep gradients, but detained in dead furrows on moderate slopes. As this result is deceiving, conclusions with respect to soil should be cautious.

There are various limitations which hinder the successful implementation of the individual alternatives or their combinations. The extent to which the limitations affect the implementation of the technologies depends on the capacity and willingness of the farmers to invest in soil management. However, as the issues of land degradation and SQ are concerns of ecological sustainability, it is more of public interest than of the individual farmers. Therefore, external technical and financial support is desirable to boost farmers' capacity and interest in favour of sustainable alternatives.

Given the current abject poverty and illiteracy of the farmers, and their short planning duration, ways of reducing the complexities and cost associated with the methods are desirable. Further, institutional and policy issues influencing agriculture and the natural resource management like: land use and land tenure policies, timely availability and cost of inputs, market for outputs and uncertainties like variation in weather deserve judicious consideration.

11.5 The soil management assessment framework

The Soil Management Assessment Framework (SMAF) as a tool for management effects on SQ (Andrews, 1998) was used with the aim of validating or testing it for the Vertisols in the Ethiopian highlands. The study suggested that SMAF is a promising tool in the area, provided that some refinements are made to accommodate the unique characteristics of the farming system. The suggested technical improvements include:

- defining the functional relationship between important SQ indicators (like soil crusting) and crop productivity
- fully defining the SQ requirements of unique crops like tef.

Further, SMAF needs to be built to comprehensively analyse SQ for various management goals. Components to scrutinize the issues related to runoff and soil erosion, air and water quality need to be incorporated. The scope and scale of its implementation, such as laboratory, green house, plot, field, watershed and regional levels deserve consideration. Moreover, consideration of the unique characteristics of the resource poor farming systems with traditional equipment in comparison with those of modern system with high input makes the tool more versatile.

12 Summary- Zusammenfassung

12.1 Summary

Land Preparation Methods and Soil Quality of a Vertisol in the Central Highlands of Ethiopia

The industrialization of agriculture led to societal concerns for environmental protection and food quality in developed countries. On the other hand, the need for increased agricultural productivity to address the persistent poverty and food insecurity in developing countries is intensified. Thus, improved management systems to meet the double objectives of increased productivity and sustained environmental quality are increasingly required. The assessment of soil quality and productivity are among the means of monitoring the various management systems to achieve the goals. Among the interrelated definitions formulated for soil quality, a committee established by Soil Science Society of America for the same purpose defined it as the capacity of soil to function within natural and managed ecosystem boundaries to sustain plant and animal productivity, maintain or enhance soil, water and air quality and support human health and habitation. The central idea in most of the definitions is the capacity of the soil to function.

The capacity of a soil to function depends on its inherent properties derived from its genesis and the dynamic properties resulting from the prevailing management systems. Most of the hitherto soil quality assessments considered agricultural production as the major management goal. As this study was conducted in the highlands of Ethiopia where food security remains a basic challenge, the primary management goal could not be different. Shortage and fragmentation of land driven by population pressure have become issues of concern in the area. With a continually dwindling national land-holding average of only one ha per household, farmers struggle to produce enough to feed their families. Since the possibility of expanding agricultural land is limited, increased production is realistic only from higher productivity per unit land per unit time.

Covering about 8 million ha, Vertisols are among the high potential soils, where significant increase in productivity is likely. However, their productivity is constrained by their physical and hydrological properties, manifested by their hardness when dry and their stickiness when wet, impeding land preparation. The traditional management systems led neither to increased productivity nor to enhanced soil quality. Thus, the need for alternative technologies is paramount.

Despite a concerted effort during the last two decades to develop improved technologies for the soils, land preparation for agricultural productivity and sustainability remains a major challenge. In addition to technical difficulties associated with their nature and deep-rooted poverty and illiteracy, lack of farmers' participation is believed to have hampered the development and adoption of robust technologies. The challenge facing the soil management research in Ethiopia is thus double fold: development of technologies that swiftly increase agricultural production and ensure judicious use of the land resources.

Farmers are the ultimate decision makers on their plots, at least in Ethiopia, often irrespective of the consequences of their decisions. Simple technologies are required to manipulate their decisions in favour of the desired goals. This requires development of technologies that fit into their aspiration, tradition and socio-cultural values with their participation in the generation and evaluation of the technologies.

This study was to identify alternative land preparation methods for increased productivity and economic profitability, while maintaining or enhancing the soil quality of the Vertisols. The hypothesis tested was that the alternative land preparation methods improve soil productivity and maintain or enhance soil quality. Three alternatives, Broad Bed and Furrow (BBF), Green Manure (GM) and Reduced Tillage (RT) with the traditional method, Ridge and Furrow (RF) were compared for 6 years, setting crop yield, economic profitability, and soil erosion and soil quality as performance indicators. This on station experiment was complemented by a participatory assessment at a small watershed scale. The objectives of the latter were identification of local soil functions, definition of soil quality concepts, and identification of soil quality indicators and evaluation of the soils for the major functions.

Land preparation methods influence soil functions through their effects on soils qualities. Among the soil physical quality indicators considered, GM increased aggregate stability and reduced surface crust strength due to its increased OM content and microbial activities. While RT led to least penetration resistance, infiltration, water-holding capacity, and moisture content were less sensitive to the treatments.

The chemical characteristics and plant nutrients response was not consistent indicating the need of longer time for the effects to show a clear trend. Organic carbon and MBC content of the soil increased due to RT and GM, but the increment was not proportional leading to lower microbial quotient. This indicates SOM build up with a long-term soil quality improvement.

The effect on runoff was inconsistent during the first three years (1998-2000), but BBF and RT slightly increased. In 2001 and 2002, BBF drained 67% and 54 %, respectively, of the seasonal rainfall as runoff while RT routed 61% and 53%. There is a non significant tendency of increased soil and nutrient losses from BBF and RT due to the increased runoff.

BBF significantly increased the grain yield of lentils by 59% (1.03 t ha^{-1} to 1.63 t ha^{-1}) compared to the control. Similarly, RT resulted in the highest grain yield of wheat (1.86 t ha^{-1}) and tef (1.34 t ha^{-1}). Economically, BBF is the most profitable option for lentils with 65% increase in total gross margin while RT resulted in 11% and 8% increase in gross margin of wheat and tef, respectively, as compared to the control.

The soil quality index was not significantly affected by the land preparation methods. Nevertheless, GM has shown a slight enhancement with the highest SQI, followed by BBF and RT. Thus, the land preparation methods are favoured in order of ***GM***$\geq$ ***BBF***$\geq$ ***RT***$\geq$ ***RF***, for soil quality. The relative enhancement of soil quality by GM was linked mainly to its increased C_{org} content.
The performance indicators (productivity, economic profitability, soil conservation and soil quality) are also affected differently. A matrix ranking of the effects on the indicators showed that none of treatments is superior for all the indicators. The average of the ranks (no weight attached) showed that BBF was the most favourable followed by RT. Therefore, the methods are preferred in the order of **BBF**$\geq$ ***RT***$\geq$***GM=RF*** considering the overall indicators. The superiority of BBF and RT corresponds to their productivity and economic benefits.
For soil quality and erosion control, GM is a favourable option. However, as its economic benefit was low, further improvement is required. In addition, lack of fast growing legumes tolerant to both shortage and excess water, failure of the short rain for planting, cost of chopping and incorporating the cover crops and the possible need of special equipment for incorporating may hinder its wider application and hence need further investigation.
The success of the alternatives depends on the farmers' capacity and willingness to invest. As the issues of soil quality and land degradation are more of societal concerns than of the individual farmers, external technical and financial incentives are desirable to enhance their capacity and to initiate their interest. Institutional and policy issues influencing agriculture and natural resource management and uncertainties like variation in weather deserve judicious consideration.

12.2 Zusammenfassung

Bodenbearbeitungsmaßnahmen und Bodenqualität auf einem Vertisol im zentralen Hochland von Äthiopien

Die Industrialisierung der Landwirtschaft hat in den Entwicklungsländern zu einer öffentlichen Besorgnis in Bezug auf den Umweltschutz und die Nahrungsmittelqualität geführt. Andererseits wächst die Notwendigkeit die landwirtschaftliche Produktivität zu steigern, um der andauernden Armut und Ernährungsunsicherheit zu begegnen. Daher bedarf es umso mehr verbesserter Anbausysteme, um beide Ziele, Steigerung der Produktivität und Erhaltung der Umweltqualität, zu sichern. Die Erfassung von Bodenqualität und Produktivität ist ein Instrument, um die Leistungsfähigkeit von unterschiedlichen Managementsystemen im Hinblick auf die Zielerreichung zu überprüfen.

Eine der mannigfaltigen Definitionen für Bodenqualität wurde von einem Kommittee der Soil Science Society of America aufgestellt. Danach ist Bodenqualität die Fähigkeit des Bodens sowohl in natürlichen als auch in bewirtschafteten Ökosystemen seine Funktionen zu erfüllen, welche sind: Pflanzen-und Tierproduktivität zu erhalten, Erhaltung oder Erhöhung von Boden- Wasser- und Luftqualität und Unterstützung der Gesundheit und des Wohnraums von Menschen.

Die Fähigkeit des Bodens seine Funktionen zu erfüllen hängt von seinen spezifischen Eigenschaften ab, die sich aus seiner Enstehung und den dynamischen Eigenschaften, die sich aus der Nutzung ergeben, ableiten. Die meisten der bisher gemachten Bodenqualitätserhebungen betrachteten die landwirtschaftliche Nutzung als Hauptnutzungsziel. In der vorliegenden Untersuchung im Hochland Äthiopiens, wo Ernährungssicherheit eine grundlegende Herausforderung ist, kann das primäre Nutzungsziel kein anderes sein.

Knappheit und Stückelung der Fläche, ausgelöst durch den Bevölkerungsdruck, sind zu den Hauptproblemen in diesem Gebiet geworden. Bei einer ständig abnehmenden mittleren Fläche von nur einem ha pro Familie (ein mittlerer Haushalt hat sieben Personen), müssen die Bauern darum kämpfen, genug Nahrungsmittel für ihre Familien zu produzieren. Da die Möglichkeiten der Ausdehnung der landwirtschaftlichen Nutzfläche begrenzt sind, ist eine Produktionssteigerung nur über eine höhere Flächenproduktivität zu realisieren.

Die Vertisole repräsentieren in dieser Region eine Fläche von 7,6 Mio Hektar und gehören zu jenen Böden mit hohem Ertragspotential, auf denen in dieser Region eine Erleichterung des Drucks auf die fragileren Böden durch signifikante Ertragsteigerungen möglich wäre. Jedoch ist deren Produktivität eingeschränkt durch ihre physikalischen und hydrologischen Eigenschaften, insbesondere ihre Härte bei Trockenheit und ihre Plastizität bei Sättigung, die eine Bodenbearbeitung erschweren. Die traditionellen Nutzungssysteme führten weder zu erhöhter Produktivität noch zu verbesserter Bodenqualität. Alternative Technologien sind deshalb von außerordentlicher Bedeutung.

Trotz konzertierter Anstrengungen während der letzten beiden Jahrzehnte verbesserte Technologien für die Böden zu entwickeln, bleibt eine auf hohe Produktivität und Nachhaltigkeit ausgerichtete Bodenbearbeitung die größte Herausforderung. Neben den technischen Schwierigkeiten, die mit der Natur der Böden zusammenhängen, der tiefen Armut und des Analphabetismus, wird die mangelnde Bereitschaft der Bauern zur Zusammenarbeit als Hemmschuh für die Entwicklung robuster Technologien angesehen. Das Bodenmanagement begegnet daher in Äthiopien einer zweifachen Herausforderung: Entwicklung von Technologien, die möglichst schnell die landwirtschaftliche Produktion erhöhen und gleichzeitig die sachgerechte Nutzung der Landressourcen sichern.

Bauern sind die letztendlichen Entscheidungsträger auf ihren Feldern. Allerdings, zumindest in Äthiopien, ohne Rücksicht auf die Konsequenzen. Einfache Technologien sind nötig, um ihre Entscheidungen zugunsten der gewünschten Ziele zu lenken. Oft adoptieren sie Methoden, die ihren Wünschen, Traditionen, soziokulturellen Werten sowie ihren primären Managementzielen entsprechen. Daher müssen sie an der Entwicklung und Bewertung neuer Technologien beteiligt werden.

Die vorliegende Untersuchung hatte zum Ziel, alternative Bodenbearbeitungsmethoden zu identifizieren, die in der Lage sind Produktivität des Bodens und ökonomische Rentabilität zu steigern und gleichzeitig die Bodenqualität der Vertisole zu erhalten bzw. zu erhöhen.

Es wurde die Hypothese getestet, dass die Bodenbearbeitungsmethoden die Produktivität des Bodens erhöhen und die Bodenqualität erhalten bzw. fördern. Drei Alternativen, Broad Bed and Furrow (BBF), Green Manure (GM) und Reduced Tillage (RT) wurden mit der traditionellen Methode (Ridge and Furrow RF) über sechs Jahre hinweg verglichen, wobei Pflanzenproduktivität, ökonomische Rentabilität, Bodenerosion und Bodenqualität als Indikatoren für die Zielerreichung gewählt wurden. Diese Untersuchung auf Feldebene, die auf einer Versuchsstation durchgeführt wurde, wurde ergänzt durch eine partizipative Erhebung auf der Einzugsgebietsebene. Die Ziele dieser Studie waren die Identifizierung von lokalen Bodenfunktionen, Definition von Bodenqualitätskonzepten, die Identifizierung von Bodenqualitätsindikatoren und die Bewertung der Böden in Bezug auf ihre Hauptfunktionen.

Bodenbearbeitungmethoden beeinflussen Bodenfunktionen durch ihre Auswirkungen auf die Bodeneigenschaften. Unter den bodenphysikalischen Indikatoren erhöhte GM die Aggregatstabilität und verminderte die Oberflächenverkrustung durch die Erhöhung des Gehalts an organischer Substanz und der mikrobiellen Aktivität. Andererseits führte RT zum geringsten Eindringwiderstand. Infiltration, Wasserhaltefähigkeit und Wassergehalt waren weniger sensitiv gegenüber den Behandlungen.

Die chemischen Eigenschaften und Pflanzennährstoffe reagierten nicht eindeutig. Längere Beobachtungszeiträume scheinen nötig, um klare Trends aufzuzeigen. Der Gehalt an organischem Kohlenstoff und mikrobieller Biomasse im Boden wurde durch RT und GM erhöht, allerdings waren die Zunahmen nicht proportional, so dass der mikrobielle Quotient kleiner wurde. Das deutet auf den Aufbau von organischer Bodensubstanz mit Langzeiteffekt hin.

Die Auswirkung auf den Oberflächenabfluss war nicht konsistent während der ersten drei Jahre (1998-2000), wurde aber durch BBF und RT leicht erhöht. In den Jahren 2001 und 2002 wurde in BBF 67 bzw. 54% des Niederschlags während der Vegetationsperiode als Oberflächenabfluss abgeführt, und bei RT 61 bzw. 53%. Es gab eine nicht signifikante Tendenz zu ansteigendem Boden- und Nährstoffverlust unter BBF und RT aufgrund eines erhöhten Oberflächenabflusses.

BBF erhöhte signifikant die Kornerträge von Linsen um 59% (von 1.03 auf 1.63 t ha^{-1} im Vergleich zur Kontrolle). Ähnlich verursachte RT den höchsten Kornertrag von Weizen (1.86 t ha^{-1}) und Tef (1.34 t ha^{-1}). Ökonomisch gesehen war BBF am rentabelsten für Linsen mit einer 65% igen Steigerung des Deckungsbeitrags während RT im Vergleich zur Kontrolle nur 11 und 8% höhere Deckungsbeiträge für Weizen und Tef lieferte.

Der Bodenqualitätsindex (SQI) wurde durch die Bodenbearbeitungsmethode nicht signfikant beeinträchtigt. Trotzdem zeigte GM den höchsten SQI gefolgt von BBF und RT. Daher ergibt sich für die Bewertung der Bodenbearbeitungsmaßnahmen in Bezug auf die Bodenqualität folgende Reihenfolge **GM>BBF>RT>RF**. Die relative Zunahme der Bodenqualität durch GM war hauptsächlich an die Erhöhung des Gehalts an C_{org} gebunden.

Die Güteindikatoren (Produktivität, Rentabilität, Bodenerhaltung und Bodenqualität) wurden unterschiedlich stark beeinträchtigt. Eine Rangfolgenmatrix der Auswirkungen auf die Bewertungsindikatoren zeigte, dass keine der Behandlungen sich für alle Indikatoren als die Beste erwies. Bildet man das Mittel der Rangfolgen (ohne Gewichtungsfaktoren) zeigt sich BBF als die günstigste Bodenbearbeitungsmethode, gefolgt von RT. Insgesamt ergibt sich, wenn man alle Indikatoren berücksichtigt, als Bewertungsrangfolge **BBF>RT>GM=RF**. Die Überlegenheit von BBF und RT entspricht ihrer höheren Produktivität und Rentabilität.

Bezüglich Bodenqualität und Erosionskontrolle ist GM die günstigste Alternative. Da jedoch ihr ökonomischer Verlust hoch war, sind weiter Verbesserungen dieser Technologie, wie Verminderung der technischen Komplexizität, der Kosten und den damit verbundenen Risiken nötig, um ihre Vorteile zu erhöhen. Zudem können folgende Probleme ihre weitere Verbreitung hindern: der Mangel an schnellwachsenden Leguminosen, die sowohl tolerant gegenüber Wasserüberschuß als auch Wassermangel sind, Ausfall der Frühregen zur Aussaat, die Kosten für das Abschlagen und Einarbeiten der Bodendecker und der eventuelle Bedarf an speziellen

Geräten für die Einarbeitung. Die Verbesserung dieser Technologie sollte daher Gegenstand weiterer Untersuchungen sein.
Der Erfolg der alternativen Bodenbearbeitungsmaßnahmen hängt von der Kapazität und Bereitschaft der Bauern zu Investitionen ab. Da in Äthiopien Bodenqualität und Landdegradierung eher für die Gesellschaft als für den einzelnen Bauern ein Grund zur Sorge sind, sollten externe technische und finanzielle Anreize in Erwägung gezogen werden, um die Kapazität der Bauern zu erhöhen und ihr Interesse zu wecken. Institutionelle und politische Aspekte, welche die Landwirtschaft und die Bewirtschaftung der natürlichen Ressourcen beeinflussen sowie andere Unsicherheiten, wie beispielsweise die Variabilität der Witterung, sollten nicht außer-acht gelassen werden.

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14 Acronyms

AASP	Atomic Absorption Spectrophotometer
ADLI	Agricultural Development Lead Industrialization
AGG	Aggregate stability
ANOVA	Analysis of Variance
AWC	Available Water Capacity
BBF	Broad Bed and Furrow
BD	Bulk density
CEC	Cation Exchange Capacity
C_{org}	Organic Carbon
CS	Nutrient/Organic Carbon content of the Sediments
CSo	Nutrient/ Organic Carbon content of the original Surface-soil
DAP	Di-Amonium Phosphate
DZARC	Debre Zeit Agricultural Research Centre
EARO	Ethiopian Agricultural Research Organization
EC	Electrical conductivity
EHRS	Ethiopian Highland Reclamation Studies
ER	Enrichment Ratio
FAO	Food and Agricultural Organisation of the United Nations
FC	Field Capacity
FGD	Focussed Group Discussion
GM	Green Manure
GPS	Global Positioning System
HI	Harvest Index
ICRISAT	International Crops Research Institute for the Semi-Arid Tropics
ILRI	International Livestock Research Institute
MBC	Microbial Biomass Carbon
MDS	Minimum Data Set
MRR	Marginal Rate of Return
OM	Organic Matter
PMN	Potentially Mineralisable Nitrogen
PRA	Participatory Rural Assessment
PWP	Permanent Wilting Point
ILCA	International Livestock Research Institute
RF	Ridge and Furrow
RPI	Relative Productivity Index
RT	Reduced Tillage
SAR	Sodium Absorption Ratio
Sc	Sediment concentration of runoff (g L^{-1})
SCRP	Soil Conservation Research Project
SIR	Substrate-induced respiration
SMAF	Soil Management Assessment Framework
SMB	Soil Microbial Biomass

SMBC	Soil Microbial Biomass Carbon
SOC	Soil Organic Carbon
SQ	Soil Quality
SQI	Soil Quality Institute
SSSA	Soil Science Society of America
UNEP	United Nations Environmental Program
UNEPGA	United Nations Environmental Program on Global Assessment
USDA	United States Department of Agriculture
NRCS	Natural Resources Conservation Service
WAS	Water Aggregate Stability
WCED	World Commission on Environment and Development
XRD	X-ray diffraction

15 Annexes

Annex 1 Some characteristics of transect 1at Caffee Doonsa in Ethiopian Highlands

Profile	Horizon	Depth (cm)	Texture	Gravel + Stone Vol. %	Soil colour		pH (H_2O)	$CaCO_3$ (%)	Field description	Crop	Rooting depth (cm)	Local name
					Moist Chroma/value	Description[c]						
1	Ap	-40	C	<1	7.5 YR 3/0	VDG	7.5	0.1	NK (<. 5%)	Chickpea	-	Abolse
	Ap2	-66	C	<1	7.5 YR 3/2	DB	8.0	1	SK (1-5%)			
	Ap3	-89	C	<1	7.5 YR 3/2	DB	8.0	0.5	VSK (0.5-1%)			
	Apk4	-100	SC	2-10	10 YR 3/2	VDGB	8.5	5	K (5-10%)			
2	Ap	-22	C	<1	7.5 YR 3/0	VDG	8.0	5	K (5-10%)	Chickpea	-	Abolse
	AB	-46	C	<1	7.5YR 3/0	VDG	8.0	1	SK (1-5%)			
	AB2	-66	C	2-10	7.5YR 3/0	VDG	8.5	5	K (5-10%)			
	BC	-87	SC	2-10	7.5YR 3/0	VDG	9.0	5	K (5-10%)			
3	Ap	-22	SLC	<1	10YR 3/1	VDG	8.0	1	SK (1-5%)	Chickpea	-	Abolse
	AB	-50	SLC	<1	2.5Y 3/0	VDG	8.5	1	SK (1-5%)			
	BC	-72	SLC	<1	7.5 YR 3/0	VDG	8.0	5	K (5-10%)			
	BC2	-100	SLC	<1	2.5Y 3/2	VDGB	9.0	5	K (5-10%)			
4	Ap	-30	SLC	<1	10YR 3/2	VDGB	8.0	5	K (5-10%)	Chickpea	2	Abolse
	Ap2	-57	SLC	2-10	10YR 3/1	VDG	9.0	5	K (5-10%)			
	AC	-83	SLC	2-10	7.5YR 3/0	VDG	9.0	5	K (5-10%)			
	C	-100	SLC	2-10	10YR 5/1	Grey	9.0	1	SK (1-5%)			
5	Ap	-31	SLC	2-10	7.5YR 4/0	DG	8.5	5	K (5-10%)	Wheat	26	Abolse
	Ap2	-59	SLC	<1	2.5Y 4/0	DG	9.0	5	K (5-10%)			
	AB	-86	SLC	2-10	7.5 YR 4/0	DG	9.0	1	SK (1-5%)			
	AB2	-100	SLC	<1	10 YR 3/1	VDG	9.0	1	SK (1-5%)			
6	Ap	-25	SLC	2-10	10YR 4/1	DG	7.5	5	K (5-10%)	Wheat	30	Carii
	Ap2	-47	SLC	<1	10YR 2/2	VDB	8.0	5	K (5-10%)			
	AC	-73	SLC	2-10	2.5Y 3/2	VDGB	9.0	5	K (5-10%)			
7	Ap	-30	SLC	2-10	10YR 3/1	VDG	8.5	5	K (5-10%)	Wheat	20	Carii
	Ap2	-53	SLC	2-10	10YR 3/2	VDGB	9.0	5	K (5-10%)			
	AC	-85	SLC	2-10	10YR 5/2	GB	9.0	5	K (5-10%)			
	AC2	-100	SLC	2-10	10YR 4/1	DG	9.0	5	K (5-10%)			
8	Ap	-30	SLC	2-10	10YR 3/1	VDG	8.0	1	SK (1-5%)	Wheat	25	Carii
	Ap2	-47	SLC	2-10	10YR 3/1	VDG	8.5	5	K (5-10%)			
	AC	-77	SLC	2-10	10YR 4/1	DG	8.5	5	K (5-10%)			
	AC2	-100	SLC	>10*	10YR 3/2	VDGB	9.0	5	K (5-10%)			
9	Ap	-30	C	2-10	10YR 3/1	VDG	7.5	5	K (5-10%)	Wheat		Abolse
	A	-45	C	2-10	10YR 3/2	VDGB	8.0	5	K (5-10%)			
	AC	-70	C	<1	10YR 3/3	DB	8.5	1	SK (1-5%)			
	C	-100	C	<1	10YR 4/6	DYB	9.0	0.5	VSCL (0.5-1%)			

Annex 1 continued

10	Ap	-30	SLC	2-10	10YR 3/1	VDG	8.0	1	SK (1-5%)	Wheat	30	Carii
	Ap2	-45	SLC	2-10	10YR 3/1	VDG	8.0	1	SK (1-5%)			
	Ap3	-75	C	2-10	10YR 4/2	DGB	9.0	1	SK (1-5%)			
	AC	-100	C	<1	10YR 3/3	DB	9.0	1	SK (1-5%)			
11	Ap	-40	SLC	<1	10YR 3/1	VDG	8.0	5	K (5-10%)	Chickpea	20	Abolse
	Ap2	-60	SLC	<1	10YR 3/1	VDG	9.0	5	K (5-10%)			
	AB	-82	SLC	<1	10YR 3/1	VDG	9.0	1	SK (1-5%)			
	AB2	-100	SLC	<1	10YR 4/1	DG	9.0	1	SK (1-5%)			
12	Ap	-34	C	2-10	10YR 3/1	VDG	8.0	1	SK (1-5%)	Fenugruk	40	Carii
	AC	-66	C	2-10	10YR 3/1	VDG	8.0	5	K (5-10%)			
	R	-80	Grav.	>80			9.0	5	K (5-10%)			
13	Ap	-21	SLC	2-10	10YR 4/1	DG	8.5	10	VK (>10%)	Fenugruk	34	Carii
	AC	-50	SLC	2-10	10YR 4/1	DG	9.0	5	K (5-10%)			
	C	-58	C	<1	10YR 3/1	VDG	9.0	5	K (5-10%)			
	R	-96	C	>70								
14	Ap	-30	C	2-10	10YR 4/1	DG	8.5	5	K (5-10%)	Wheat	55	Carii
	AB	-52	SLC	<1	10YR 3/2	VDGB	9.0	1	SK (1-5%)			
	AB2	-72	SLC	<1	10YR 5/3	Brown	9.0	1	SK (1-5%)			
	BC	-90	SLC	<1	10YR 5/4	YB	9.0	1	SK (1-5%)			
15	Ap	-30	SLC	<1	7.5YR 3/0	VDG	8.5	5	K (5-10%)	Lathyrus	45	Abolse
	Ap2	-50	C	<1	10YR 3/1	VDG	9.0	5	K (5-10%)			
	Ap3	-66	C	<1	10YR 4/1	DG	9.0	5	K (5-10%)			
	BC	-100	C	<1	10YR 3/2	VDGB	9.0	1	SK (1-5%)			
16	Ap	-30	C	2-10	10YR 3/1	VDG	8.0	5	K (5-10%)	Wheat	38	Abolse
	AB	-52	C	<1	10YR 3/1	VDG	8.5	1	SK (1-5%)			
	AB2	-74	C	<1	10YR 3/1	VDG	9.0	1	SK (1-5%)			
	ACk	-100	C	2-10	10YR 3/1	VDG	9.0	5	K (5-10%)			
17	Ap	-28	SLC	<1	2.5Y 3/0	VDG	8.5	5	K (5-10%)	Wheat	60	Kooticha
	AB	-54	SLC	<1	2.5Y 3/0	VDG	9.0	1	SK (1-5%)			
	AB2	-72	C	<1	2.5Y 3/2	VDGB	9.0	1	SK (1-5%)			
	AB3	-100	C	<1	10YR 3/2	VDGB	9.0	1	SK (1-5%)			
18	Ap	-30	C	<1	7.5YR 3/0	VDG	8.5	1	SK (1-5%)	Wheat	65	Kooticha
	Ap2	-49	C	<1	7.5YR 3/0	VDG	9.0	1	SK (1-5%)			
	Ap3	-72	C	<1	7.5YR 3/0	VDG	9.0	5	K (5-10%)			
	Ap4	-100	C	<1	7.5YR 3/0	VDG	9.0	1	SK (1-5%)			

* C, SLC, SC, SCL represent Clay, Silty Clay and Sandy Clay, Sandy clay loam, slightly calcareous, respectively.

**NK, VSK, K, SKL, VK represent not calcareous, very slightly calcareous, calcareous, slightly calcareous and very calcareous, respectively.

[c] DG= dark grey, GB = Grey brown, DYB = Dark yellowish brown, YB = Yellowish brown, VDG = Very dark grey, DB = Dark brown, VDGB = Very dark grey brown, VDB = Very dark brown, LGB = Light grey brown, LOB = Light olive brown, PB = Pale Brown.

Annex 2. Some characteristics of transect 2

Profile	Horizon	Depth (cm)	Texture *	Gravel + Stone Vol. %	Soil colour Moist Chroma	Description	pH (H2O)	CaCO3 (%)	Field description**	Land use	Crop	Rooting depth (cm)	Slope
1	Ap	-36	C	<1	7.5YR 3/0	VDG	7.0	1	SK (1-5%)	Cultivated	Wheat	77	Flat
	Ap2	-54	C	<1	7.5YR 3/0	VDG	7.5	1	SK (1-5%)				
	Ap3	-77	C	<1	10YR 3/1	VDG	8.0	1	SK (1-5%)				
	Ap4	-100	C	<1	2.5Y 3/0	VDG	7.0	1	SK (1-5%)				
2	Ap	-30	C	<1	10YR 3/1	VDG	7.0	1	SK (1-5%)	Cultivated	Wheat	40	Gentle
	Ap2	-46	C	<1	10YR 3/1	VDG	7.5	1	SK (1-5%)				
	Ap3	-84	C	<1	7.5YR 3/0	VDG	8.5	1	SK (1-5%)				
	Ap4	-100	C	<1	7.5YR 3/0	VDG	8.5	1	SK (1-5%)				
3	Ap	-36	SLC	2-10	2.5Y 3/0	VDG	7.5	1	SK (1-5%)	Cultivated	Wheat	55	Moderate
	Ap2	-62	SLC	2-10	10YR 3/1	VDG	8.0	5	K (5-10%)				
	AB	-82	C	2-10	10YR 6/2	LBG	9.0	5	K (5-10%)				
	AC	-100	C	<1	10YR 6/3	PB	9.0	5	K (5-10%)				
4	Ap	-34	SLC	<1	2.5Y 4/0	DG	7.0	1	SK (1-5%)	Cultivated	Wheat	34	Moderate
	Ap2	-66	C	<1	2.5Y 4/0	DG	8.0	1	SK (1-5%)				
	Ap3	-100	C	<1	2.5Y 3/0	VDG	9.0	1	SK (1-5%)				
5	Ap	- 28	SLC	2-10	10YR 3/1	VDG	8.0	10	VK (>10%)	Cultivated	Wheat	74	Moderate
	Ap2k	-56	SLC	<1	10YR 3/1	VDG	9.0	10	VK (>10%)				
	Ap3k	-88	SLC	<1	10YR 3/2	VDGB	9.0	10	VK (>10%)				
	B	-100	SLC	<1	10YR 2/2	VDB	9.0	1	SK (1-5%)				
6	Ap	-30	SLC	<1	10YR 3/2	VDGB	9.0	5	K (5-10%)	Cultivated	Wheat	75	Depression
	AB	-51	SLC	<1	2.5Y 3/2	VDG	9.0	1	SK (1-5%)				
	BC	-76	SC	<1	2.5Y 5/4	LOB	9.0	1	SK (1-5%)				
	BC2	-90	SC	<1	2.5Y 7/2	LG	8.5	1	SK (1-5%)				
7	Ap	-30	SLC	<1	10YR 5/1	Grey	8.5	5	K (5-10%)	Cultivated	Lentil	73	Steep
	AB	-50	SLC	<1	10YR 5/1	Grey	9.0	1	SK (1-5%)				
	AB2	-70	SLC	<1	10YR 4/1	DG	9.0	1	SK (1-5%)				
	BC	-100	SLC	<1	10YR 4/2	DGB	9.0	1	SK (1-5%)				
8	Apk	-30	SLC	2-10	10YR 5/2	GB	9.0	10	VK (>10%)	Fallow land	Grass	65	V. Steep
	Ap2	-53	SLC	<1	10YR 6/2	LGB	9.0	5	K (5-10%)				
	AB	-85	SLC	<1	10YR 5/3	Brown	9.0	1	SK (1-5%)				
9	Ap	-35	SLC	<1	7.5YR 4/0	DG	8.0	5	K (5-10%)	Cultivated	Lentil	75	Steep
	AB	-54	SLC	<1	7.5YR 4/0	DG	8.5	1	SK (1-5%)				
	AB2k	-77	SLC	<1	7.5YR 4/0	DG	9.0	5	K (5-10%)				
	BC	-100	C	<1	2.5Y 5/2	GB	9.0	1	SK (1-5%)				

Annex 2 continued

10	Ap	-30	SLC	<1	10YR 4/1	DG	9.0	5	K (5-10%)	Cultivated	Chickpea	24	Flat
	AB	-75	SLC	<1	10YR 3/1	VDG	9.0	1	SK (1-5%)				
	AB2	-100	C	2-10	10YR 5/2	GB	9.0	1	SK (1-5%)				
11	Ap	-40	SLC	<1	10YR 4/1	DG	8.5	5	K (5-10%)	Cultivated	Wheat	55	Steep
	AB	-70	SLC	<1	10YR 4/1	DG	9.0	1	SK (1-5%)				
	AB2	-90	C	2-10	10YR 4/1	DG	9.0	1	SK (1-5%)				
12	Ap	-28	C	<1	10YR 4/1	DG	8.5	1	SK (1-5%)	Cultivated	Wheat	70	Moderate
	Ap2	-50	C	2-10	10YR 4/1	DG	9.0	5	K (5-10%)				
	B	-80	C	<1	10YR 3/1	VDG	9.0	1	SK (1-5%)				
	CR	-100	C	>10	10YR 5/1	Grey	9.0	1	SK (1-5%)				
13	Ap	-23	SLC	<1	10YR 4/1	DG	8.0	1	SK (1-5%)	Cultivated	Wheat	67	Moderate
	Ap2	-46	SLC	<1	10YR 4/1	DG	9.0	1	SK (1-5%)				
	Ap3	-67	SLC	2-10	10YR 3/1	VDG	9.0	1	SK (1-5%)				
	Ap4	-100	C	<1	10YR 3/1	VDG	9.0	1	SK (1-5%)				

Annex 3 Total element content of the soils

Soil type	Profile depth (cm)	Content (%)							Content (mg. kg^{-1})			
		Na	Mg	Al	Si	K	Ca	Fe	P	Ti	Mn	Zr
Carii	-40	0.38	1.81	8.38	27.48	1.44	4.55	6.92	336	9648	1515	397
	-80	0.34	1.66	8.12	27.03	1.36	4.88	7.24	285	9781	1450	407
	-100	0.40	1.44	9.54	27.79	1.41	2.49	7.40	290	11658	1666	481
	-125	0.29	1.57	8.71	27.44	1.32	4.01	7.14	256	10512	1453	441
Abolse	-40	0.44	1.50	8.66	28.53	1.38	2.41	6.68	253	11046	2065	459
	-70	0.34	1.61	8.50	28.00	1.41	3.89	6.87	288	10136	1827	411
	-100	0.34	1.58	8.30	27.75	1.36	3.90	6.75	259	10073	1838	413
	-125	0.30	1.69	8.45	27.54	1.25	4.58	6.83	251	9944	1453	407
Kooticha	-40	0.37	1.41	8.25	27.75	1.35	3.34	6.56	249	10694	2014	442
	-80	0.35	1.47	8.40	28.01	1.41	3.51	6.90	278	10341	2193	416
	-120	0.37	1.47	8.54	28.29	1.37	2.57	6.72	245	10956	1695	457
	-150	0.37	1.46	8.63	28.37	1.39	2.21	6.62	245	11025	1680	456

Annex 4 Total element content of the soils in oxide forms

Soil type	Profile depth (cm)	Content (%)										
		Na_2O	MgO	P_2O_5	Al_2O_3	SiO_2	K_2O	CaO	TiO_2	MnO	Fe_2O_3	ZrO_2
Carii	-40	0.51	3.00	0.08	15.84	58.78	1.73	6.36	1.61	0.20	9.89	0.05
	-80	0.46	2.76	0.07	15.35	57.83	1.63	6.82	1.63	0.19	10.35	0.06
	-100	0.54	2.39	0.07	18.03	59.44	1.70	3.48	1.94	0.22	10.58	0.06
	-125	0.40	2.61	0.06	16.46	58.68	1.59	5.62	1.75	0.19	10.21	0.06
Abolse	-40	0.60	2.49	0.06	16.36	61.03	1.66	3.37	1.84	0.27	9.54	0.06
	-70	0.46	2.67	0.07	16.05	59.90	1.70	5.45	1.69	0.24	9.83	0.06
	-100	0.60	2.62	0.06	15.68	59.36	1.64	5.46	1.68	0.24	9.65	0.06
	-125	0.41	2.79	0.06	15.98	58.92	1.51	6.41	1.66	0.19	9.77	0.05
Kooticha	-40	0.50	2.34	0.06	15.58	59.35	1.62	4.67	1.78	0.26	9.37	0.06
	-80	0.47	2.44	0.06	15.88	59.92	1.70	4.92	1.73	0.28	9.87	0.06
	-120	0.50	2.43	0.06	16.14	60.52	1.66	3.59	1.83	0.22	9.61	0.06
	-150	0.50	2.42	0.06	16.32	60.69	1.67	3.09	1.84	0.22	9.47	0.06

Annex 5 Effect of land preparation methods on agronomic parameters

Land preparation methods	1998 (Wheat)				1999 (Lentil)					2000 (Tef)		
	DH	DM	NTP	PLH	DH	DM	NTP	PLH	DH	DM	NTP	PLH
BBF	75^{a}	116^{b}	2	78^{c}	55^{C}	125^{a}	7.3^{a}	41	68^{ab}	125^{a}	7.3^{a}	41
GM	73^{b}	118^{b}	2	97^{ab}	68^{a}	120^{b}	4.3^{c}	38	68^{ab}	120^{b}	4.3^{c}	38
RF	70^{c}	122^{a}	3	107^{a}	65^{b}	118^{b}	6.3^{ab}	38	69^{a}	118^{b}	6.3^{ab}	38
RT	72^{b}	118^{b}	3	94^{b}	67^{ab}	118^{b}	5.7^{bc}	39	67^{b}	118^{b}	5.7^{bc}	39
CV (%)	1.2	0.88	21	5.2	1. 5	1. 8	13. 1	6.0	1.0	1. 8	13. 1	6.0
LSD (5%)	1.79	2. 08	NS	9.76	1.97	4.22	1.63	NS	1.37	4.22	1.63	NS
Rain fall (mm)*	541				767					908		
Remark on rainfall data	Shortage				Recorded only July to December					Normal		

Annex 5 continued

Land preparation methods	2001(Wheat)			2002 (Lentil)				2003 (Tef)			
	DM	NTP	PLH	DH	DM	NTP	PLH	DH	DM	NTP	PLH
BBF	130	5.3^{a}	75	67^{b}	117	4.3^{a}	107^{a}	74.7^{b}	132.3	5.7	78^{ab}
GM	130	5.3^{a}	73	69^{ab}	119	3.7^{ab}	99^{bc}	76.0^{a}	132.0	6.0	75^{b}
RF	131	4.0^{b}	73	70^{a}	115	4.3^{a}	106^{ab}	76.0^{a}	132.3	6.7	80^{b}
RT	130	5.0^{ab}	73	68^{ab}	115	3.3^{b}	98^{c}	75.7^{ab}	132.7	5.7	78^{ab}
CV (%)	0.5	13.6	7.6	1.8	1.6	12.8	4.0	0.8	1.5	19.3	3.0
LSD (5%)	1.37	1.33	NS	2.49	NS	1.0	6.4	1.0	NS	NS	4.0
Rainfall (mm)*	1051			702				na			
Remark on rainfall data	Excess			Shortage and irregular distribution							

DH = Days to heading; DM = Days to maturity, PLH = Plant height (cm), NTP = Number of tillers per plant.

Means in the same column followed by the same letter are not statistically significant at 5%, NS = not significant, na = data not available, *Rainfall data is for the growing period.

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