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Sustainable Dryland Smallholder Farming in Sub-Saharan Africa

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Abstract: The African smallholder farmer faces a bleak future unless some basic trends can be reversed. While the West seems to be moving philosophically towards more organically based low input agricultural systems, we suggest that if Africa adopts similar policies, the results will be an even bigger disaster than is currently the case. What is clear from this review is that there is no single method of soil and water management that will fit all circumstances to achieve sustainable agricultural production at the small holder level in sub-Saharan Africa. Each technology/option has advantages and limitations, depending on the biophysical (soil and rainfall) resources, crops grown, availability of crop residues and manures, farmer resources, and farmers' diverse and complex criteria for decision making. However, significant increases in crop yields will only occur when improved conservation practices, like conservation tillage, are combined with improved soil fertility management (both organic and inorganic), and effective weed management. The more recent research results also indicate that the performance of soil and water management technologies is highly dependent, not only on an extreme variability of the soil's natural potential, but even more on the management capacity of farmers themselves. Unless smallholder farmers themselves help develop the understanding and skills required to manage their land in a way, which combines production and conservation, the potential impact of all this knowledge and research will remain unfulfilled. This insight sets the stage for the future focus of research and extension into sustainable agriculture, not only in southern Africa, but in all developing areas of the world.

Key words: Soil and water management, sustainable agriculture, farmer resources, crop yields, conservation tillage, soil fertility, weed management.

Over the past 40 years, the world's agricultural systems have been changing in response to population pressures (Waterlow *et al.*,1998). Slash and burn systems (up to 20 to 25 year rotations) have been proressively replaced by bush fallows (up to a 6 to 10 year rotations), which have, in turn, been replaced by short fallows (1 to 2 years), annual cropping and even multi-cropping with irrigation. Population growth and local economics are driving both the intensification of agriculture and its extensification into marginal lands, where risks of crop failure and environmental degradation are high.

Much of this land which is being brought into agricultural production is in harsh, water scarce semi-arid regions (FAO, 1996) and is farmed by resource-poor, subsistence farmers who endeavour to feed their families from one harvest to the next, and to produce enough surpluses to provide cash for school fees, clothing and other necessities. With the exception of cotton and some oilseed crops such as sunflowers, few commercial crops only can be grown profitably on semi-arid, rain-fed land. A typical semi-arid cropping enterprise is based on a farming family unit cultivating an average of 1 to 5 ha using family labor, often with draught animal inputs. Livestock are grazed on an extensive basis with little differentiation between land uses, except during the cropping season when livestock are excluded from cropped fields. The prevailing crop and soil husbandry are often inappropriate as they are 'imported' from higher potential areas.

Smallholder farmers operating in these harsh marginal semi-arid regions have to juggle multiple objectives that minimize risk and maximize returns with a heterogeneous set of resources (land, labor, draught power availability, cash) and little surplus money to invest in new technologies. As Lal (1987) points out, 'subsistence farmers, who face famine, would consider a successful technology to be one that produces some yield in the worst year rather than one that produces high yields in the best'. Although most farmers are conscious of the quality and limitation of their natural resource base, it is generally of minor concern to the farmers, largely because of a lack of capital (financial and human) to implement any technological intervention that could increase productivity. Unfortunately, much of the available technology, with the exception of improved crop varieties, has had little to offer to the smallholder farmer (Dixon *et al.*, 1989). Experience has shown that technologies which increase labor and draught power requirements, or require more than a minimum of capital input, will be rejected by most smallholder farmers

Shifting the focus from increased agricultural productivity, *per se*, to the development of sustainable production systems and improved rural livelihoods has a history of less than 10 years. If sustainable agriculture is to become a reality, far greater emphasis must be given to an effective combination of farmers' traditional knowledge with contributions from science (Table 1). Crops can be grown in different ways and farmers are continually innovating in response to many different factors and, therefore, farming systems are continually evolving. Unfortunately, communication between researchers and farmers is still very poor and the situation is aggravated because the extension service, the principal link between research and practical farming, has declined in many countries through a lack of money. However, in recent years, scientists have begun to try to understand the true dynamic nature of farmer innovations and this has led to a number of initiatives to learn from and build upon the farmers' traditions (Reij *et al.*,1996; Briggs *et al.*,1998).

Given well adapted crop genotypes, the absence of disease and freedom from significant pests which are not considered in this review, six external factors contribute to the growth of most crop plants. These are (i) physical/mechanical support, (ii) light, (iii) air, (iv) heat, (v) water (moisture) and (vi) nutrients. With the exception of light, the soil plays a major role in supplying

Table 1. Characteristics of indigenous soil and water management and introduced technologies for sustainable smallholder agriculture

Indigenous technologies	Introduced technologies
Integration of soil fertility enhancing, soil moisture and soil conserving techniques	Often specific to a single requirement
Integral component of land management and cropping systems	New management techniques may be required
Limited loss of land	Up to 20% of land area lost for cropping
Flexible	Inflexible
Low cost using existing materials and tools	Higher cost, additional tools
Provide an immediate payback	Often require an initial investment, annual maintenance with indeterminate benefits occurring over a long period
Can be labor intensive with gender specific activities, but flexibility allows use of labor at off-peak periods	Usually labor intensive with demand coinciding with existing labor peak

each of these external factors. Thus, in developing sustainable farming systems for resource-poor farmers, it is essential to have an understanding of the relevant soil properties and processes (biophysical and socio-economic) which determine the supply of these external factors. It is necessary to maintain and/or improve the soil conditions so that the supply of these factors is compatible with plant growth. The full range of the components for a sustainable soil management system for crop production in the semi-arid tropics at the smallholder level are summarised in Table 2. This review looks at the current status and some of the current thinking on soil and water management in southern Africa.

Southern Africa: An Overview

Figure 1 shows the political and economic boundaries of sub-Saharan Africa. The fourteen member states of the Southern African Development Community (SADC) cover an area of 9.3 million sq. km (29% of Africa), and are characterised by a wide diversity of fragile and contrasting ecosystems, from the readily eroded well-watered highlands, through dry, increasingly deforested savannah woodlands of Malawi, Mozambique, Tanzania, Zambia and Zimbabwe, to the deserts of Namibia and Botswana. The largest land area, Democratic Republic of Congo (2.3 million sq. km), has only 3.5% arable land, whereas smaller countries such as Malawi (0.13 million sq. km), Swaziland (0.017 million sq. km) and Lesotho (0.03 million sq. km) have 24.0, 11.6 and 9.6%, respectively, as is shown in Table 3 (FAO, 1996). Although the majority of the populations in the region are rural based and dependent upon subsistence agriculture for their livelihoods, less than 30% of the population is actually active in agriculture, a very similar scenario to India (Table 3).

Climate

Except for the extreme north and some highland areas, the climate of this region is characterised by a unimodal rainy season from October/November to March (Fig. 2), followed by a long dry spell in the winter, conforming with the ideal for a tropical semi-arid environment, locally tempered by

Table 2. Example of a sustainable soil management systems for the semi-arid tropics (Modified from a Table by Greenland et al., 1998)

Components of a sustainable agricultural system	Role
Training and extension	• To understand current practices/traditional skills and knowledge • To identify where an intervention might fit in current systems • To work with rural communities in the identification and development of interventions • To develop capacity of rural communities to resolve problems of production and supply • To work with rural communities in the identification and development of interventions • To develop capacity of rural communities to resolve problems of production and supply
Animals	• Assist in the transfer of nutrients • Provide manures • Provide food and income • Provide source of draught power
Fertilisers	• To increase yields • To replace nutrients lost due to off-farm sales
Grassed contour strips, hedgerows or contour bunds, green manures, cover crops	• To control erosion • To provide animal feeds • To provide mulch and compost materials • To provide fuel wood • To provide building materials
Tree wind-breaks	• To control erosion by wind • To provide a source of fuel wood • To provide building materials • To provide animal feeds • To provide mulch and composting materials
Irrigation and drainage	• To supplement rainfall • To avoid salinity and waterlogging
Rural shops and artisans	• To ensure supply of inputs to the farmer • To ensure supply and maintenance of implements
Rural markets	• To provide outlets, source of income and credit for farmers

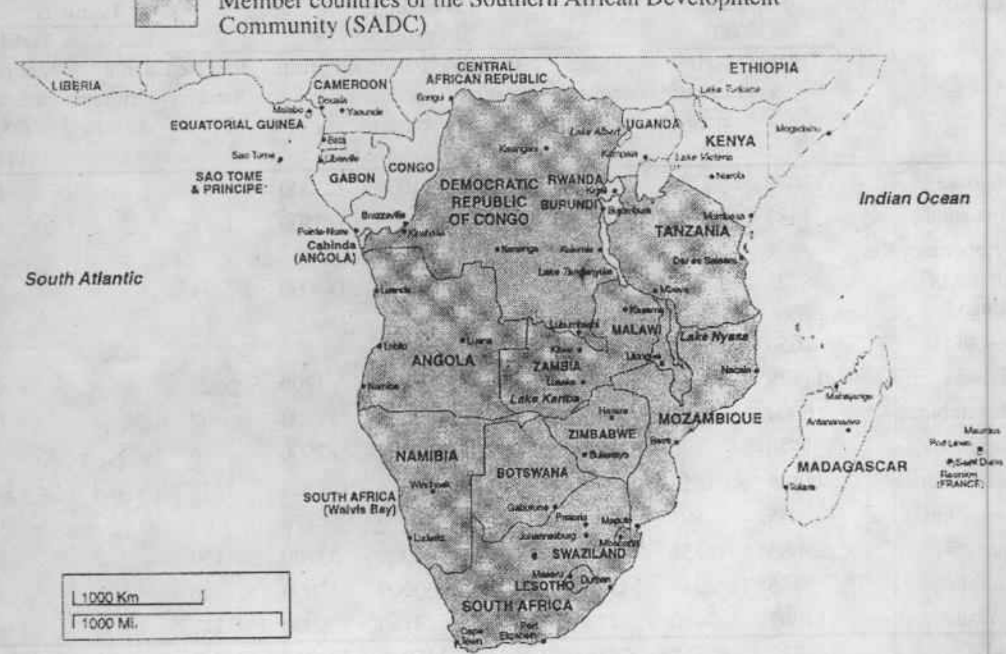

Fig. 1. Political and economic boundaries of sub-Saharan Africa.

altitude (Arnon, 1972). Consequently, most of the farming in the region is rainfed, with countries bordering the Indian Ocean receiving higher rainfall than those on the Atlantic seaboard. For example, annual rainfall on the Atlantic seaboard ranges from 100 mm on the coast of Namibia to 640 mm in the east of Angola, compared to Tanzania, where annual rainfall ranges from 500 to more than 2000 mm per year on the shores of Lake Malawi. In addition to the differences in annual rainfall across the region, total rainfalls are erratic and highly variable in both space and time, especially at the beginning and middle of the wet season, when it tends to occur as intense storms of short duration. Distribution and reliability are, therefore, more important considerations than total rainfall. This can lead to fairly severe, prolonged dry spells within the growing season, leading to crop water stress, the formation of crusts and seals on the soil surface, which can seriously inhibit the emergence of seedlings, reduce infiltration and increase the incidence of runoff and hence erosion (Hoogmoed, 1995).

Soils

The diversity of topography and soils in the region is so great that it is impossible to generalise (Thomas, 1994). They range from the dense Luvisols of Botswana, with bulk densities in excess of 1.8 Mg m^{-3} that limit both infiltration and root penetration (Willcocks, 1981), to significant areas of the self-loosening Vertisols found in

Table 3. Population, land usage and inorganic fertilizer inputs for the SADC region and India

Country	Population ('000)		Land area ('000)					Fertilizer	
	Total	Active in agriculture	Arable crops	Permanent crops	Permanent pasture	Forests	Irrigated land	Inorganic fertilizer (kg/ha)	Fertilizer production ('000 MT)
Angola	11072	3784	3000	500	54000	23000	75	–	0
Botswana	1487	258	420	0	25600	26500	1	1	0
Democratic Republic of Congo	46723	12174	7280	620	15000	173000	11	–	0
Lesotho	2050	329	320	0	2000	–	3	–	0
Malwai	11129	4682	1670	30	1840	3700	28	–	0
Mozambique	16004	6831	2950	230	44000	17300	107	1	0
Namibia	1540	290	660	2	38000	12500	6	–	0
South Africa	41465	1857	12365	814	81378	8200	1270	64	831
Swaziland	855	107	187	4	1070	120	67	–	0
Tanzania	29685	12731	3000	500	35000	33700	150	8	0
Zambia	9456	2944	5265	8	30000	32000	46	16	3
Zimbabwe	11261	3480	2750	128	17150	8900	117	45	136
SADC	182727	49467	39867	2836	345038	338920	1881	28	970
India	935744	249140	166100	3550	11400	68500	48000	62	10501

Zimbabwe, Malawi, Tanzania and Zambia. Many of the soils are commonly sandy in texture, poorly buffered and acidic, with few weatherable minerals, which require careful management if desired productivity levels are to be achieved on a sustainable basis (FAO, 1977; Anderson *et al.*, 1993; Rowland, 1993). The current rate of fertiliser use throughout Africa is estimated at 8.5 kg ha^{-1}, with many countries in the SADC region using less (Table 3), which, in effect, means their soils are being mined of nutrients.

Regional Constraints to Sustainability

Poverty in the region

Although the percentage of the total world population living in poverty has been reduced over the past three decades, partly because of the adoption of new agricultural technologies, rural poverty remains unacceptably high with numbers living in absolute poverty continuing to grow (1.3 billion people living on less than US$1 per day). Jazairy *et al.* (1992) identified the poor as being largely smallholders, landless, nomadic pastoralists, ethnic minorities, fisher-folk, refugees and households headed by women. In Africa the poor are largely smallholders. These include minor ethnic groups, refugees and households headed by single women, with highest incidences of poverty being in regions of low resource endowments, high land degradation and political conflict. Rural poverty has been created and perpetuated

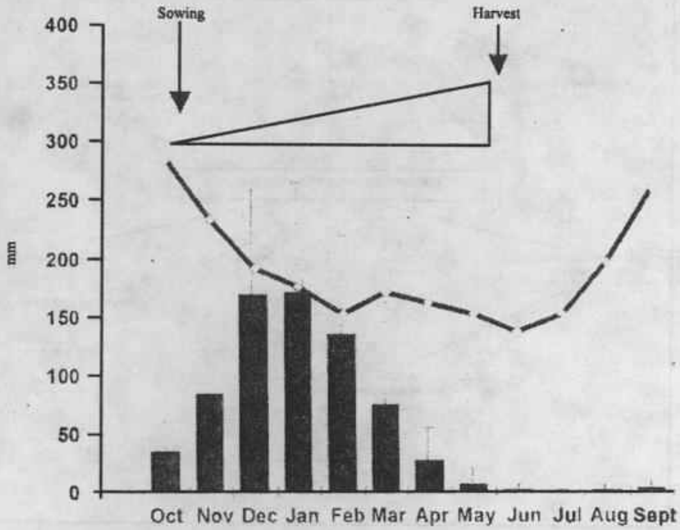

Fig. 2. Schematic crop production calendar for semi-arid Zimbabwe (▌ monthly rainfall; ◇ open pan evaporation; T rainfall standard deviation).

by a number of closely interlinked socio-economic problems and processes, which combine to have impact on the environment (Fig. 3), resulting in land degradation, productivity decline and further poverty.

Traditional systems are thought to be generally sustainable under conditions of low population pressure and lack of outside influences, with productivity geared towards subsistence. In these circumstances, production and conservation are adapted to the limits and potential of the natural resource base. Resource management systems focus on resource regeneration, recycling and conservation. Through farmer experimentation (trial and error), low-cost practices are evolved. Such systems are sustainable until change occurs at too fast a rate. Increases in internal and external demands often force intensification, whereupon rapid growth, without adequate conservation, degrades the resource base. Sustainable intensification requires protection against soil erosion, moisture conservation and maintenance of soil fertility. Households which do not follow sustainable practices will, in the long term, suffer increased poverty. There is no simple solution such as low input agriculture or increased local participation. A combination of innovative approaches is required (Ellis-Jones and Mason, 1999).

Innovation can evolve indigenously or result from external intervention. Well- documented examples of such transformations include the Machakos in .Kenya (Tiffen *et al.*, 1994) and community forestry management in various countries (Jackson *et al.*, 1998). Surveys on the use of indigenous technologies (Critchley *et al.*, 1994; Reij *et al.*, 1996), as well as more detailed investigations on

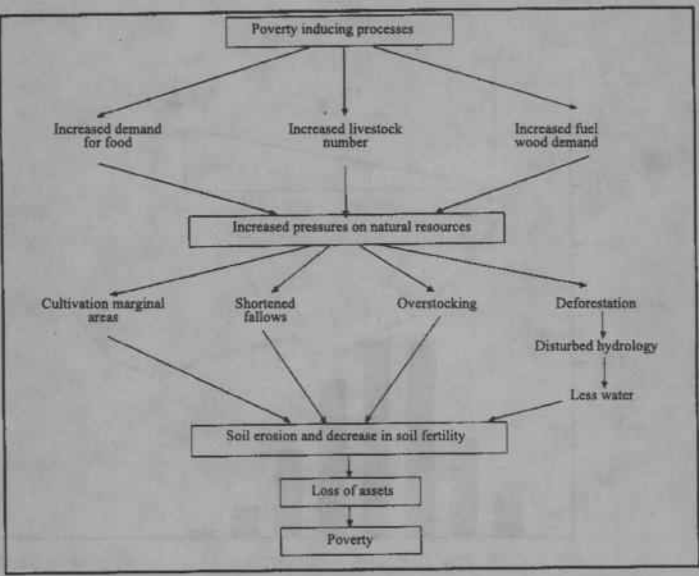

Fig. 3. The consequences of poverty processes (Templeton and Scherr, 1996).

the strengths and weaknesses of indigenous soil and water conservation in Kenya, Tanzania, and Uganda (Briggs *et al.*, 1998; Tengberg *et al.*, 1998), have concluded that it is desirable to design interventions based on existing systems rather than to introduce external technologies which may not be technically sound or viable.

Sustainability and natural resource degradation

Hardly a paper is written on natural resources which does not mention the word sustainable. What is sustainable in one place, may not be sustainable in another, or sustainable indefinitely (Reeves, 1997). Sustainability is about being able to recover from stresses and being resilient in the face of natural and human induced processes. Farmers live in a constantly changing political, social and economic environment with dynamic biological, physical and economic systems. No farming system in any region remains sustainable without continual change, supported by new knowledge, new practices, new technology and appropriate extension systems. Poor farmers are often under pressure to produce more food from less land, which forces them to deplete the soil and shift to increasingly marginal areas. Where farmers try to extract higher levels of output from their land than their inputs can sustain, the result is a downward spiral of land degradation and declining productivity. There are many technological and institutional innovations that have been promoted by aid organisations and yet many seem generally not to have been adopted (Biot *et al.*, 1995)

Factors Affecting the Adoption of Soil and Water Conserving Technologies

Although there are many potential technical fixes for land degradation, unless

Table 4. Preconditions necessary for household adoption of soil and water conservation technologies

	Precondition		Reasons for non-acceptance
1.	Land degradation is recognized as a problem	**No**	- Very slow process, regarded as normal - More land readily available - Land not owned - Insecure future in farming
	Yes		
2.	The cause of productivity decline is recognised	**No**	- Other factors may be contributing to low productivity - Lack of knowledge - Land cultivated by others - Infrequent visits to land - Symptoms have appeared very recently
	Yes		
3.	The household is aware of alternative technologies that could reverse productivity declines	**No**	- Unaware of any technologies - Poor experience with development organisations - Inadequate extension - Poor information flow within the community
	Yes		
4	The household is willing and able to undertake new practices	**No**	- Need to secure food production in the short term - Insecure land tenure - Incompatibility with present farming system - Insufficient labor - No access to inputs - Poor financial return - Benefits are too long term - Other problems have higher priority
	Yes .... possible *Adoption*		

Source: Ellis-Jones and Mason, 1999.

there is sound understanding of the farming systems, farmers' decision making and adoption processes (Table 4), adoption is likely to be elusive.

The use of participatory technology development techniques, based on people-centred extension involving key stake-holders, with development incentives for land investment, will be an essential component of any development intervention. In considering new technologies, households will consider the socio-economic and biophysical resources at their disposal (Table 5)

Land tenure of arable areas is not considered an issue where conservation and soil fertility management (SFM) techniques require an annual input and provide an immediate and annual response. It may prove an issue where soil and water conservation (SWC) and SFM require an initial investment with returns being realised only over a number of seasons (Rukuni, 1994). In such cases, investment and credit may be better secured through freehold title, although some continue to argue that customary/tribal rights can provide this security (Moyo, 1995).

The availabilities of labor and draught animal power (DAP) are the key resources for crop production in small farm systems. The availability of labor is influenced by

Table 5. Socio-economic and bio-physical factors considered by households

Socio-economic factors	Biophysical factors
Land availability (and land tenure)	Rainfall
Labor availability	Soil type and soil fertility
Draught power availability	Soil moisture
Implement availability and condition	Crop establishment methods
Timeliness and risk considerations	Weeding methods
Profitability of farming systems	

household composition, labor productivity and other claims on household time, notably household duties and off-farm work. Labor productivity is influenced by sex, age, nutritional status, health, food availability and off-farm income opportunities. Overall it is estimated that women contribute 60-80% of the labor for food crops (FAO, 1995) and although cash crops are usually the responsibility of men, women provide much of the labor.

Female heads of household account for a significant proportion of rural households in sub-Saharan Africa. For example, in Zimbabwe, more than 50% of rural households are headed by women (Chiduza, 1994). The most vulnerable are those where the male adult is totally absent; they are prone to poverty with incomes less than 50% of male headed households. This is in contrast to those households, where male migrants regularly send home remittances, which have the highest income levels (Lacher and Dikito, 1991).

Different soil types have different characteristics related to soil moisture holding capacity, drainage, waterlogging during the wet season, weed burdens and soil fertility. These in turn are associated with risk and timeliness of carrying out tillage operations. Farmers have a range of crop establishment and weeding options available to them and will decide which to use, based on the resources (draught power, labor and implements) available to them, soil type, soil conditions (based on actual and predicted rainfall), as well as their perceptions of risk and timeliness.

Farm Power and Implements

All agricultural operations demand mechanical energy for their execution and usually involve the use of tools and equipment. The most immediately available and widely used source of energy is human labor, followed by animal power and engine power. Table 6 shows that in 1987, the proportion of human labor was greater for sub-Saharan Africa than elsewhere, and the changes that have occurred in SSA since then (e.g., from droughts) are likely to have

Table 6. Proportional contribution (%) of the total energy use for crop production in developing countries (from FAO, 1987)

Region	Human	Animal	Tractor
North Africa	69	17	14
Sub-Saharan Africa	89	10	1
Asia (excluding China)	68	28	4
Latin America	59	19	22
Overall	71	23	6

Note: Animal and tractor contributions estimated by converting to man-day equivalents per hectare.

Table 7. Proportions (%) of land in five SADC countries cultivated by different power sources (from COMSEC, 1992)

Country	Human	Animal	Tractor
Botswana	20	40	40
Kenya	84	12	4
South Africa	10	20	70
Tanzania	80	14	6
Zimbabwe .	15	30	55

increased the contribution made by human power. The break-down within SSA is given in Table 7 but, unlike Table 6, this is based on the area of land cultivated.

The availability of farm power (labor and draught animals, and limited access to tractors in some areas) is the key non-biophysical resource for crop production in small farm systems. They determine the area that is cropped, the timeliness of operations, the utilisation of other inputs and, hence, the productivity of the farming system. Although many people have seen tractorisation as means of increasing productivity at the smallholder level (e.g., through tractor hire schemes, often subsidised by Government), few, if any, schemes have helped alleviate rural poverty or contributed to the overall sustainability of smallholder farmers. A recent study in Botswana (Panin, 1995) clearly showed that the current systems of tractor hire for ploughing and crop establishment had no impact on total area cultivated, crop yields or total crop output (Table 8). In fact, the introduction of tractors had a negative impact upon the farming system, reducing crop production income and raising the demand on household labor for other farming operations and resulting in an overall economic loss for the country, when compared with the traditional animal draught systems.

Table 8. Effects of tractorisation on smallholder farming in Botswana (adapted from Panin, 1995)

Resource Type	ADHS[1]	THHS[2]
Sample size	36	91
Area cultivated (ha)		
Per household (ha)	6.96 (0.58)	6.86 (0.36)
Per active worker	2.94 (0.4)	3.34 (0.25)
Labor (h/ha)		
Ploughing and planting	37.40 (2.26)	4.96 (1.42)
Weeding	58.56 (18.52)	136.00 (11.65)
Harvesting and threshing	42.43 (21.67)	143.70 (24.81)
Draught power (h/ha)	13.85 (0.68)	2.41 (0.43)
Total production cost (Pula/ha)	5.62	112.27
Crop yields (kg/ha)		
Sorghum	182.50 (39.60)	234.50 (33.27)
Maize	168.30 (55.83)	126.60 (10.26)
Total crop output (Pula/ha)	62.81 (16.32)	92.00 (10.26)
Income (Pula/ha)	57.19 (12.97)	-20.27 (8.16)

1: Households using draught animal power, 2: Households using hired tractors, ( ): Standard error.

The greatest demands for mechanical energy in crop production operations are for land preparation and weed control; either or both of these can limit the output of a smallholder farmer (O'Neill, 1998) and "bottlenecks" can occur. For land preparation, the limit is due primarily to the intensity of the energy demand, whilst for weed control, the duration of the demand is likely to be more restricting (Rogan and O'Neill, 1993). The maximum rate of working (i.e., power developed) that may be expected of a smallholder is around 40 watts over a 6-hour working day (Dibbits, 1993) and this energy (totalling around 0.9 MJ) would be applied rather inefficiently through the use of simple handtools, typically hoes of various designs (Anon, 1992). Although weeding is associated with a lower power demand than land preparation, the time available may be inadequate to complete the task. This is exacerbated by the drudgery of long hours of weeding, a burden borne mainly by women, who must accommodate weeding within their schedule of domestic tasks. The use of hoes for weeding in Zimbabwe has been investigated by Chatizwa (1997), who concluded from studies using female subjects that, of the four designs, the garden hoe was the best overall tool in terms of work rate and effort, but that the *badza*, the local traditional tool, had the highest weeding efficiency.

For both land preparation and weeding tasks, the use of draught animal power (DAP) can improve the timeliness of farmers' operations by supplementing the farmers' own muscle power (and that of their families). Draught animals can provide the effort needed to pull a plough or cultivator and to complete the task more quickly than would be possible by human labor alone. It is generally considered not to be economically feasible nor sustainable for a small farmer with a typical land holding to own a tractor. Nevertheless, there are many instances of smallholder farmers hiring tractors occasionally, particularly for opening new ground, and then continuing the crop production cycle without the use of engine power (O'Neill *et al.*, 1999).

The draught capability of working animals, suitably trained and in good condition, depends primarily on the body-weight of the animal as this provides a fair indication of its muscle mass. A simple "rule of thumb" (but one which underestimates the performance of the better animals) is that an animal can pull 10% of its body weight. The work capabilities of various species of animals used by smallholders are given in Table 9.

The work rate in terms of area can be estimated if the (effective) working width of the implement is known.

When animals are spanned, good hitching and harnessing systems reduce unnecessary wastage of animals' effort and reduce injuries, which would further impair work output. For draught animals to flourish, the local farming system must have the capacity to support livestock, to nourish and sustain them in a healthy condition (Pearson, 1996). In return, the farmers receive the benefits of owning livestock which yield meat, skins, manure and milk (females), as well as draught work and transport opportunities. In these respects, cattle are more valuable than donkeys in SSA. As additional requirements, particularly from the cultural perspective, farmers must have

Table 9. Sustainable power of individual animals in good condition (from Inns, 1992)

Species	Typical weight (kg)	Typical draught force (N)	Typical working speed (m/s)	Power output (W)	Working hours/ day	Energy output/day (MJ)
Ox	450	500	0.9	450	6	10
Buffalo	550	650	0.8	520	5	9.5
Horse	400	500	1.0	500	10	18
Donkey	150	200	1.0	200	4	3
Mule	300	400	1.0	400	6	8.5
Camel	500	650	1.0	650	6	14

Note: For animals of different weights, the power output and energy output per day may be adjusted proportionately.

some insight or predisposition towards the care, husbandry and training of animals, and the fabrication, or at least maintenance, of animal-drawn implements must be within the capabilities of local blacksmiths.

Despite the obvious attractions of DAP to smallholder farmers, not all farming systems are suited to the application of DAP and caution should be exercised if recommending DAP as part of a mechanisation strategy. The equipment typically used in draught animal operations, which may or may not constitute part of a mechanisation strategy, is listed in Table 10, together with relevant comments. Ploughs are the most universally owned and used implements, and it is not uncommon to find farmers who own a plough (or ploughs) yet do not own draught animals (Francis, 1996). Farmers who do not own cultivators are likely to use their ploughs for weeding as well as land preparation. If the farmer owns a mouldboard plough (rather than an ard), s/he may weed using just the share with the mouldboard removed, as discussed later. According to Chatizwa and Koza (1998), again in Zimbabwe, farmers may use one implement for several operations, as shown in Table 11.

Such improvisation leads to ridgers, tines and planters being relatively uncommon compared to ploughs and cultivators. Nevertheless, in Zimbabwe, there is a wide choice of all these implements (Mbanje and O'Neill, 1997). However, there is strong evidence (collected in Zimbabwe, but assumed to be representative of the situation in adjacent countries) to suggest that implements are being used inefficiently because of both their poor condition and inadequate farmer knowledge on how to properly use and maintain them (Chatizwa and Koza, 1998, Chatizwa and Ellis-Jones, 1997).

Farmers who own working animals can, and often do, derive considerable benefit by using them for transport with either carts or sledges or, in the case of donkeys, as pack animals. The ability to transport nutrients from one part of the farm to another is a key component of SFM. Animals can also be used to power stationary equipment, such as for water-raising, or to expedite post-harvest operations such as threshing, milling or crushing (sugar cane). However,

Table 10. Equipment suitable for DAP applications

Implement	Comments
Traditional/ard ploughs	Cut furrows and disturb soil without inverting it. Usually made at local levels, generally of wood but with a metal tip.
Mouldboard ploughs	Cut the soil and turn the furrow "slice" burying weeds and trash. Made of steel, usually in factories, but some blacksmiths capable of fabrication. Commonest share and m-b sizes for DAP are 6, 8 and 10 inch (150, 200 and 250 mm). Should have adjustable hitch point and may have wheel or skid to improve stability.
Seeders	Comprise furrow opener (tine), seed dispenser (if seed metered, called a drill), followed by furrow closer. May be combined with fertiliser dispenser. Complex and expensive for smallholder farmers.
Cultivators	For interculture in row crops. Tines vary in number (usually 3 to 5 for DAP) and shape (e.g., flat, curved, spring rigid, sweep, duckfoot, etc.) and may be fitted with width adjusting mechanism. Some rotary cultivators suitable for DAP are available.
Ridgers	For making ridges, bunds or raised beds by the action of mouldboards or discs.
Harrows	Comprise a number (usually 20 to 40 for DAP) of steel teeth/spikes mounted on a metal frame (traingular, square, diamond, etc.).
Tool bars	Metal frame, usually with land-wheel, to which different soil-working tools (e.g., tines, shares mouldboards, ground-nut lifters, etc.) can be attached.
Wheeled tool-carriers	Platform with axle to which a wide range of tools can be attached. Can often be converted into a cart. Rather expensive for smallholder farmers.

because of the complexity and cost (use of gears, robustness) and inconvenience, farmers favour the use of electric motors or small internal combustion engines, and would only resort to animal draught where there is no alternative. There is not a strong economic argument for using animals to power stationary equipment even when a farmer already owns them.

The successful use, or introduction, of draught animals, depend on a number of factors. These include the intensity of agricultural production, the local population density, access to markets, soil type and the length of the growing season (Ehui and Polson, 1993). In their review, Jaeger and Matlon (1990) concluded that, where draught animals are successfully used for land

Table 11. Utilization of animal-drawn implements (Chatizwa and Koza, 1998)

Implement	Main use	Other uses
Plough	Conventional ploughing	Weeding, ridging, furrow marking (m/board removed)
Cultivator	Weeding	Planting, furrow making, seed covering
Harrow	Clod breaking	Clearing stover, seed covering, breaking soil cap
Ripper tine	Plough-pan breaking	Planting, furrow making
Ridger	Ridge making	Weeding

preparation, animal-drawn weeding equipment can significantly raise labor productivity during the most critical labor bottleneck period. From a more ecological perspective, Thomas (1999) stated that ruminants, through the provision of DAP and manure and their ability to utilise cover crops and forages, can contribute significantly to the process of improving soil conservation and fertility.

Soil and Water Management for Crop Production

Population pressures in southern Africa are forcing people to crop on land of an increasingly diverse and fragile nature, where the risks of environmental degradation through losses of soil and water, are high and crop yields are unsustainable. Both Government and Non-Government Organisations (NGOs) have been working towards developing improved tillage/soil management systems that conserve soil and water resources, and improve the productive potential of these areas. Some measures to reduce land degradation have been widely adopted, notably, contour ridges and *fanya juus* (a ditch dug on the contour with the soil thrown uphill to form a bank that is then seeded with grass) to reduce gully and rill erosion. These, however, were enforced during the colonial era, making adoption inevitable, but not necessarily leading them to be effective in soil and water conservation (Reij *et al.*,1996; Hagmann, 1998; Briggs *et al.*, 1998). Unfortunately, promotion of 'improved' conservation tillage practices in sub-Saharan Africa over the past twenty years have tended to be based on large scale dryland farming systems developed in the USA (Unger, 1984; FAO, 1993; Morse, 1996). Such systems do not take into account the technical, social and economic constraints faced by resource poor-farmers (Willcocks and Twomlow, 1993; Twomlow *et al.*, 1995; Hagmann, 1998).

With the cropping period in most semi-arid regions being relatively short (Fig. 2), the timing of field operations is critical. Conservation tillage offers potential for increasing productivity (Elwell, 1993; Benites *et al.*, 1998), but adoption by farmers remains low (Sarapinda, 1990; Ellis-Jones and Mudhara, 1995). Some projects have tried to address these factors (Willcocks, 1988) and current initiatives in Zimbabwe have taken a more multi-disciplinary approach and include agronomic, socio-economic, meteorological, farm power and soil issues that relate to actual production systems (Willcocks *et al.*, 1993). Improved technologies should not require costly inputs and unavailable skills, nor compete for labor or DAP when crops or land demand attention (Barrow, 1988). Farmer uptake must be the goal and this will entail the innovative use of existing implements and resources (Ellis-Jones and Mudhara, 1995; Reij *et al.*, 1996).

Tillage and Weed Control

Recent studies have examined the effects of tillage practices and landforms (e.g., mulches, potholes, furrows and contour structures) on soil and water conservation for smallholder semi-arid crop production (Tagwira, 1992; Twomlow *et al.*, 1995; Briggs *et al.*, 1998; Benites *et al.*, 1998).

Table 12. Annual soil losses and mean maize yields for five tillage treatments at Makoholi, Zimbabwe

Treatment/ Year	Seasonal rainfall (mm)	Annual total soil loss (t/ha)				
		Conventional	Hand hoeing	Clean ripping	Mulch ripping	Tied ridging
1988-89	425.00	0.70	–	0.50	0.50	0.00
1989-90	742.00	1.30	0.90	1.30	1.00	0.10
1990-91	342.00	5.70	1.80	2.10	0.60	0.10
1991-92	174.00	0.70	0.80	0.40	0.30	0.10
1992-93	697.00	11.80	12.00	12.70	3.70	2.70
1993-94	472.00	40.20	10.70	5.80	0.20	3.00
Mean soil loss		10.07	5.24	3.80	1.05	1.00
Mean maize yield (t/ha)		3.26	1.92	2.93	3.24	2.51

Source: Chuma and Hagmann, 1995.

From these studies, it is clear that farmers in southern Africa already employ tillage practices with the aim of accomplishing several short-term goals, including seedbed preparation, weed control and rainwater retention (Waddington, 1991). In Zimbabwe, it has been reported that farmers recognise that timely inter-row cultivation is important for both weed control and for maintaining a rough soil surface, which can retain subsequent rainfall (Ellis-Jones *et al.*, 1993). The widespread adoption of minimum-till and no-till systems in the capital-intensive agricultural systems of North America, Australia and other countries has been facilitated by innovations in equipment and herbicide technology (Halvorson *et al.*, 1997). Modified tillage regimes, including no-till tied ridging, proposed as a sustainable conservation tillage system in both Zambia (Meijer, 1992) and Zimbabwe (Elwell and Norton, 1988), to reduce soil and water losses, and improve the utilization of available draught power resources, have not been adopted on any scale. This is attributed to the resource needs of the system being beyond those available to many households. There are also other problems perceived by farmers, including practical difficulties in ridge construction, crop establishment, maintenance and weeding (Riches *et al.*, 1997).

Tillage trials on sandy soils in Zimbabwe have shown that sheet erosion is negligible under no-till tied ridging (Table 12), but the system may generate adverse edaphic micro-environments for crops (Vogel, 1993; Chuma and Hagmann, 1995). As might be expected from the soil loss figures, patterns of runoff were very similar, with tied ridging and mulch ripping reducing seasonal runoff by as much as 75%, when compared to the conventional flat treatment. Despite the obvious conservation of soil, the different conservation systems had no significant impact on crop yields. In fact, highest yields were consistently recorded on the conventionally ploughed treatments. Similar patterns of crop response and soil loss have been observed for wetter sites in Zimbabwe, both on-station and on-farm (Munyati, 1997).

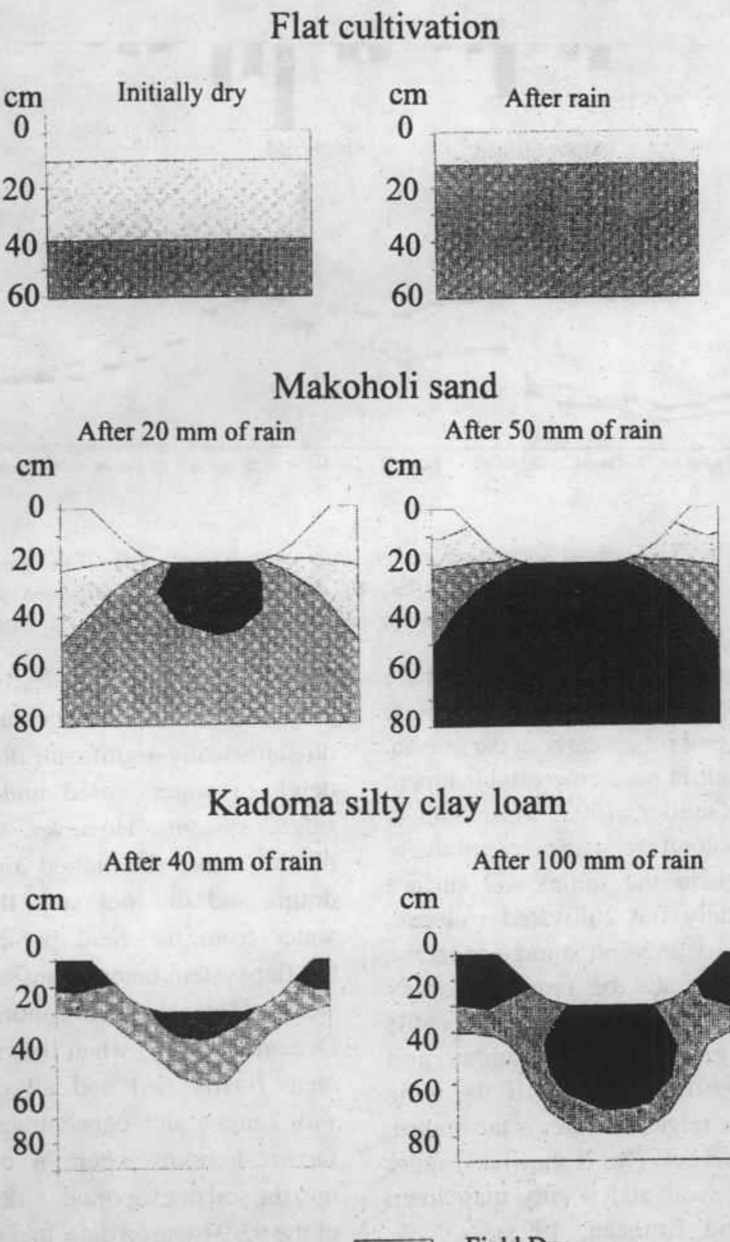

Fig. 4. Progression of wetting fronts for a conventional flat system compared to ridges constructed on Makoholi sand and Kadoma silty loam from an initially dry state to wet state.

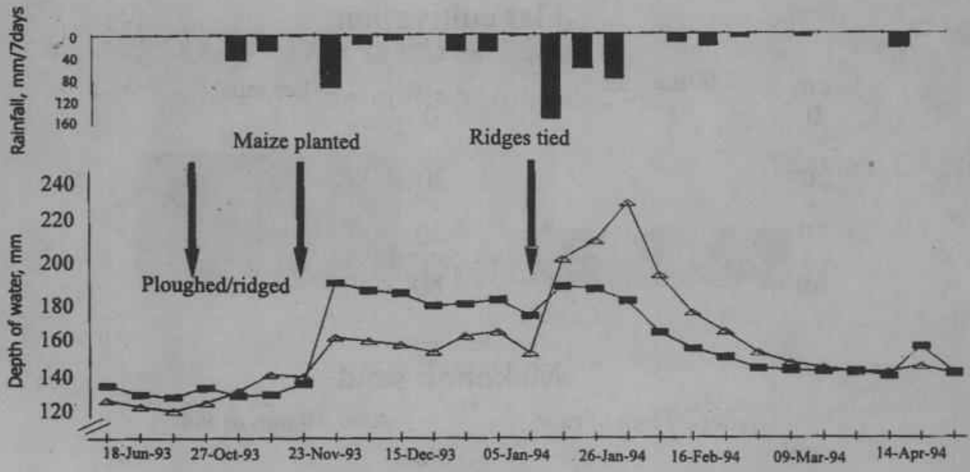

Fig. 5. Seasonal fluctuations in soil water content (mm) of the Ntini sandy loam in response to flat (■) and tied ridge (Δ) cultivation for the 1993-94 season when ridges were tied late.

The major disadvantages with ridges are higher soil temperatures and incomplete wetting of the tied ridges early in the season, which can result in poor crop establishment and growth (Gollifer, 1993; Mashavira *et al.*, 1995). This contrasts with conventionally tilled soils where the initial soil surface of a traditionally flat cultivated soil can, due to its high depression storage capacity, trap more water and be more uniformly wet in the top 300 mm of the soil profile than the ridge systems (Bruneau and Twomlow, 1999), particularly if the tying operation of the ridge structures is incomplete or poorly carried out. This is shown in Figure 4 for a sandy soil and a silty clay loam (Twomlow and Bruneau, 1998).

The impact of tied and untied ridges on seasonal fluctuations in soil water content is illustrated in Figure 5 for the Ntini sandy loam during the 1993/1994 season when the ridges were tied late. Early in the season, prior to the onset of the rains, there was no statistically significant difference in the depth of water stored under the flat or ridged systems. However, with the onset of the rains, the untied ridges acted as drains and did not stop the outflow of water from the field, which resulted in the flat system being significantly ($P<0.01$) wetter. This scenario continued until late December, 1993, when the ridge structures were finally tied and all of the rainfall was caught and concentrated in the tied furrow bottoms where it could infiltrate into the soil or evaporate. A detailed analysis of the 93/94 season data, and the subsequent 94/95 data set, showed that the positive impact of ridges, in terms of moisture conservation, was statistically significant only after the ridges had been tied and had opportunity to fully wet up (Fig. 5).

Table 13. Economic analysis of method of ridging trial at Makoholi Experimental Station, 1992-93

Tillage system	Flat control	Ridged by hand	Ridged by plough	Ridged by ridger
Grain yield, kg ha^{-1}	2772	2976	2682	2662
Stover yield, kg ha^{-1}	1424	1582	1539	1500
1. Gross income Z$[a]	2953	3172	2862	2840
2. Purchased inputs Z$	1985	2028	1966	1962
3. DAP cost Z$	301	301	410	447
4. Labor cost Z$	252	340	252	252
5. Total cost Z$ (2+3+4)	2538	2669	2628	2661
6. Gross margin Z$ (1-5)	415	503	234	179
7. Total labor, hours	275	362	282	284
8. Returns to labor Z$ h^{-1} [(6+4)/7]	2.43	2.33	1.72	1.52
9. Return to cash expenditure Z$ Z$$^{-1}$ (1/2)	1.49	1.56	1.46	1.45

a Maize grain: 1050 Z$ t^{-1}, Maize stover: 30 Z$ t^{-1}, (Twomlow *et al.*, 1997c).

However, during the dry season (May to September), these differences disappeared: total soil water contents for the flat and ridged systems were very similar and, as a result, there was little carry over of water from one season to the next. Similar observations were recorded by Riches *et al.* (1997) for a sandy soil in Zimbabwe, provided weed management is consistent.

Other problems with ridge systems, compared to flat cultivation practices, include a high labor requirement for construction (Twomlow *et al.*,1997c), difficulties in planting and weeding (Meijer, 1992), and ridge maintenance, with no overall economic benefit (Table 13) compared to traditional systems they are intended to replace. Low resource-endowed farmers tend to choose cheaper and less labor demanding techniques for sustainable crop production. Recent studies in east Africa have shown that in general farmers have a good understanding of their circumstances (biophysical and economic) and rationalise their farming practices to address these issues (Tengberg *et al.*,1998). Similar observations have been made in southern Africa, where studies have confirmed that farmers have a good understanding of the strong relationship between crop growth, soil fertility, water and labor availability. Here, in this drought-prone region, many farmers preferentially apply what organic and inorganic fertilisers they have to areas, or technologies where water is less limiting (Harris *et al.,* 1994; Mugwira and Murwira, 1997; Chuma *et al.*,1998; Mmopelwa, 1998). Consequently, research is required to identify low input improved land and crop husbandry options that are appropriate to the wide range of environmental, social and economic constraints faced by farmers who wish to increase available crop water and reduce the level of inputs (Ellis-Jones and Mudhara, 1995; Benites *et al.*,1998).

In recent research in Kenya, local farmers identified eight soil and water conservation technologies common to the semi-arid regions of Embu District, Kenya (Tengberg *et al.*,

Table 14. Variation in runoff (mm), soil loss (kg/ha) and biomass production in response to the April 1997 seasonal rainfall of 502 mm

Treatment	Spacing (m)	Runoff (mm)	Soil loss (kg/ha)	Maize grain yield (kg/ha)
Control		136	3221	36.5
Fanja juu	15	n.d.	7928	518.8
Large stone bund (0.6 m by 0.3 m)	15	n.d.	14000	569.7
Small stone bund (0.3 m by 0.15 m)	15	62.6	2841	413.9
Large fixed trashline (0.6 by 0.3 m - 3.6 t/ha stover)	15	58.7	3357	522.3
Large mobile trashline[1] (0.6 by 0.3 m - 3.6 t/ha stover)	15	63	1156	561.5
Small mobile trashline[1] (0.3 by 0.15 m - 1.8 t/ha stover)	15	78.7	1442	414.4
Small trashline (0.3 by 0.15 m - 3.6 t/ha stover)	7.5	27.9	1442	571.1
Treatment s.e.d*		3.188***	1466**	106.8

* Significant treatment difference, ** P<0.01, *** P<0.001, n.d. no data.
[1] Trashline is moved 3 m down slope at the start of each season, just prior to planting.
(Source: Okoba *et al.*, 1998).

1998), and these were subsequently evaluated over four cropping seasons under controlled conditions at Machanga Research Station using hand tillage (Okoba *et al.*, 1998). The technologies included various sizes of trash lines with different horizontal spacings and various size stone bunds, compared to a flat control and *fanya juu*'s, the recommended technology for the region. Crop yields, runoff, soil losses and water contents were monitored. Results showed that both mobile trash lines at a 15 m spacing (moved 3 m down slope every season), and trash lines with a spacing between structures reduced to 7.5 m, consistently reduced runoff and soil loss and increased yields, when compared to the control (Table 14). More importantly, soil losses from the permanent structures, such as stone bunds and *fanya juus* at 15 m spacing, were consistently greater than the losses from control plots. Although surprising, similar observations have been made on farmers' fields in the first season after construction, where the soil losses observed were attributed to the quantities of soil disturbed at construction and during any maintenance operations. However, the choice of conservation structure by the farmer was strongly related to the farmer's resource base (Tengberg *et al.*, 1998). Higher resourced farmers on more fertile land tended to adopt physical structures for soil and water conservation, as they had more cattle which were fed the crop residues. This was in contrast to the poorer resourced farmers, who had few heads of livestock and tended to use crop residues as trash lines.

In the southern highlands of Tanzania, the *ngoro* or *matengo* pit and the *matuta* ridge systems are two traditional soil and water conservation technologies that have been locally developed in response to prevailing environmental and socio-economic constraints (ICRA, 1992; Ellis-Jones *et al.*,1998a). The *ngoro* system consists of a regular series of pits, used mainly on steep slopes. Crops are planted only on the surrounding ridges, under which buried plant residues are decomposing. In

Table 15. Economic analysis of maize on Ngoro and Matuta ridges with and without fertiliser

Conservation	Yield (kg/ha)	Inputs		Gross margin per ha[4]		Returns to		Rank
		Labor[2] Days/ha	Materials[3] $	Inc. labor $	Exc. labor $	Cash[5] (%)	Labor[6] ($ per day)	
Ngoro	1559	60	20	61	144	721	2.40	3
Matuta ridge	1270	53	18	36	116	650	2.20	4
Ngoro with fertiliser[1]	3745	62	164	151	229	139	3.69	2
Matuta with fertiliser[1]	5162	55	175	287	267	210	6.73	1

Notes:

1 Fertiliser includes 150 kg triple super phosphate and 50 kg urea.

2 Labor rates are based on those shown by Martin *et al.* (1998b) and have been valued at tsh 1000 (US $ 1.50) per day.

3 Materials include local seed varieties and bags at 1997 market prices.

4 Gross-margins have been calculated with and without the costs of labor, in order to show the effect of household supplied labor

5 The values of gross income (yield x market prices) as a percentage of cash outlay (excluding household supplied labor)

6 Gross-margin excluding labor costs divided by labor input.

the alternative *matuta* ridge system, all vegetation prior to hand tillage is slashed and the residues are roughly aligned across the hillside, as in the *ngoro* system, with soil thrown downslope to form a ridge over the organic residues (ridge+OM). However, if labor is limiting, the organic residues are burnt prior to ridge construction (ridge-OM). Both systems are said by their respective exponents to conserve moisture in soil, reduce soil erosion and, where organic residues are incorporated, improve soil fertility (Ellis-Jones *et al.*,1998a).

From recent studies (Martin *et al.*, 1998a, b), it has been found that *ngoros* were generally larger than the historically quoted 1.5 x 1.5 m. The average size of a pit is 2.4 m long by 2.1 m wide, aligned down the slope with only limited evidence of sheet erosion. This is in contrast to fields with the *matuta* ridge system, where gullying was the dominant form of erosion. In fact, erosion only failed to occur on those ridges aligned on the contour or combined with live barriers. In the *ngoro* system, the majority of soil was redeposited in the pits, meaning a small, if any, net loss of soil, but in the ridge systems, much of the soil was transported out of the study areas.

On a seasonal basis, no statistical differences were observed in the amount of water stored under *ngoro* or *matuta* ridge systems irrespective of slope. Nevertheless, economic analysis has indicated that *ngoro* provides highest productivity where fertiliser is not applied, although at low soil fertility levels, all systems. are likely to give negative gross margins (Table 15). Where fertiliser is applied, the *matuta* ridge systems are likely to give higher returns. Future work in Tanzania must be concentrated on the introduction of field boundary management techniques that prevent watershed from land above entering fields and creating erosion problems. In

Table 16. Total crop biomass (kg/ha), total crop water use (mm/ha) and water-use efficiency (WUE, kg/mm) in response to time and frequency of weeding at Makoholi Experimental Station

Weeding treatment	1991-92			1992-93		
	Biomass	Crop water use	WUE	Biomass	Crop water use	WUE
Weed at 2 weeks	760	218.9	3.47	3143	396.4	7.89
Weed at 2+4+6 weeks	1350	210.3	6.42	4147	367.9	11.17
Weed at 4 weeks	1485	214.9	6.91	3235	411.2	8.13
Kept weed-free	1805	163.8	11.01	3178	393.1	8.09
Unweeded control	489	210.0	2.33	1014.8	465.4	2.17
s.e.d.#	132.1***	6.63***	1.75**	496.5***	11.12***	1.467**

Significant treatment effect, ** P>0.05, ***P>0.001. Source: Twomlow *et al.*, 1996b.

addition, ridges must be aligned along the contour and some form of physical or a biological barrier that can reduce slope lengths must be introduced. Lastly, but most importantly, the farmers must be empowered to understand the economic value of fertilisers and organic residues and be encouraged not to burn them.

In contrast to the majority of farmers in Kenya and Tanzania, smallholder farmers in semi-arid Zimbabwe rely heavily on DAP and ox-drawn mouldboard ploughs for primary tillage and crop establishment. Seed is planted by hand into a furrow made by the plough and covered during the next pass, ensuring that maize germinates in a relatively weed-free seedbed. Farmers face the problem that the peak demand for DAP coincides with the time that animals are in weakest condition after a long dry season (Shumba *et al.*, 1992). Achieving timely planting and good germination is particularly important, which can be difficult for those without access to adequate DAP. Farmers recognise the need for weed control to remove weeds and allow enhanced capture of rainfall. Weed management is a key component of conservation tillage (Norton, 1987; Riches *et al.*, 1997) and with weeding (with either hand tools or DAP implements), accounting for up to 60% of pre-harvest labor input for maize production (Akobundu, 1987; MLARR, 1992; Rogan and O'Neill, 1993), considerable strain is placed on household supplied labor. This can be reduced through the use of the ox-cultivator or plough.

Despite this investment in labor, experimental evidence suggests that with existing weeding practice, more than 30% of the potential yield of cereal crops is commonly lost to weed infestation (Vernon and Parker, 1983; Carson, 1987). This may be due to late and inadequate weeding, with high labor demands for hoe weeding and a shortage of DAP and suitable implements for ox-cultivation contributing to weed problems (Waddington, 1991; Kwiligwa *et al.*, 1994). In semi-arid southern Africa, studies of the optimum timing for weeding, based upon identification of the "critical period of competition", typically indicate the need to maintain maize free of weeds from 2 to 6 weeks from planting to achieve maximum water use efficiency and crop productivity (Twomlow *et al.*, 1997a; Table 16). Weed management is, therefore, a key element in the design of

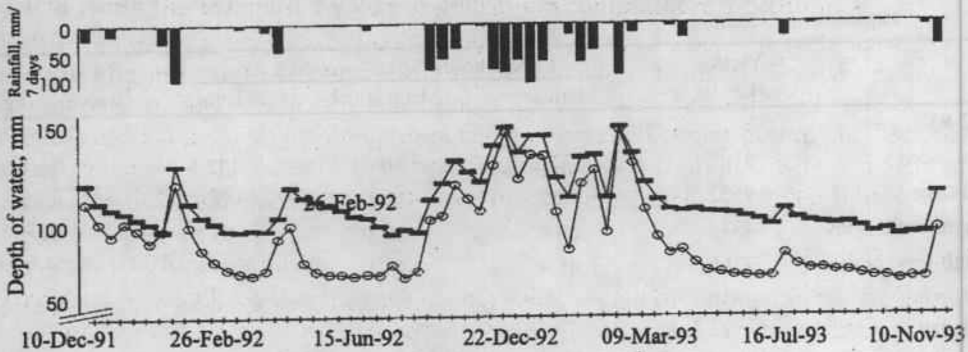

Fig. 6. Impact of weeds on the soil water regimes that develop under a maize crop grown on the Makoholi sand. O, *unweeded maize crop;* ■, *weed free maize crop.*

any sustainable and adoptable tillage system aimed at raising smallholders' production and has a major impact on both yield and available soil water (Fig. 6; Twomlow and Bruneau, 1998).

Recent work in Zimbabwe has focussed on developing weed control strategies that complement primary tillage techniques for the majority of communal area farmers who cannot afford purchased inputs, including herbicides. Because of poor returns to cropping and an acute shortage of labor in many households, tillage/weed control systems should be based on low cost, labor saving technologies (Ellis-Jones and Mudhara, 1995). Riches *et al.* (1997) reported that the use of the mouldboard plough with body attached during weeding allows the creation of a ridge and furrow landform that can enhance soil-water retention (Table 17). The soil thrown towards the crop row smothers weeds and reduces the need for subsequent labor-intensive inter-plant weeding. Labor productivity, in terms of grain harvested, can be considerably higher with this technique than following the use of existing hand hoe or cultivator followed by hoe systems. While 76% of households own a plough in southern Zimbabwe, only 23% own a cultivator, so "plough weeding" provides an opportunity for increasing the timeliness of weed control, for farmers who currently weed by hand, without the need for additional capital investment, if they have access to DAP.

Prior work has shown the advantages of establishing a crop within either a rip line (Shumba *et al.*, 1992) or a planting furrow opened with a plough on winter or previously spring ploughed land (Mashavira *et al.*, 1995; 1997; Muza *et al.*, 1996; Twomlow *et al.*, 1995). Although these techniques of crop establishment can reduce DAP inputs for seedbed preparation and allow timely planting, a heavier and earlier weed burden results as compared to that for overall ploughing and planting together, the prevailing practice (Shumba *et al.*, 1992; Mabasa *et al.*, 1998). If combined with

Table 17. Maize yields, labor requirements and returns to labor for four weeding systems at Makoholi Experimental Station

	Yield (kg ha^{-1})	Labor hours spent weeding			Returns to weeding (kg h^{-1})
		Manual	Mechanical	Total	
1992-93					
Hand-weed	5195	132.5	0	132.5	39.3
Cultivator	4552	52.2	16.2	68.3	66.7
Plough with body	4345	26.8	28.3	55.2	78.7
Plough-less body	2766	45.4	40.4	85.8	32.5
Expt. s.e.	310	–	–	–	4.41
1993-94#					
Hand-weed	2251	126	0	126	17.9
Cultivator	2092	45.3	15.1	60	35.0
Plough with body[1]	3047	20.3	36.8	57	53.5
Plough-less body	1636	45.3	36.3	82	20
Expt. s.e.	204	–	–	–	
1994-95					
Hand-weed	3670	155.6	0	155.6	23.6
Cultivator	3990	42.6	13.5	56.1	71.1
Plough with body[1]	3896	0	34.6	34.6	112.6
Plough-less body	2590	41.4	34.7	76.1	34.0
Expt. s.e.	344	–	–	–	8.3

1 Ridges were tied after weeding in 1993-94 and 1994-95.
Labor for hand-hoeing estimated from on-farm records.
Source: Riches *et al.*, 1997.

weeding with a plough (or a cultivator with ridging blades), timely planting, better soil water conservation, weed control and labor reduction could be achieved (Table 18).

Although there is a steady upward trend in the use of herbicides in developing countries, primarily in relation to the cost and availability of labor where industrialisation of emerging economies is taking place (Terry, 1996), there has been little adoption by smallholders in southern Africa. Cost is regularly advanced as a major constraint to herbicide adoption and liquidity, at the beginning of the season, is essential if farmers are to choose chemical weed control. The institutional environment must, therefore, be conducive (e.g., supported by seasonal credit facilities), as in the cotton-growing belt of the Sudano-sahelian zone of West Africa, where there is now considerable use of herbicide on the crop (Marnotte,1997; Martin and Gaudard, 1997). On-farm studies in Zambia (Parker and Vernon, 1982) indicated that although herbicide use could eliminate early season weed competition, it was unlikely to be economic in maize. Reducing herbicide inputs by banding over the crop row and cultivating the inter-row with DAP equipment or by hand may be more feasible for farmers, particularly in cotton, which is a more valuable crop, and contributes more to the

Table 18. Maize yield response to methods of crop establishment and weeding on spring ploughed land, winter and spring ploughed land and unploughed fallow land in 1995-96

Crop establishment	Spring ploughed land			Winter and spring ploughed land			Unploughed weedy fallowed land		
	Grain yield (kg/ha)	Total labor (h/ha)	Return to labor (kg/h)	Grain yield (kg/ha)	Total labor (h/ha)	Return to labor (kg/h)	Grain yield (kg/ha)	Total labor (h/ha)	Return to labor (kg/h)
Hand plant	620.9	193.1	3.2	596.2	144.8	4.1	395.0	215.1	1.8
Open plough furrow plant	596.8	98.1	6.1	796.3	95.4	8.3	961.3	124.9	7.7
Rip to 0.3 m depth	961.3	105.9	9.1	1276.5	85.9	14.9	973.9	135.4	7.2
Method of weeding									
Hand-hoe	587.4	194.1	3.0	856.4	166.0	5.2	779.4	175.8	4.4
Ox-cultivator	953.5	106.2	9.0	680.0	65.9	10.3	748.8	165.0	4.5
Ox-plough	638.0	111.5	5.7	1018.6	88.0	11.6	802.0	134.6	6.0
Tillage s.e.	187.2	6.05***#	2.3*	286.3	7.36***	3.42**	132.9***	14.56**	1.29***
Weeding s.e.	187.2	6.05*	2.3***	247.9	7.24***	2.96*	132.9	14.56**	1.3

Significant treatment effect, *P>0.05, **P>0.01, ***P>0.001.
Source: Mashavira *et al.*, 1997.

December peak in labor demand than maize weeding does (Parker and Vernon, 1982). Working with maize in Zimbabwe, Shumba *et al.* (1992) concluded that the main benefit of using a pre-emergence application of the herbicide atrazine, in combination with tine tillage/planting, is to release labor for timely, supplementary hand weeding rather than to increase maize yields directly. They suggested that cash-constrained farmers might find the use of the herbicide unattractive although labor costs for hand weeding were 4.5 times the cost of herbicide use. Combining mechanical inter-row cultivations with pre-emergence herbicide banded along the crop row will keep an open rainfall receptive soil surface (Richards and Thomas, 1971). When rainfall in the growing season was less than 400 mm, shallow cultivation (50 to 75 mm), in addition to pre-emergence herbicide use resulted in significantly higher cotton yields in Zimbabwe compared to use of herbicide alone.

Weeds respond dynamically to a wide range of farming practices and the species composition at any particular site reflects antecedent tillage and weed management (Liebman and Gallandt, 1997; McLaughlin and Mineau, 1995). Where tractor ploughing is available, for example, occasional deep tillage will aid the control of some annual species, including the grasses *E. indica* and *R. cochinchinensi*, whose seeds lose viability at depth (Schwerzel, 1976). Under reduced tillage systems, shifts toward grasses (perennial and wind disseminated species) are common (Swanton *et al.*, 1993). Indeed, both Meijer (1992) in Zambia and Vogel (1994) in Zimbabwe have reported that land managed by reduced tillage techniques, in comparison with mouldboard ploughing, quickly developed a severe perennial weed problem. The rhizomatous perennial grass, *Cynodon dactylon*, is a particular problem on sandy soils in semi-arid southern Africa (Hillocks *et al.*, 1996) and, when present,

Table 19. The effect of herbicide and ploughing treatments on C. dactylon dry weights at six sites at Gutu Communal Area on 7/01/95 and mean maize grain yields

Farm/	*C. dactylon* dry weights (g m^{-2})							Mean yield
treatment	1	2	3	4	5	6	Mean	(kg ha^{-1})
FGWPSP	28.3	74.1	21.2	14.8	9.6	8.1	26.0	822.0
HGWPSP	27.6	105.2	21.2	48.9	6.3	7.9	36.2	1084.0
WPSP	51.4	96.7	31.3	18.2	6.2	1.5	34.2	852.0
FGSP	0.0	103.0	0.0	13.0	0.0	0.0	19.3	1182.0
DSP	1.6	118.9	1.5	19.3	1.3	1.2	24.0	1032.0
SP	31.7	253.7	13.8	22.6	11.0	4.8	56.3	663.0
s.e. Farm			10.40***				s.e. Yield	142***
s.e. Treatment			104.00*					
s.e. Farm Treatment			25.40**					

***P>0.001, **P>0.01, *P>0.05; FG - full rate glyphosate 2.2. kg a.e. ha^{-1}; HG - half rate glyphosate 1.1 2.2 kg a.e. ha^{-1}; WP - winter ploughing; SP - Spring Ploughing; DSP - Double spring ploughing
Source: Mabasa *et al.*, 1995.

is a constraint to crop production using a no-till ridge system, as farmers owning only a plough have no opportunity to control weeds effectively without recourse to hand weeding. *C. dactylon* is also able to proliferate under systems based on a single shallow mouldboard plough/planting operation. It has been demonstrated that it can be brought under control by occasionally ploughing twice before planting, provided the rainy season starts early and sufficient time is allowed between tillage passes to ensure desiccation of rhizomes (Phillips, 1993). Harrowing, on the other hand, undertaken by some farmers to remove rhizomes from the land prior to planting, promoted greater regrowth of *C. dactylon* (Twomlow *et al.*, 1997b). Recent work has also shown that the herbicide glyphosate applied to *C. dactylon* regrowth following the onset of spring rains combined with the traditional practice of a single pre-plant ploughing, can suppress the weed and increase maize yields by 20-50% over ploughing alone (Table 19, Mabasa *et al.*, 1995). Application costs may be reduced by spraying only the patches of individual fields which are infested and by using a reduced rate, applied post-harvest, followed by double spring ploughing which also contributed to higher levels of moisture in the soil profile. Selective spraying is also gaining favour in advanced cropping systems because of the associated economic and environmental benefits (Miller *et al.*, 1995; 1997).

It is being increasingly recognised that farmers in sub-Saharan Africa often have a clear understanding of the interrelationships between the range of issues, including available household resources, which need to be integrated to achieve a good crop stand, and to grow a weed-free crop in synchronisation with available soil moisture (Bonitatibus, 1991; Riches *et al.*, 1998). Baker (1987) found that recommendations for early and multiple weeding in Botswana, based largely on technical considerations

Table 20. Farmers' perceptions of crop establishment and weeding method

Practice	Strengths	Weaknesses
Crop establishment		
Third furrow planting behind plough	Combines ploughing and planting, giving an overall saving in DAP and labor Ensures early weed control	Poor germination Higher labor and DAP than rip and OPFP
Rip or Open Plough furrow planting	Good crop emergence DAP and labor reducing Improves soil moisture retention Loosens plough pan Increases yields	Land has to be ploughed before planting operation Early weed growth between crop rows Seed may not be well covered
Weeding		
Hand hoe	Ensures clean weeding	Labor intensive and back breaking
Ox-drawn five tine cultivator	Labor saving and fast for interrow weeding	Weeds must be small Crop damage
Ox-drawn plough with mouldboard	Labor saving, smothers weeds, conserves moisture when ridges tied, promotes drainage in vleis	Crop damage May cause erosion if ridges are not tied

Source: Riches *et al.*, 1998.

of weed/crop competition, are unlikely to be adopted, particularly in drought years: farmers are unwilling to invest limited labor resources in weeding until they are certain that the rains will be sufficient to produce a yield. Rather than being prescriptive, researchers and extensionists need to work closely with farmers to explain more fully how and why a particular practice works, so that they are in a better position to determine for themselves what they can and can not afford to do (Shaxson and Riches, 1993). The risks and benefits of technology options can then be evaluated by farmers according to their criteria and their resources (Table 20). In southern Zimbabwe, for example, many farmers seem prepared to accept that earlier weeding, with greater draught and labor inputs, will be needed after planting into a rip line, so long as this consistently allows timely planting and results in a good crop stand (Riches *et al.*, 1998). Although farmers are looking for technologies which ease labor and DAP constraints, they are prepared to accept certain tradeoffs to achieve the all-important crop stand with a minimum of risk. The success with which tradeoffs in the system and flexibility in management decision-making can be maintained as the season unfolds and weather patterns change, depend largely on a household's access to resources. Some 35% of the communal farms in southern Zimbabwe, with only limited labor, and who either hire or borrow DAP from other families, are probably unable to respond to the changing soil moisture situation by weeding with a plough, for example, to conserve moisture on the dry sandy upland fields or to encourage drainage in the seasonally inundated valley bottom *vlei* fields. It is difficult to foresee how these resource- constrained households can benefit from the introduction of sustainable production methods, even those which involve limited modification of existing systems, without considerable financial support.

Soil Fertility Management

Towards sustainable soil fertility

The African smallholder farmer is backed by generations of experience to enable him and his family to survive in difficult situations. However, he faces the inescapable problem that unless soil fertility is maintained, or increased, on his smallholding, he will fail, surely and swiftly. Many farming communities in sub-Saharan Africa are aware that increasing infestation of cereal crops by the parasitic witchweeds (*Striga* species) and associated yield loss, is an indicator of decreasing soil fertility, but, in Malawi for example, given the lack of new land and increased fertiliser prices, farmers feel powerless to reverse the process (Shaxson and Riches, 1993). The past option of shifting agriculture has largely gone. There is also considerable migration from the land to the cities by the younger people, with all the associated social problems.

Soil organic matter dynamics

Soil organic matter is of special importance for soil fertility because it influences so many other soil properties. It acts as both a sink and a source of plant nutrients, especially N, P and S, as a vital determinant of soil physical structure and water holding properties, and as an energy source for the micro- and macro-organisms in soil. It, therefore, plays a central role in smallholder farming.

While much of soil organic matter is apparently inert, there is a small, variable pool of micro-organisms and their metabolites, which is comparatively much more active. It is the turnover of this 'active fraction' and the flux of nutrients through it, which disproportionately controls the supply of N and much of the P to crops unless inorganic fertilizers are used (Brookes *et al.,* 1995).

The world-famous Kabete field experiment in Kenya demonstrated clearly both the need for long-termism in experiments and to maintain soil organic matter levels. In the first ten years, there were no differences in yields between plots given inorganic fertilizers (NPK) and those given farmyard manure (FYM). However, after this, the yields declined more rapidly when only NPK was applied than when FYM was given. In all cases, the soil organic matter declined over the twenty or so years of the experiment (Swift *et al.,* 1994).

As Swift *et al.* (1994) pointed out, it would be naive in the extreme to extrapolate any of these results too far in the direction of the farmer. Certainly, the long-term use of inorganic fertilizer, without additional organic manure, could have been catastrophic.

The classic approach of villages and families adopting practices such as slash and burn and shifting agriculture shows that in much of Africa, the low levels of available nutrients and organic matter are serious constraints to crop production. However, the pressure on land means that these farming practices are no longer able to meet the ever increasing demand for food.

Often, organic inputs, such as crop residues and animal manures, are the only sources of nutrients available to the smallholder. If they are to offset the losses of nutrients in removed produce, it is obviously important that organic residues are imported from other sites or nutrient depletion must inevitably result. In fact, this is seldom the case and the nutrients supplied from organic sources alone, even green manures and inter-crops such as *Crotalaria juncea* and *Sesbania sesban*, are rarely sufficient to meet crop demands beyond a single season (Waddington *et al.*, 1998). Thus, despite the evident importance of soil organic matter in smallholder farming, its use alone will seldom redress the problem of nutrient depletion.

The level of organic matter in soil is determined by the balance between those factors which determine its formation and those which determine its degradation. Factors promoting its formation include the quality and quantity of the organic inputs to soil and those which influence its degradation includes soil type, pH and climatic conditions. Upon conversion from forest to arable, soil organic matter levels inevitably fall to, eventually, a new, lower, equilibrium level. This can be reversed by a number of methods, but primarily by increasing the inputs of organic matter. Management changes such as transferring from ploughing to minimum tillage also promote organic matter accumulation.

Good organic matter management is important, and indeed it is often one of the very few active management practices open to the smallholder. Nevertheless, if relied upon in isolation, and in very closed farming systems, it cannot provide a sustainable agricultural system for Africa. While the West seems to be moving philosophically towards more 'organically' based agricultural systems, with excessive use of nutrients being more common than shortfalls, if Africa were to follow the same path, the result would be an even bigger disaster than now. Only by increasing the nutrients supplied to crops can nutrient depletion be reversed and the population adequately fed. The way forward has to be by judicious use of inorganic fertilizers and pesticides at the smallholder level and beyond, while simultaneously conserving, and, where possible, increasing, soils' organic matter contents.

Weeds as a resource in soil fertility management

Off-season weeds may have an important role in nutrient conservation in arable land. They act as sinks of nutrients during post-harvest periods, protecting nutrients from losses by leaching, erosion or fixation. Weeds may also transport nutrients from greater depths than most crops and increase total nutrient availability. Weeds may also be composted in mounds for many months to mineralize before being incorporated.

Improvements in soil properties, such as increased water retention, aeration and better soil aggregation have all been observed following incorporation of weeds (Kuhunda, 1999).

Phosphorus

The soils of most smallholders' farms are deficient in plant-available phosphate (P) and P is commonly the nutrient most limiting to crop production. Replenishment of soil

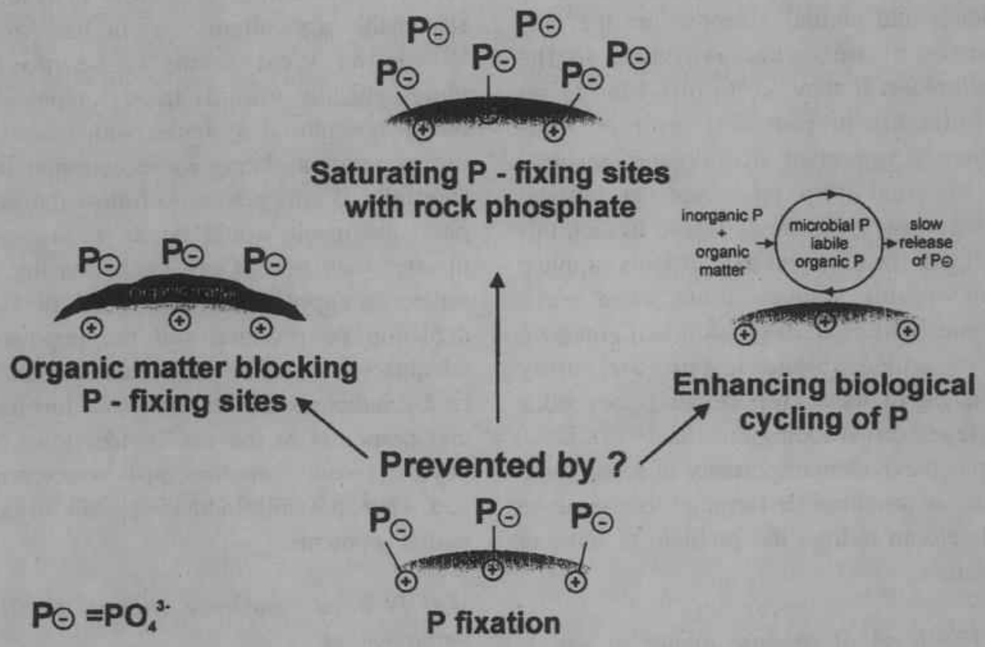

Fig. 7. Possible strategies to overcome the effects of P fixation in soils.

P reserves is best done with soluble fertilizers, rock phosphate, or a combination of the two. Dependence solely upon the cycling of P, through organic systems, is likely to be unsuccessful in supplying the crop's needs, unless abundant P-rich organic manure is available.

Since there are about 530 M ha of P fixing soils in Africa, representing about 25% of total land area, this represents yet another problem for the African smallholder (Sanchez *et al.*, 1997). African smallholder farmers are frugal (by necessity) but innovative. It is common to see farmers applying fertilizer directly around the planted seed or around the base of individual maize plants for example, rather than broadcasting it. This both cuts down upon the total amount of fertilizer used and, by increasing the local concentrations of soil P, helps to saturate the P-fixing sites and so increases the immediate availability of P to plants (e.g. Yost *et al.*, 1981). While soluble inorganic P fertilizers such as superphosphates are rapidly available to plants, rock phosphate only dissolves effectively in soils below pH 6.2 (Sanchez *et al.*, 1997).

The idea of increasing the availability of soil P, especially in P-fixing soils, led Sanchez and Palm (1996) to develop the concept of P capital. This implies the building up of soil P stocks by the use of local rock phosphate or superphosphates to concentrations where it is not limiting and high-energy P binding sites in the soil are saturated (Fig. 7). This stage may be reached by smaller annual P additions or a single large application. After this, only small annual additions of P would be needed to maintain high levels of plant-available P. This approach is worthy of much more work and debate. It could provide high levels of soil fertility for a decade or more, and, in conjunction with legume production to increase N inputs, it could also have big synergistic benefits.

The conversion of inorganic P, at high risk of fixation by soil, to a labile pool of microbial and organic P, which become available to plants during the process of turnover, also helps to increase the availability of P to crops (Fig. 7). George Ayaga at the Kenyan Agricultural Research Institute (personal communication) showed significantly increased yields of maize following applications of farm-yard manure (FYM) and superphosphates in combination, rather than singly in a high P fixing Kenyan soils, compared to a Kenyan soil of lower P fixing properties given identical treatments. Also, by sorbing on soil surfaces, organic matter may help increase P availability to plants by preventing fixation of P by the soil (Fig. 7).

Nitrogen

The three main sources of N for the smallholder, or any farmer, are from biological N_2 fixation, green or animal manures and composts generated from within the smallholder's own farm or from a wider area and inorganic N fertilizers. Unlike P, N can be 'imported', by biological fixation to the soil, but in turn, this depends on a satisfactory supply of other nutrients (Waddington *et al.*, 1998).

A 'broad sweep' review of the literature leads to the conclusion that it is really not feasible to maintain soil organic matter reserves in Africa at levels where N mineralization from organic matter could sustain yields over the medium to long-term. The fast decomposition of crop residues once incorporated, coupled with the rapid turnover of soil organic matter makes it basically impossible for smallholder farmers to maintain adequate levels of soil organic matter. In addition, there is evidence that the organic matter pool formed in tropical soils is more completely degraded, i.e., has less potential to mineralize N per unit of organic matter, than in temperate soils (Grisi *et al.*, 1998).

The availability of inorganic N to crops may be decreased, at least in the short-term, if crop residues of wide C/N ratios are incorporated. The microbial biomass, which has a narrow C/N ratio, often 'out-competes' the developing crop for N, at least during the early stages, leading to N deficiency in the crop. This microbial N may well be subsequently partially re-mineralized, but by then the peak demand of the crop may have passed and yield potentials are irretrievably lost.

Legumes have had a very long history in the economics of smallholder farming. Their obvious attraction is that by converting atmospheric N_2 to biologically available forms, the need for either other organic or inorganic N sources is decreased. Unfortunately, and obviously, they, like all plants, need available P, K and other nutrients to produce a crop. Also, most of their fixed N is in the harvested grain and even when the other residues are returned to the soil, there is a net removal of N from the soil (Giller *et al.*, 1997).

Table 21. Fertilizer imports in Ethiopia (1000 tonnes)

Year	DAP	Urea	N	P	Growth over previous year (%)
1993	97	22	27	20	–
1994	181	28	45	37	74
1995	202	44	56	41	18
1996	280	65	80	57	41

Source: Quinones *et al.* (1997).

There are exceptions to this. Giller *et al.* (1997) reported that longer duration legume varieties of pigeonpea and cowpea could lose substantial amounts of leaf and root biomass before harvest, which could provide up to 40 kg N ha^{-1} and other nutrients to the next crop. However, they make the vital point that most of the information currently available on N_2 fixation by legumes is from research stations, where the crops have received adequate rates of fertilizer N and P. They also suggest that the frequent claims for direct transfer of N to companion cereal crops from legumes are poorly substantiated. Main benefits are probably to the subsequent crop from mineralization of root and stubble residues of the legumes. Agroforestry systems and intercropping offer ways of capitalizing on N_2-fixation by legumes.

Inorganic fertilizer

Most African countries apply, on average, less than 8 kg N ha^{-1} of inorganic fertilizer (including N) to food crops (Table 3). This is the lowest rate to food crops in the world (Quinones, 1997). It is now accepted that the factor most limiting to crop production in Africa is the limitation of nutrient availability (Jansson, 1995). During the last 30 years, cumulative crop removals from about 200 million ha of farmed land in Africa have been about 660 kg N ha^{-1}, 75 kg P ha^{-1} and 450 kg K ha^{-1}. It is inconceivable that nutrient depletion on this scale can be restored without massive returns of nutrients to the land. That it can be done is documented by the dramatic reversal of the decline in agricultural production in Ethiopia from 1993, as outlined by Quinones *et al.* (1997). Since then, fertilizer inputs of N and P have increased at least five-fold (Table 21). With the increased fertilizer inputs, coupled with improved seed varieties, better extension services and the good fortune of favourable rainfall, Ethiopia recorded its highest crop harvests ever in 1996-1997. Over this period, the total crop yield represented a 21% increase over the 1995-1996 estimated yield of 9.7 x 10^6 tonnes.

Surely, there must be a lesson here. Anyone with some knowledge of smallholder farming must realise that mighty steps forward cannot be made overnight. There has been much work done by excellent and dedicated scientists into green manuring, agroforestry, organic matter dynamics and the biological cycling of plant nutrients. These have often provided much needed breathing spaces over the years by permitting the cycling of scarce nutrients in agricultural soils. We also know that inorganic fertilizers alone may not be enough. For example, soil acidification, caused largely by inappropriate use of ammonium-based fertilizers has caused problems. There is also evidence that the dual uses of inorganic and organic fertilizer may be more beneficial than either used alone. However, the case for encouraging a judicious use of inorganic fertilizer at all levels of African agricultural production is very clear on agronomic grounds (Waddington *et al.*, 1998). There is not enough organic fertilizer to supply the food demand of Africa now, let alone in the future.

Discussions with smallholder farmers do reveal interesting misconceptions about the apparent damaging effects of fertilizers. Farmers sometimes maintain that they 'destroy the strength of the soil', and that 'once they are used, nothing else can be'. Certainly, if used wrongly, soil acidification can result and, if applied at the wrong times, (e.g., during periods of drought or high rainfall), they can similarly waste scarce money. However, where we have successfully included the farmer in the research process, the case for using inorganic fertilizer is normally fully apparent to the smallholder before the end of the first growing season (Phia *et al.*, 1998).

Implications for Policies, Institutions and Technologies

In view of the recurrent failures and ineffectiveness of many interventions, there has been increasing concern to look to traditional systems and to build on these to suit present day circumstances (Ellis-Jones and Mason, 1999). Three key elements can play a crucial role in preventing degradation and reducing poverty (Jodha, 1998).

- *Reviving the community stake in the natural resource base*. This requires ensuring genuine local autonomy for local resource management, with a support system for NR user groups encouraging resource protection, investments and use of new technologies for regeneration. It would require a collective stake in ensuring genuine involvement of local communities in NR management.
- *Restoring local control over local resources.* This requires genuine decentralisation of decision making powers and resources to local communities, which in turn requires rebuilding of human and social capital, using participatory techniques to increase NR productivity.
- *Use of local perspectives and traditional knowledge systems*. This requires a focus on bottom-up approaches, sensitisation of decision-makers to local community perceptions. It needs to identify and incorporate appropriate traditional practices into new technological and institu- tional measures.

Policies

Such strategies call for integration of productivity improvement with conservation and management of natural resources. Policies are required to ensure that the poor are specifically targeted and become involved in local decision making processes. Discrimination against marginal areas in public investments needs to be corrected with rural income growth and diversification encouraged, particularly from high value niche products. This will require issues of road access, transport facilities, access to credit and off farm income to be addressed, with appropriate price incentives in place to promote investment in land improvements.

Table 22. Future requirements to achieve sustainable dryland smallholder farming in sub-Saharan Africa

Topic	Current status	Future requirement
Risk minimization	Researchers are just beginning to appreciate the risks that smallholder farmers operate under.	All projects must incorporate farmers attitudes to risk at the project implementation stage.
Quick pay back on investment of scarce resources	Too little attention is paid to the demands a technological interventions have on scarce resources such as cash and labor.	Research must understand the time horizons of the smallholder farming system they are operating within (Liquidity at the start of the season may determine adoption more than final profitability of a technology).
Developing options for each soil type/ farming systems	Too little attention paid to small-holders own land use classification systems.	Researchers must understand local classification systems to ensure results of their work can have a generic applicability.
Interventions developed from an integration of traditional and scientific knowledge	Research is just beginning to undertstand and appreciate tradi-tional soil and water management practices.	On farm research work should acknowledge smallholders tradition.
Pay appropriate attention to biophysical, economic and cultural factors	Frequently ignored in the current research models and is often the reason why uptake of technological interventions does not occur.	Multidisciplinary approaches that acknowledge the complexities of the farming system and the interactions that occur.
Selection of appropriate power sources for crop management	Researchers commonly work in isolation of the farmers and do not appreciate the farm power constraints.	Involve the farmers in the research process, from planning through to implementation and evaluation.
Use of draught animal power to improve soil quality and crop yields/Exploiting livestock to its true potential	Contribution of livestock, particularly draught animals frequently ignored in researcher managed trials.	Contribution of livestock, particularly draught animals to be included in evaluation of technological interventions.
Weed control	Weed research of ten carried out in isolation of the whole cropping system.	Need to understand the interactions between primary land preparation, crop establishment techniques and weed control.
Soil and water conservation	Much research fails to define whether it is conserving soil or water.	Need to understand the complex interactions between soil manipulation, climate and soil water availability.
Long term soil degradation and restorative measures	Work frequently carried out in isolation from the farmers, and often reductionist in approach.	Future research must closely involve the farmer and acknowledge the biophysical and socioeconomic-constraints within which the farmer operates.
Short term effects	The current three year project cycle encouraged by many donors frequently mask climatic and socioeconomic trends.	Need for longer term analyses of interventions through a combination of a longer cycle and judicious use of models.
Issues of land tenure, water rights, grazing rights, etc.	Few if any research projects acknowledge any of these issues.	For uptake to be achieved these issues must be included in the research process to ensure that interventions are appropriately targetted.

This in turn requires appropriate property rights to encourage long term land investments, as well as the design and implementation of innovative, effective and efficient policies on water distribution.

Technologies

Technologies that simultaneously improve productivity and natural resource management are required. This means focussing on developing resource management practices that conserve soil, water and vegetation that increase productivity and reduce risk. The availability of such technologies is limited. It requires diversified farming systems that provide higher returns through vertical integration that will enhance and add value to farm products. At the same time, inputs must be low cost and affordable by the poor.

Conclusions

The goal of research and extension has to be the improvement of farmers' capacities to manage their land sustainably. Management-intensive technologies (which are knowledge-intensive) like soil and water management in particular, require a high level of 'land literacy' and skills. The development and adaptation of innovative practices are one of the vehicles to achieve this goal. However, the major lessons learnt during several decades of research and extension highlight that unless these techniques are built upon farmers' existing knowledge, resource base and decision making criteria, they remain 'on the shelf'. The introduction and imposition of exotic technologies developed in the isolation of the research station has had little success.

Many of the existing recommendations for SWC and SFM practices increase the demand for both labor and DAP, accentuating peak requirements. If these peaks can be reduced or spread through the year, the uptake of new practices is likely to be increased. Practices which reduce peak requirements are attractive and likely to be adopted. The establishment of crops on the flat and ridging up at weeding can meet this requirement and has resulted in widespread adoption by those with adequate DAP. There should, however, be no standard recommendation or package for SWC/SFM promotion in semi-arid areas. Blanket approaches should be avoided.

Innovative ideas and technologies from a variety of sources including farmers, extensionists, researchers and other stakeholders are needed. There is a need to increase technology options through blending traditional and modern technologies reconciling traditional resource-extensive and resource-intensive systems. Simultaneously the organisation of innovation, in terms of services provided by different players (security of land tenure, inputs, credit, marketing, processing, etc.), to enable diversification and intensification need to be taken into account. Ultimately, the end users have to integrate these factors and innovations into their individual farming and livelihood strategies. If sustainable agriculture at the smallholder level is to be achieved in southern Africa and, for that matter, throughout the developing regions of the world, research and extension has to take account of this complexity (Table 22).

Smallholders, like all farmers, are, quite rightly, suspicious of self-professed experts. However, they are generally curious and interested in new approaches provided they do not cost hard-earned money! Farmer-participatory trials, where treatments are applied on small plots on the farmer's field, with the farmer and his family helping directly with soil preparation, planting, application of treatments and harvesting, can break down a number of barriers very fast (Carter *et al.,* 1998).

While fully replicated field trials familiar in the West are rarely practical, other techniques are available to help target research to address the farmers' needs. For example, participatory approaches employed by multidisciplinary teams of researchers, with farmers being part of the research process, rather than the object (Okali *et al.,* 1994; van Veldhuizen *et al.,* 1997). This can then allow a single replicate of each of a set of different treatments (i.e., a block, to include an inorganic fertilizer treatment), to be applied on single farms. With each farm considered as a single block, the whole approaches a fully replicated factorial designed experiment and can be analyzed statistically.

References

Akobundu, I.O. 1987. *Weed Science in the Tropics: Principles and Practices*. Chichester, UK: John Wiley.

Anderson, I.P., Brin, P.J., Moyo, M. and Nyamwanza. B. 1993. *Physical Resource Inventory of the Communal Lands of Zimbabwe - An Overview.* NRI Bulletin 60. Chatham, UK: Natural Resources Institute. 186 p.

Anonymous 1992. *Tools for Agriculture*. Intermediate Technology Publications Ltd. London. 238 p.

Arnon, I. 1972. *Crop Production in Dry Regions.* Volume I. Leonard Hill, London, 683 pp.

Baker, D. 1987. Weed control during drought: A fact sheet. In *Weeds, Their Growth, Impact and Control in Botswana* (Ed. W.T. Stewart-Jones), pp. 9-16. Gaborone, Botswana: Division of Arable Crops Research.

Barrow, C.J. 1988. The present position and future development of rain-fed agriculture in the tropics. *Outlook in Agriculture* 17: 112-119.

Benites, T., Chuma, E., Fowler, R., Kienzle, J., Molapong K., Manu, J., Nyagumbo, I., Steiner, K. and van Veenhuizen, R. 1998. *Conservation Tillage for Sustainable Agriculture*: Part II (Annexes). Proceedings of an International Workshop, Harare, Zimbabwe, 22-27 June 1998. GTZ, Germany. 324 p.

Biot Y., Blaikie, P.M., Jackson, C. and Palmer-Jones, R. 1995. *Rethinking Research on Land Degradation in Developing Countries.* World Bank discussion Paper No. 289. World Bank. Washington DC.

Bonitatibus, E. 1991. Kenya: more than old wives tales. *AERDD Bulletin* 31: 25-31.

Briggs, S.R., Ellis-Jones, J. and Twomlow, S.J. (Eds.) 1998. *Modern Methods from Traditional Soil and Water Conservation Technologies.* Proceedings of a DFID Land Management Workshop, 13-15 January 1998, Kabale, Uganda.

Brookes, P.C. 1995. Measurement, properties and role of the soil microbial biomass in organic matter dynamics and the maintenance of soil fertility. In *Integrated Plant Nutrition Systems* (Eds. R. Dudal and R.N. Roy), pp. 113-128. Report of an Expert Consultation, Rome, 13-15 December 1993.

Bruneau, P. and Twomlow, S. 1999. Hydrological and physical responses of a semi-arid sandy soil to tillage. *Journal of Agricultural Engineering Research* 72: 385-391.

Carson, A.G. 1987 Improving weed management in the draft animal-based production of early pearl millet in The Gambia. *Tropical Pest Management* 33: 359-363.

Carter, S.E., Chuma, E., Goma, H.C., Hagmann, J., Riley, J. and Sokotela, S.B. 1998. On-farm research into the tropical soil biology and fertility programme (TSBF): experiences in smallholder systems of tropical Africa. In *Report of the EU Project No. TS3-CT94-0337: Biological management of small-scale farming systems in tropical Africa* (Eds. S. Carter and J. Riley), Chapter XI, pp. 189-206.

Chatizwa, I. 1997. Mechanical weed control. *Proceedings of the Brighton Crop Protection Conference*, Paper 3C-8, Vol 1, 203-208.

Chatizwa, I. and Ellis-Jones, J. 1997. Zimbabwe smallholder farmers: an assessment of the use and maintenance of tillage implements. In *Improving the Productivity of Draught Animals in sub-Saharan Africa* (Eds. J. Ellis-Jones, A. Pearson, D. O'Neill, and L. Ndlovu), pp. 131-134. Proceedings of a Technical Workshop, Harare, 25-27 February 1997. Report IDG 97/7, Silsoe Research Institute, Silsoe, UK.

Chatizwa, I., Ellis-Jones, J., Mazhangara, E., Riches, C.R. and Twomlow, S.J. 1998. *Participatory Development of Tillage and Weed Control Technologies in Zimbabwe.* (A report on research and development activities in Zimuto Communal Area and Mshagashe Small-Scale Commercial Area, Masvingo Province, Zimbabwe, November 1995 to November 1997). Silsoe Research Institute Report IDG/98/1.106 p.

Chatizwa, I. and Koza, T. 1998. *Current Utilisation of Draught Animal Power Implements and Farmer Needs for Training and Support.* Paper presented to CARE Zimbabwe Agronomy Planning Workshop, Cotton Training Centre, Kadoma, Zimbabwe, 20-22 May 1998. 9 pp.

Chiduza, C. 1994. *Farm Data Handbook, Crop and Livestock Budgets, Communal Areas Agro-ecological Zones I-V.* Rome: Farm Management and Production Economics Service.

Chuma, E. and Hagmann, J. 1995. Summary of results and experiences from on-station and on-farm testing and development of conservation tillage farming systems in the semi-arid Masvingo, Zimbabwe. In *Soil and Water Conservation for Smallholder Farmers in Semi-arid Zimbabwe - Transfer between Research and Extension, Proceedings of a Technical Workshop* (Eds. S. Twomlow, J. Ellis-Jones, J. Hagmann, and H. Loos), 3-7 April 1995 in Masvingo. 41-60.

Chuma, E., Murwira, K. and Hagmann, J. 1998. Experiences with participatory approaches in the development and dissemination of conservation tillage. In *Conservation tillage for Sustainable Agriculture. Proceedings of an International Workshop, Harare, Zimbabwe* (Eds. Bentes ***et al.***) 22-27 June 1998. Published jointly by FAO, GTZ, ZFU, FARMESA, ARC. Part II (Annexes), 99-108

COMSEC, 1992. *Report of an Expert Consultation on the Establishment of NAMA.* Nairobi, June 1992 (Ed. G.C. Mrema). 108 p. FPRD - Commonwealth Secretariat, London.

Critchley W.R.S., Reij, C. and Willcocks, T.J. 1994. Indigenous soil and water conservation. A review of the state of the knowledge and prospects for building on tradition. *Land Degradation and Rehabilitation.* Vol. 5. pp. 293-314.

Dibbits, H.J. 1993. Human and draught animal power in crop production, past experiences and outstanding problems. In *Human and Draught Animal Power in Crop Production. Proceedings of the Silsoe Research Institute/CEC/FAO Workshop* (Eds. D.H. O'Neill and G. Hendriksen), 18-22 January 1993, Harare. Printed by FAO, Rome, 11-25.

Dixon, J., James, D.E. and Sherman, P.B. 1989. *The Economics of Dryland Management.* Earthscan Publications, London.

Ehui, S. and Polson, R 1993. A review of the economic and ecological constraints on animal draft cultivation in Sub-Saharan Africa. *Soil and Tillage Research* 27: 195-210.

Ellis-Jones, J., Dihenga, H., Tengberg, A., Nyenza, E., Kyambo, B., Martin, H.L. and Twomlow, S.J. 1998a. Farmers' decision making in soil and water conservation: An example from Tanzania. In *Modern Methods from Traditional Soil and Water Conservation Technologies. Proceedings of A DFID Land Management Workshop* (Eds. S.R. Briggs, J. Ellis-Jones and S.J. Twomlow). January 13-15, 1998. The White Horse Inn, Kabale, Uganda

Ellis-Jones, J., Gatsi, T., Mazhangara, E., Chatizwa, I., Twomlow, S.J. and Riches, C.R. 1998b. Tillage and Weed Control Interactions on A Semi-arid Granitic Catena. III. Economic Assessment of Options. *Paper presented at CIMMYT 6th Regional Maize Conference for Eastern and Southern Africa.* Addis Ababa, September 21-25, 1998. 12 p.

Ellis-Jones, J. and Mason, T. 1999. Consideration of livelihood strategies and assets of small farmers in the evaluation of soil and water management practices in the temperate inter-Andean valleys of Bolivia. Paper accepted for publication. *Mountain Research and Development*, 1999.

Ellis-Jones, J. and Mudhara, M. 1995. Factors affecting the adoption of soil and water conservation technologies in semi-arid Zimbabwe. In *Soil and Water Conservation for Smallholder Farmers in Semi-Arid Zimbabwe - transfers between research and extension*. Proceedings of a Technical Workshop (Eds. S.J. Twomlow, J. Ellis-Jones, J. Hagmann, and H. Loos), 3-7 April 1995, Masvingo, Zimbabwe. Silsoe Research Institute Report OD/95/16. 104-117.

Ellis-Jones, J., Twomlow, S.J., Willcocks, T., Riches, C.R., Dhliwayo, H. and Mudhara, M. 1993. Conservation tillage/weed control systems for communal farming areas in semi-arid Zimbabwe. *Brighton Crop Protection Conference - Weeds*, 1161-1166.

Elwell, H.A. 1993. *Development and adoption of conservation tillage practices in Zimbabwe. In FAO (1993), Soil Tillage in Africa: Needs and Challenges.* Soil Resources, Management and Conservation Service, Land and Water Development Division, FAO Soil Bulletin 69. pp. 129-190.

Elwell, H.A. and Norton, A.J. 1988. *No-till Tied Ridging, A Recommended Sustained Crop Production System.* Institute of Agricultural Engineering, Harare. 40 p.

FAO, 1993. *Soil Tillage in Africa: Needs and Challenges.* FAO Soils Bulletin 69. FAO, Rome. 190 pp.

FAO, 1995. *Farm Power Considerations in Farming Systems in Sub-saharan Africa.* Agse and Agsp. Agricultural Support Systems Division. Fao, Rome.

FAO, 1996. The state of food and agriculture. *FAO Agriculutral Series No. 29*. Food and Agriculture Organisation, Rome.

Francis, J. 1996. *The Draught Animal Power Situation in Zimbabwe: A Diagnostic Report.* Animal Power Network of Zimbabwe (APNEZ) Publication.

Giller, K.E., Cadisch, G., Ehalotis, C., Adams, E., Sakala, W.D. and Mafongoya, P.L. 1997. Building nitrogen capital in Africa. In *Replenishing Soil Fertility in Africa* (Eds. R. Buresh, P.A. Sanchez and F. Calhoun), pp. 151-192. SSA Special Publication No. 51.

Gollifer, D.E.1993. A review of interventions aimed at increasing water supply for dryland farming with emphasis on the semi-arid tropics. *Proceddings of 3rd Scientific Conference. SADC-Land and Water Management Programme.* Harare, Zimbabwe. 267-277.

Greenland, D.J., Gregory, P.J. and Nye, P.H. 1998. Land resources and constraints in crop production. Chapter 3. In *Feeding a World Population of more than Eight Million People: A Challenge to Science* (Eds. J.C. Waterlow, D.G. Armstrong, L. Fowden and R. Riley). Oxford University Press in association with The Rank Prize Funds. 39-55.

Grisi, B., Grace, C., Brookes, P.C., Benedetti, A. and Dell'Abate, M.T. 1998. Temperature effects on organic matter and microbial biomass dynamics in temperate and tropical soils. *Soil Biology and Biochemistry* 30: 1309-1315

Hagmann, J.1996. Mechanical soil conservation with contour ridges: Cure for, or cause of, rill erosion? *Land Degradation and Development*: 7: 145-160.

Hagmann, J. 1998. *Conservation Tillage for Sustainable Crop Production Systems. Documented output of the Agritex/GTZ Project 1988-1996.* ARDA-GTZ Integrated Rural development Programme, Masvingo.

Halvorson, A.D., Havlin, J.L. and Schlegel, A.J. 1997. Nutrient management for sustainable dryland farming systems. *Annals of Arid Zone* 36: 233-254.

Harris, D., Fry, G.J. and Miller, S.T. 1994. Microtopography and agriculture in semi-arid Botswana. 2. Moisture availability, fertility and crop performance. *Agricultural Water Management* 26: 133-148.

Hillocks, R.J., Logan, J.W.M., Riches, C.R., Russell-Smith, A. and Shaxson, L.J. 1996. Soil pests in traditional farming systems in sub-Saharan Africa - a review. Part 1. Problems. *International Journal of Pest Management* 42: 241-251.

Hoogmoed, W.B. 1995. The role of tillage in the management of problems in crusting and hardsetting soils. In *Sealing, Crusting and Hardsetting Soils: Productivity and Conservation.* Proceedings of the Second International Symposium on Sealing, Crusting and Hardsetting soils: Productivity and Conservation. The University of Queensland, Brisbane, Australia, 7-11 February 1994. 259-278.

ICRA, 1991. *Analysis of the Coffee based Farming Systems in the Matengo Highlands, Mbinga District, Tanzania. Working document Series,* 15. 120 p.

Inns, F. 1992. Field power. In *Tools for Agriculture.* Intermediate Technology Publications Ltd., London.

Jackson, W.J., Tamrakar, R.M., Hunt, S. and Shepherd, K.R. 1998. Land-use changes in two middle hills districts of Nepal. *Mountain Research and Development* 18:(3) 193-212.

Jaeger, W.K. and Matlon, P.J. 1990. Utilization, Profitability, and the adoption of animal draft power in West Africa. *American Journal Of Agricultural Economics* 72: 35-48.

Jansson, S.L. 1995. Fertilizers and welfare development. *The Fertilizer Society Proc. No. 368.* Greenhill House, Peterborough, England.

Jazairy, I., Alamgir M. and Panuccio, T. 1992. *The State of World Poverty: An Enquiry into its Causes and Consequences.* IFAD. New York University Press, New York.

Jodha, N. S. 1998. *Poverty - Environmental Resource Degradation links: Questioning the Basic Premises.* ICIMOD. Issues in mountain development 98/1. ISSN 1027-0027.

Kuhanda, A.H. 1999. Contribution of off-season weeds to the supply and conservation of soil nutrients under sweet potato ridges at Gairo, Tanzania. *M.Sc. Thesis,* Sokoine University of Agriculture, Moroguro, Tanzania.

Kwiligwa, E.M., Shetto, R.M., Rees, D.J. and Ley, J. 1994. Weed management systems based on animal-drawn cultivators for maize production in the southern Highlands of Tanzania. *Soil and Tillage Research* 29: 383-395.

Lacher, C. and Dikito, M.S. 1991. *Socio-economic Survey with Specific Considerations of Gender Issues in Gutu District Communal Lands, within the CARD programme,* Zimbabwe. Consultancy report. 123 p.

Lal, R. 1987. Managing the soils in sub-Saharan Africa. *Science* 236: 1069-1076.

Liebman, M. and Gallandt, E.R. 1997 Many little hammers: Ecological management of crop-weed interactions. In *Ecology in Agriculture* (Ed. L.E. Jackson), pp. 291-343. Academic Press, San Diego, USA.

Mabasa, S., Riches, C.R., Nyahunzvi, S., Twomlow, S.J., Dhliwayo, H.H. and Chatizwa, I. 1998 Tillage and weed control responses on a semi-arid granitic catena. 1 Weed responses. *Proceedings Sixth Southern African Regional Maize Conference,* Addis Ababa, Nairobi, Kenya CIMMYT.

Mabasa, S., Twomlow, S.J. and Riches, C.R. 1995 Integrated control of *Cynodon dactylon* in communal areas of Zimbabwe. *Brighton Crop Protection conference - Weeds,* 201-206.

Marnotte, P. 1997 Herbicide use constraints and prospects. *Agriculture et Development,* May issue, 2-10.

Martin, J. and Gaudard, L. 1997. Paraquat, diuron and atrazine for the renewal of chemical weed control in northern Cameroon. *Agriculture et Development,* May issue, 29-41.

Martin,L.M., Kayomba, B., Dihenga, H., Nyenza, E., Twomlow, S.J. and Willcocks, T. 1998a. Traditional soil and water conservation in south west Tanzania. I. Technical assessment of Matengo (*Ngoro*) pits. In *Modern Methods from Traditional Soil and Water Conservation Technologies* (Eds. S.R. Briggs, J. Ellis-Jones and S.J. Twomlow). Proceedings of a DFID Land Management Workshop. January 13-15, 1998. The White Horse Inn, Kabale, Uganda. 54-68

Martin, L.M., Kayomba, B., Dihenga, H., Nyenza, E., Twomlow, S.J. and Willcocks,T. 1998b. Traditional soil and water conservation in south west Tanzania. II. Alternatives to the Matengo (*Ngoro*) pits. In *Modern Methods from Traditional Soil and Water Conservation Technologies.* Proceedings of a DFID Land Management Workshop (Eds. S.R Briggs, J. Ellis-Jones and S.J. Twomlow). January 13-15, 1998. The White Horse Inn, Kabale, Uganda, 69-82.

Mashavirà, T.T., Dhliwayo, H.H., Mazike, P. and Twomlow, S.J. 1997. Agronomic Consequences of Reduced Tillage. In *Improving the Productivity of Draught Animals in Semi-Arid Sub-Saharan Africa' Proceedings of a technical Workshop* (Eds. J. Ellis-Jones, A. Pearson, D.O'Neill and L. Ndlovou), 25-27 February 1997, Institute of Agricultural Engineering, Harare, Zimbabwe. 169-177.

Mashavira, T.T., Hynes, P., Twomlow, S.J. and Willcocks, T.J. 1995. Lessons learned from 12 years of conservation tillage research by Cotton Research Institute under semiarid smallholder conditions. In *Soil and Water Conservation Tillage for Smallholder Farmers in Semi-Arid Zimbabwe - Transfers Between Research and Extension' Proceedings of a Technical Workshop* (Eds.

S.J. Twomlow, J. Ellis-Jones, J. Hagmann and H. Loos), Masvingo, Zimbabwe 3-7 April 1995. 22-31.

Mbanje, E and O'Neill, D, 1997. Database for animal drawn tillage implements. In *Improving the Productivity of Draught Animals in sub-Saharan Africa", Proceedings of a Technical Workshop* (Eds. J. Ellis-Jones, A. Pearson, D.O'Neill and L. Ndlovou), pp. 77-119, Harare, 25-27 February 1997. Report IDG 97/7, Silsoe Research Institute, Silsoe, UK.

McLaughlin, A. and Mineau, P. 1995 The impact of agricultural practices on biodiversity. *Agriculture, Ecosystems and Environment* 55: 201-211.

Meijer, R.A. 1992. *Ridging as a Primary TIllage Practice. Results of Three Years of Applied Research.* Report from Animal Draught Power Research and Development Programme, Magoye, Zambia. 14 p.

Miller, P.C.H., Hague, T., Tillet, N.D. and Marchant, J.A. 1997. Approaches to the detection of individual plants in horticultural row crops and implications for pesticide applications. *Brighton Crop Protection Conference - Weeds* 3: 151-158.

Miller, P.C.H., Stafford, J.V.S., Paice, M.E.R., Drew, L.J. 1995. The patch spraying of herbicides in arable crops. *Brighton Crop Protection Conference - Weeds* 3: 1077-1076.

MLARR 1992. *The Second Annual Report for Communal Area Farm Units, 1989/90 crop season.* Harare, Zimbabwe: Economics and Markets Branch, Ministry of Agriculture and Rural Resettlement.

Morse, K. 1996. *A review of Soil and Water Management Research in Semi-arid Areas of Southern and Eastern Africa.* Chatham, UK: Natural Resources Institute. LR14. 187 p.

Moyo, S. 1995. *The Land Question in Zimbabwe.* Sapes Books, Harare, Zimbabwe. 333 p.

Mugwira, L.M. and Murwira, H.K. 1997. *Use of Cattle Manure to Imrprove Soil Fertility in Zimbabwe: Past and Current Research and Future Research Needs.* Soil Fertility Network Researc Results Working Paper 2. CIMMYT, Zimbabwe 24 p.

Munyati, M. 1997. Conservation tillage for sustainable crop production: Results and experiences from on-station and on-farm research in natural region II (1988-1996). *The Zimbabwe Sciences News* 31(2): 27-33.

Muza, L., Dhliwayo, H. and Twomlow, S.J. 1996. Dryland maize response to different combinations of tillage and weeding methods. In *Maize Productivity Gains through Research and Technology Dissemination. Proceedings of 5th Regional Maize Conference for Eastern and Southern Africa* (Eds. J.K. Ransom, A.F.E. Palmer, B.T. Zambezi, Z.O. Mduruma, S.R. Waddington, K.V. Pixley and D.C. Jewell), Arusha, Tanzania, Addis Ababa, Ethiopia, CIMMYT. 110-114.

Norton, A.J. 1987 *Conservation Tillage: What Works.* Paper presented to Natural Resources Board Workshop on Conservation Tillage, June 1987. Harare, Zimbabwe: Institute of Agricultural Engineering.

Okali, C., Sumberg, J. and Farrington, J. 1994. *Farmer Participatory Research: Rhetoric and Reality.* Intermediate Technology Publications. 156 p.

Okoba, O., Twomlow, S.J. and Mugo, C. 1998. Evaluation of indigenous soil and water conservation technologies for runoff and soil loss control in semi-arid Mbeere District, Kenya. In *Modern Methods from Traditional Soil and Water Conservation Technologies. Proceedings of a DFID Land Management Workshop* (Eds. S.R. Briggs, J. Ellis-Jones and S.J. Twomlow), 25-41. January 13-15, 1998. The White Horse Inn, Kabale, Uganda.

O'Neill, D.H. 1998. Ergonomics issues in agricultural development. In *Global Ergonomics* (Eds. P.A. Scott, R.S. Bridger and J. Charteris), pp. 63-67. Elsevier Science Ltd., Oxford.

O'Neill, D.H., Sneyd, J., Mzileni, N.T., Mapeyi, L., Njekwa, N. and Israel, S. 1999.The use and management of draught animals by smallholder farmers in the former Ciskei and Transkei, Eastern Cape Province, South Africa. *Development Southern Africa* 16(3): 319-333.

Panin, A. 1995. Empirical evidence of mechanization effects on smallholder crop production systems in Botswana. *Agricultural Systems* 47: 199-210.

Parker, J.M.H. and Vernon, R. 1982. Maize herbicides for small-scale farmers in Zambia. *Tropical Pest Management* 28: 259-265.

Pearson, A. 1996. Feeding strategies for cattle and buffalo used for work. *World Animal Review* 87: 45-55.

Phia, M., Machikicho, J. and Pangenyama, W. 1998. Evaluation of a fertiliser based soil management package for variable rainfall in communal areas of Zimbabwe. In *Soil Fertility Research for Maize-Based Systems in Malawi and Zimbabwe. Proceedings of the Soil Fertility Network Results and Planning Workshop* (Eds. S.R. Waddington, H.K. Murwira, J.D.T. Kumwenda, H. Hikwa and F. Tagwira), pp. 223-228. 7-11 July, Africa University. Mutare, Zimbabwe. Soil Fert Net and CIMMYT-Zimbabwe, Harare, Zimbabwe.

Phillips, M.C. 1993. Use of tillage to control *Cynodon dactylon* under small-scale farming conditions. *Crop Protection* 12: 267-292.

Quinones, M.A., Borlang, N.E. and Dowswell, C.R. 1997. A fertilizer based green revolution for Africa. In *Replenishing Soil Fertility in Africa* (Eds R.J. Buresh, P.A. Sanchez and F. Calhoun), pp. 81-96. SSA Special Publication No. 51.

Reeves, T.G. 1997. *Sustainable Development of Agriculture.* Mexico, DF. CIMMYT.

Reij, C., Scoones, I. and Toulmin C. 1996. *Sustaining the Soil. Indigenous Soil and Water Conservation in Africa.* Earthscan Publications, London.

Richards, P.V.M. and Thomas, P.E.L. 1971 Effects of cultivation after planting on yields of seed cotton. *PANS*, 17: 484-485.

Riches, C.R., Ellis-Jones, J., Twomlow, S.J., Mazhangara, E., Dhliwayo, H.H., Mabasa, S. and Chatizwa, I. 1998. Participatory development of tillage/weed management practices for maize farmers in semi-arid Zimbabwe: Who benefits? In *Proceedings of 15th International Symposium of the Association for Farming Systems Research and Extension*, Volume 3, pp. 1480-1488, Pretoria, South Africa.

Riches, C.R., Twomlow, S.J. and Dhliwayo, H.H. 1997. Low-input weed management and conservation tillage in semi-arid Zimbabwe. *Experimental Agriculture* 33: 173-187.

Rogan, A. and O'Neill, D. 1993. Ergonomics aspects of crop production in tropical developing countries: a literature review. *Applied Ergonomics* 24: 371-386.

Rowland, J.R.J. (Editor), 1993. *Dryland Farming in Africa.* Macmillan Press Ltd. 336 p.

Rukuni, M. 1994. *Report of the Commission of Inquiry into Appropriate Agricultural Land tenure Systems.* Technical reports for His Excellency The President of the Republic of Zimbabwe. Government Printer, Harare.

Sanchez, P.A. and Palm, C.A. 1996. Nutrient cycling and agroforestry in Africa. *Unasylva 185*, 47: 24-28.

Sanchez, P.A., Shepherd, K.D., Soule, M.J., Place, F.M., Buresh, R.J., Izac, A.M., Mokwunye, A.U., Kwesiga, F.R., Ndiritu, C.J. and Woomer, P.L. 1997. Soil fertility replenishment in Africa: an investment in natural resource capital. In *Replenishing Soil Fertility in Africa* (Eds. R. Buresh, P.A. Sanchez and F. Calhoun), pp. 1-46. SSSA Special Publication No. 51.

Sarapinda, C.D. 1990. *Adoption of Dry Seasons CARD Production Recommendations.* Report No. 7. Monitoring and Evaluation Unit, AGRITEX, Harare. 11 p.

Schwerzel, P.J. 1976 The effect of depth of burial in the soil of some common Rhodesian weed seeds. *Rhodesian Agricultural Journal* 73: 97-99.

Scoones, I. 1995. Investigating difference: applications of wealth ranking and household survey approaches among farming households in southern Zimbabwe. *Development and Change* 26: 67-88.

Shaxson, L.J. and Riches, C.R. 1993. Incorporating farmer knowledge in the design of weed control strategies for smallholders. *Brighton Crop Protection Conference - Weeds* 3: 1149-1154.

Shumba, E.M., Waddington, S.R. and Rukuni, M. 1992. Use of tine tillage with Atrazine weed control, to permit earlier planting of maize by smallholder farmers in Zimbabwe. *Experimental Agriculture* 28: 443-452.

Swanton, C.J., Clements, D.R. and Derksen, D.A. 1993. Weed succession under conservation tillage: A hierarchical framework for research and management. *Weed Technology* 7: 286-297.

Swift, M.J., Seward, P.D., Frost, P.G.H., Quereshi, J.N. and Muchena, F.N. 1994. Long-term experiments in Africa: developing a database for sustainable land use under global change. In *Long-term Experiments in Agricultural and Ecological Sciences* (Eds. R.A. Leigh and A.E. Johnston), pp. 229-252. CAB International.

Tagwira, F.1992. Soil erosion and conservation techniques for sustainable crop production in Zimbabwe. *Journal of Soil and Water Conservation* 47: 370-374.

Templeton, S.R. and Scherr, S.J. 1996. *Population Pressure and the Microeconomy of Land Management in Hills and Mountains of Developing Countries.* EPTD Discussion paper No 26. International Food Policy Research Institute, Washington DC, USA.

Tengberg, A., Ellis-Jones, J., Kiome, R. and Stocking, M. 1998. Applying the concept of agrodiversity to indigenous soil and water conservation in eastern Kenya. *Agriculture, Ecosystems and Environment* 70: 259-272.

Terry, P.J. 1996. The use of herbicides in developing countries. In *Proceedings of the Second International Weed Control Congress,* Copenhagen, pp. 601-609.

Thomas, D.1999. *Ruminants in Crop-animal Systems in Developing Countries: Beasts or Benefactors?* Inaugural Lecture Series, University of Greenwich, UK.

Thomas, M.F. 1994. *Geomorphology in the Tropics: A study of Weathering and Denudation in Low Latitudes.* John Wiley & Sons. 460 p.

Tiffen, M., Mortimore, M. and Gichuki, F. 1994. *More People, Less Erosion. Environmental recovery in Kenya.* London, Wylie and Sons.

Twomlow, S.J. and Bruneau, P.M.C. 1998. Soil water regimes in semi-arid Zimbabwe. In *Hydrology in a Changing Environment. Volume 2 Theme 5. Proceedings of the British Hydrological Society International Conference*(Eds. H. Wheater and C. Kirby), pp. 437-446. Exeter, July 1998.

Twomlow, S.J., Dhliwayo, H.H., Riches, C.R., Zvarevashe, V., Rufu, N. 1998. Tillage and weed control interactions on a semi-arid granitic catena. I. Maize yield responses. *Paper presented at CIMMYT 6th Regional Maize Conference for Eastern and Southern Africa.* Addis Ababa, September 21-25, 1998. 12 p.

Twomlow, S.J., Ellis-Jones, Hagmann, J. and Loos, J. (Eds) 1995. *Soil and Water Conservation Tillage for Smallholder farmers in Semi-Arid Zimbabwe - Transfers between Research and Extension. Proceedings of a Technical Workshop, Masvingo, Zimbabwe 3-7 April 1995.* OD/95/16. 200 p.

Twomlow, S.J. and Hagmann, J. 1998. *A Bibliography of References on Soil and Water Management for Semi-Arid Zimbabwe.* Silsoe Research Institute Report IDG/98/19.

Twomlow, S., Riches, C.R. and Mabasa, S. 1997a. Weeding - It's contribution to water conservation in semi-arid maize production. *Brighton Crop Protection Conference - Weeds,* 185-190.

Twomlow, S., Riches, C., Mabasa, S. and Nyahunzvi, S. 1997b. Tillage options to control *Cynodon dactylon* in maize crops in semi-arid Zimbabwe. In *Agroecological and Ecological Aspects of Soil Tillage, Bibliotheca Fragmenta Agronomica, 2B/97,* pp. 653-656.

Twomlow, S.J., Zvarevashe, V., Ellis-Jones, J. 1997c. An evaluation of tied ridging as a conservation measure for smallholder African farmers. *Bibliotheca Fragmenta Agronomica, 2B/97 (presented to 14th ISTRO Conf. Agroecological and ecological aspects of soil tillage). Pulawy, Poland.* 657-660.

van Veldhuizen, L., Waters-Bayer, A., de Zeeuw, H. 1997. *Developing Technology with Farmers: A trainer's guide for Participatory Learning.* Zed Books. 230 p.

Vernon, R. and Parker, J.M.H. 1983. Maize/weed competition experiments: Implications for tropical small-farm weed control research. *Experimental Agriculture* 19: 341-347.

Vogel, H.1993. Tillage effects on maize yield, rooting depth and soil water content on sandy soils in Zimbabwe. *Field Crops Research* 33: 367-384.

Vogel, H. 1994 Weeds in single-crop conservation farming in Zimbabwe. *Soil and Tillage Research* 31: 169-185.

Unger, P.W. 1984. *Tillage Systems for Soil and Water Conservation.* FAO, Rome, Soil Bulletin No. 54: 278 p.

Waddington, S.R. 1991. Agronomic problems related to tillage in smallholder cereal production, and some research opportunities. In *Tillage, Past, Present and Future.* Farming Systems Workshop Report No. 22, Harare, Zimbabwe: CIMMYT.

Waddington, S.R., Murwira, H.K., Kumwenda, J.D.T., Hikwa, H. and Tagwira, F. (Editors), 1998. *Soil Fertility Research for Maize-Based Systems in Malawi and Zimbabwe.* Proceedings of the Soil Fertility Network Results and Planning Workshop, 7-11 July, Africa University, Mutare, Zimbabwe. Soil Fert Net and CIMMYT-Zimbabwe, Harare, Zimbabwe. 312 p.

Waterlow, J.C., Armstrong, D.G., Fowden, L. and Riley, R. (Eds) 1998. *Feeding a World Population of more than Eight Million People: A*

Challenge to Science. Oxford University Press in assoc. With The Rank Prize Funds.

Willcocks, T.J. 1981. The tillage of clod forming sandy loams in the semi-arid climate of Botswana. *Soil and Tillage Research* 1: 323-350.

Willcocks, T.J. 1988. Tillage systems for sustainable rainfed crop production in semi-arid regions of developing countries. *Proceedings of the International Conference on Dryland Farming, August 15-19, 1988. Amarillo, Texas, USA*. 535-540.

Willcocks, T., Dhliwayo, H., Twomlow, S.J., Mashavira, T., Ellis-Jones, J., Mudhara, M., Riches, C., Hynes, P. and Blessley, C. 1993. *Conservation Tillage Research Programme 1990-1993 and 1993-95*. AFRC Silsoe Research Institute OD/93/25. 129 p.

Willcocks, T.J. and Twomlow, S.J. 1993. A review of tillage methods and soil and water conservation in southern Africa. *Soil and Tillage Research* 27: 73-94.

Yost, R.S., Kamprath, G.C., Naderman, G.C. and Lobato, E. 1981. Residual effects of phosphorus applications on a high phosphorus absorbing oxisol of central Brazil. *Soil Science Society of America Journal* 45: 540-543.