# Effect of Tillage Equipment on Maize Production

## A model for semiarid small holder agriculture

By

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# Declaration

This thesis is my original work and has not been presented for a degree in any other university.

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This thesis has been submitted for examination with our approval as university supervisors.

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# Dedication

This thesis is dedicated to all smallholder farmers who, like my mother did, are striving to improve quality of life for their children with limited resources

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**Gichuki Muchiri**

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# Nomenclature

## Abbreviations and Acronyms

| | |
|---|---|
| ACIAR | Australian Center for Agricultural Research |
| ACT | African Conservation Tillage Network |
| ADP | Animal Draft Power |
| AME | Adult men Labour Equivalent |
| ASAE | American Society for Agricultural Engineers |
| BP | Break Power |
| CM/KEN | Ceres Maize-Kenya |
| COHH | Land Preparation by Custom Hired Oxen, Planting and Weeding by Hand |
| COHO | Land Preparation by Custom Hired Oxen, Planting and Weeding by Hired Oxen |
| COHOTHO | Combination of THO and COHH |
| CONTIL | Conservation tillage |
| FAO | Food and Agriculture Organization |
| FEQ | Farm Equipment |
| FPE | Farm Power and Equipment |
| FYM | Farm Yard Manure |
| HHH | Land Preparation, Planting and Weeding by Hand |
| HYV | High Yielding Variety |
| IARI | Indian Agriculture Research Institute |
| ICAR | Indian Council of Agricultural Research |
| ICRISAT | International Crops Research Institute for Semi-Arid Tropics |
| IRAT | International Crops Research Institute |
| IIRR | international institute of Rural Construction |
| KARI | Kenya Agricultural Research Institute |
| LP | Linear Programming |
| LR | Long Rains |
| MH | Man Hours |
| NCOHO | New Ox-Equipment Custom Hired for Land Preparation and Weeding |
| NIAE | National Institute for Agricultural Engineering |

| | |
|---|---|
| NOHO | New Ox-Equipment for Land Preparation and Weeding |
| OHH | Land Preparation by Oxen, Planting and Weeding by Hand |
| OHO | All Operations by Owned Oxen except Planting |
| OHOTHO | Combination of OHO and THO |
| OXH | Ox-Team Hours |
| PAU | Punjab Agricultural University |
| POR | Package of Recommendations |
| SAT | Semi-Arid Tropics |
| SR | Short Rains |
| SOM | Soil Organic Matter |
| THH | Land Preparation by Tractor the rest by Hand |
| THO | Land Preparation by Tractor, Planting by Hand, Weeding by Oxen |
| TP | Tractor Power |
| TPH | Tractor Hours |

## Greek symbols

| | |
|---|---|
| $\eta$ | efficiency |
| $\lambda$ | fuel calorific value |
| $\tau$ | machine economic life |

## Operators

| | |
|---|---|
| $\Sigma$ | Summation |

# ABSTRACT

The main problem addressed in this thesis is inadequate utilization of farm equipment for conservation tillage in maize production. This problem is manifested in the form of inadequate soil loosening, low application of organic fertilizers, late planting and weeding. These are some of the main causes of low maize yield estimated at one tonne per ha, which is less than half the potential after adoption of available package of recommended practices. Therefore the purpose of the study was to analyse the effect of tested farm equipment on optimum maize production subject to available labour, land, power and specified crop residue recycle. After selecting and testing available tools and equipment it was found that land breaking, furrow making, timely planting and weeding are possible. It was also found that innovative animal draft power (ADP) tillage equipment could significantly minimise runoff. A single objective linear programming (LP) model was formulated to estimate optimum production with input data drawn from technical test performance. The input parameters used were: available farm labour, land, schedule of maize production tillage operations and expected yield for various levels of timeliness of planting and weeding. Variables in the objective function were areas of land planted and weeded at various timeliness combinations whereas the corresponding coefficients were the net maize yields. The output production was therefore in kilograms of maize grain dry matter available per farm. The constraint equations included weekly man-hours, ox-hours and tractor hours available for the scheduled operations over the critical time period starting with the period before the rains. Other constraints included available land for cultivation and surplus crop residue after recycling a specified quantity.

Goal programming was carried out to determine optimum energy use subject to specified crop residue recycles. This time the energy consumption for various timeliness combinations was substituted for yield as the coefficient of the objective function to minimize energy use. At the same time the solution of the linear programming objective function formulation with production as the objective function was stated as an additional constraint to ensure that the optimum production achieved under single objective LP formulation was not violated.

Results show that farmers who own ADP equipment do not require tractor powered (TP) mechanization for seasonal operations unless more than 4.0 ha per farmer cultivated land is available. For farmers who do not own ADP, it is more beneficial to switch to new ADP

equipment than to supplement their capacity with hired tractors. The model experiments show that farmers having 3 ha cultivated land and 3 adult labour equivalent can double maize production from 1800 kg to 3740 kg by simply moving from hiring traditional ADP equipment to hiring innovative ADP equipment. Alternatively the farmer can potentially realise 3550 kg by hiring tractors for land preparation. It can therefore be concluded that TP is justified only when the higher quality of work in terms of depth of tillage and land forming are needed once in three to four years. These results provide the basic information necessary to carry out benefit cost analysis for investment on infrastructure to support sustainable adoption of innovative ADP and supplementary tractor hire service when necessary.

The model developed in this thesis provides a mathematically valid methodology for quantifying the effect of innovative equipment on production before major investments on support infrastructure are made. The model is also appropriate for quantifying the effect of combining ADP and TP and showing that they are complimentary and not mutually exclusive. Application of this model for the mechanization of semi arid agriculture in Kenya can have positive effect on food security, incomes and employment and thus contribute to the realization of vision 2030.

# CHAPTER ONE
# INTRODUCTION

## 1.1 Small Scale Farming in Semi Arid Tropics

Semi arid tropics (SAT) are areas of land where annual rainfall ranges between 50 and 25 percent of evapotranspiration (Jaetvold and Schimidt 1983). They occupy 21 million km$^2$ of land; 70% (14.6 million km$^2$) of it being in Sub-Saharan Africa alone (El-Swaify *et al*, 1987; Kampen and Burford, 1980). Due to a rapid rate of natural population increase and migration from already densely populated high potential humid and semi-humid areas, otherwise ecologically balanced nomadic grazing and shifting cultivation has given way to continuous crop cultivation, deforestation and overgrazing (FAO, 1984; FAO, 2000; FAO, 2001). The ensuing environmental impact has adversely affected the emerging farming systems especially in Sub Sahara Africa.

### *Sub Sahara Africa*

Sub Sahara Africa (SSA) has a total population of 626 million people of whom 384 million (61%) are classified as agricultural. With 2455 million ha total land area of which only 173 million ha (about one quarter of the potentially arable areas) is under cultivation or permanent crops, the region is relatively well endowed with natural resources. More than half of the population (70% in western Africa) live in the humid and sub humid areas. Therefore much of the abundant natural resources in the semiarid areas are under pressure of a rapidly increasing population both due to natural increase as well as out migration from adjacent high potential humid and semi humid areas. The result is a multiplicity of smallholder farmers using animal draft power for continuous cultivation and thus causing soil degradation, low yields and associated poverty, food insecurity and unemployment. This is well manifested in the gross domestic product (GDP) which, at constant prices, was lower in 1990 than in 1970. Moreover nineteen of the 25 poorest countries in the World are found in SSA and income inequality is high; 43% of the population living in countries where per capita GDP is less than US $300 i.e. below the international poverty line of one dollar per person per day (FAO 2001).

## 1.2Maize Mixed Farming System

According to FAO (2001) one of the major farming systems in SSA known as 'maize mixed farming system' accounts for 246 million ha or 10% of SSA land area, 32 million ha (19% of SSA cultivated land) and is settled by an agricultural population of 60 million (15% of SSA agricultural population). The climate varies from moist sub humid to dry sub-humid. However the farming system is continually expanding into semi arid areas. The marginal land between dry sub-humid and semi-arid areas is relevant to this study. At the altitude of 800 to 1500m this area covers parts of Eastern, Central and Southern Africa. A typical household of the maize mixed farming system includes:

*A husband, wife and four children of their own plus an older relative and several orphans left by one of the husband's deceased brothers. It would have 1.6ha cropped land, 2 or 3 cattle and use own oxen to plough the land. The yields would be 1.2 t/ha for maize and around 900kg/ha for sorghum, 800kg/ha millet and 500kg/ha pulses. One son works outside the farm and sends occasional remittances used to pay school fees and clothing (FAO 2001).*

There is a need to increase food production and income generation in order to meet the needs of the rapidly increasing population. One of the strategic options is to improve land husbandry by adopting conservation farming including conservation tillage (ACT & IIRR, 2005). Moreover there are signs of entrepreneurs establishing themselves in the rural areas. Access to basic infrastructure of transport, a line of credit, and a market in the vicinity have encouraged the initiation of small primary processing, for example threshing, oil extraction, milling and similar activities with far reaching implications for employment creation *(FAO 2001)*. There is a need for agricultural intensification to generate investment capital necessary to sustain these initiatives. The *sine qua non* for these developments is food security in which maize production plays a pivotal role.

## 1.3 The Kenyan Case Study

In the Kenyan context, the area of interest is classified as wet semi-arid which consists of transitional land of marginal agricultural potential lying between semi humid and dry semi arid areas (Jaetvold and Schimidt, 1983). This area is occupied by farmers who have migrated from adjacent densely populated humid and sub humid areas. Being the staple diet, maize has virtually replaced traditional millets, sorghums and pulses. The latter is the typical semiarid area occupying 8.6 million ha which is about 50% of all the Kenyan rain-fed agricultural land. Traditionally it is pastoral land but recently significant crop cultivation of millets, sorghums, cowpeas, grammes and drought resistant maize varieties have been introduced. Currently 10 million people live in arid and semi arid areas and form the bulk of the 10 million currently affected by hunger crisis in Kenya which was declared by the President in 2009.

## 1.4 Development Challenge

The main concern in the development of semiarid smallholder agriculture is that farmers are not able to produce enough for food security and extra income despite the fact that they have excess land and there is under employment and unemployment in the rural areas. Although a package of recommended practices for maize production has specification for bio-chemical inputs such as improved seed, fertilizer, plant protection and spacing, the average yield is still about one tone per ha which is less than half the expected yield had the recommendations been carried out efficiently. Additional recommendations include timely planting, timely weed control, soil and water conservation, and application of organic fertilizers. These additional recommendations are not clear about how timeliness can be achieved. The reality is that farmers are generally late for land preparation due to subsurface soil compaction or the plough pan which has developed over the years. Late planting competes for labour with the weeding of early planted crop and thus causing late weeding (Nadar, 1984; Steward, 1984). The low yields therefore can be attributed to soil moisture deficit as well as soil nutrient deficit due to low organic matter in the soil and relatively shallow rooting system. In other words farmers have not been able to benefit from available package of recommended practices.

The significance of this problem can further be underscored by the fact that Kenya has in the last thirty years experienced varying levels of maize importation, at 224,000 metric tones in 1980/81 to over one million metric tones required in 2009. If adoption of technologies for conservation tillage can help expand cultivated land by about 10 percent of the 11.3 mha semi arid land in Kenya (i.e. one million ha), at a modest maize yield of 1.8 tones per ha, the additional food amounting to 1.8 million tones can eliminate maize importation and restore Kenya's status as a maize exporter. This is implied in the vision 2030 where the government has planned crop expansion of 1.2 mha in the semiarid areas.

## 1.5 Problem definition

Factors that affect maize crop yield in semi arid small holder agriculture are discussed by Keating *et al* (1992). They include; improved seed, early planting, and early weed control, application of both organic and inorganic fertilizers, plant spacing and plant protection. The rates of adoption of some selected components of this extension package in 1980 and 1990 were observed by Parton and Muhammad (1992). They concluded that inefficient and low adoption of some of the components is the main cause of low maize yield estimated at less than one tone per ha. This is less than half the potential yield estimated by Keating *et al* (1992).

Agricultural Mechanization Branch of the Ministry of Agriculture carried out surveys and workshops for the development of a National Agricultural Mechanization Strategy (NAMS). The study (Ministry of Agriculture, 1994) came up with the problem analysis which showed that the core problem was inadequate mechanization which means inadequate utilization of farm equipment. As a result land preparation including soil loosening, organic fertilizer application, time of planting and weed control were carried out inefficiently and late. At the same time labour and land resources were not fully utilized.

On the one hand three factors namely low crop yield, low utilization of labour and land combine as the main causes of low production of food and associated raw materials for agro-industries. On the other hand the immediate cause of these problems is inadequate mechanization as a result of poor planning, design and back up services (Stout, 1971). The development problem addressed in this thesis arise due to the fact that increased farm incomes, food security and employment are unlikely to be realized if the policy makers will not allocate the necessary investment to empower farmers in accessing and utilizing the necessary farm equipment.

## 1.6 Justification

The national public policy is to meet the overall goal of increasing farm income, food security, and employment through increased production of food and raw materials using available land, labour and power, to achieve the feasible production potential for the target farmers (Figure 2.1). Researchers have responded by providing a package of recommended practices which farmers must adopt to realize that potential. The problem is that this potential is not being realized by farmers. The response from researchers in this case is that although farmers' adoption of the bio-chemical part of the package including improved seed, plant population and plant protection is significant, realisation of associated benefits is constrained by inadequate timeliness of planting and weeding (Parton and Muhammad, 1992). Moreover inadequate amount of crop residue is being recycled. Naturally this is a demonstration of inadequate utilization of farm equipment for tillage. Past R&D efforts to address the problem were piece meal for example, provision of tractor hire services (THS) for land preparation only without providing equipment for planting and weed control. Moreover evaluation and testing of animal draft power equipment was not accompanied with a good understanding of the costs and benefits associated with subsequent adoption programmes (Ministry of Agriculture, 1994). There is need for capacity building in farm equipment selection based on adequate planning, design and backup services in order to guarantee adequate utilization. This implies the need for assessment of farm level needs, resources and constraints, search for appropriate farm equipment designs worldwide as well as evaluation and testing under controlled field experiments (Wright, 1977 and Muchiri, 1984). It also implies that there is a need for national infrastructure of roads, workshops, R&D, manufacturing and training institutions. The *sine qua non* for these developments is a reliable prediction of the expected increase in production due to farm equipment adoption.

## 1.7 Objectives

The main objective of this study was to develop a model for quantifying the effect of tillage and equipment on maize production. Specific objectives were to:

1. Assess farm level needs, resources and constraints to tillage and equipment adoption for increased maize production in the case study area of Eastern Kenya.
2. Establish the field capacity of tillage system methods and equipment under controlled field experiments in the case study area.
3. Analyze the effect of tested tillage system methods and equipment for semiarid smallholder agriculture on optimum maize production and energy use subject to available labour, land, power and specified crop residue recycle.

## 1.8 Out line of the thesis

The thesis comprises literature reviews, field experiments and computer modelling. Field experiments were conducted at Katumani National Dryland Farming Research Station in Eastern Kenya whereas a limited set of experiments were conducted on the Rhine basin in Holland. Computer modelling included linear optimization and goal programming. Chapter two covers literature review to identify Animal Draft Power (ADP) tillage and equipment for semiarid smallholder maize production, effect of tractor mechanization on smallholder agriculture and methodologies for quantifying the effect of technology on small farm production. It ends with Section 2.4 which is the synthesis of the review culminating in the problem analysis and identification of objectives.

Chapter three covers methodology in three sections according to the three objectives. It starts with discussion of the conceptual model which shows the input and output parameters. This is followed by detailed discussion of methodologies including the models used and associated equations. Details of data collection, analysis and specific examples of input data processing are given in appendices A, B, and C. Chapter four is the results and discussion. Farm level production as predicted by the model is illustrated in both kilograms per farm unit as well as Kenya shillings at 1990 prices. The result show definite trends as farmers achieve various levels of farm equipment adoption. It is clear that adoption of innovative ADP equipment is superior to tractor hire service (THS) unless the latter is adopted specifically to reclaim land through sub soiling (20 – 30 cm).

Chapter five is the general discussion, conclusions and recommendations. It has given the summarized results, which show that the objectives of the study were met. Thus the effect of tillage and equipment on production was predicted subject to available labour, land, power and specified crop residue recycle. That means that the tested equipment innovations if adopted can meet such a level of timeliness as to more than double farm production. Moreover the recycle of crop residue is feasible plus a surplus for animal feed. The runoff can also be controlled by the micro-relief created.

It is recommended that researchers consider long term quantifiable productivity attributable to farm equipment for smallholders as one of the prerequisite for mechanization selection (as is the case with irrigation technology). This is facilitated by the fact that the model is based on conventional mathematics, statistics, linear and goal programming with software already in the market. This is the main contribution that this thesis has made to the smallholder agricultural development agenda.

# CHAPTER TWO

# LITERATURE REVIEW

## 2.1 Identification of Animal Draft Power Equipment for Semiarid Smallholder Maize production

### *2.1.1 Introduction*

Crop cultivation based on conventional tillage (land breaking turning in trash and harrowing to produce a smooth seed bed) was brought to Sub Sahara Africa by former European farmers during colonization in the $19^{th}$ Century. The farming was based on horse drawn mould board plough from Europe where conventional tillage was well established. The Animal Draft Power (ADP) Victory plough which spread to East Africa after the First World War is a smaller version of the European horse drawn plough. It is owned by 65% of farmers in typical semi-arid areas in Eastern Kenya (Mutebwa, 1979). In general, conventional tillage has contributed to soil degradation including subsurface compaction, loss of Soil Organic Matter (SOM) and associated low water infiltration rate and low water holding capacity (Hudson, 1961 & 1995; FAO, 1971;).

Conservation tillage evolved from Europe and North America primarily to counteract severe soil erosion observed especially in the Western United States. The principle of reduced, minimum or zero tillage and retention of crop residue on soil surface is meant to reduce surface runoff, reduce surface soil temperature and associated evaporation. At the same time SOM is increased. The above principle implied major changes in the design of soil engaging tools. Tined implements such as chisel shares are designed to loosen soil without inversion but leaving most of the trash on soil surface. Thus the benefits of soil and water conservation as well as soil organic matter build-up are realized.

The purpose of this section is to identify appropriate tillage and equipment for conservation tillage for adoption in smallholder semiarid areas. Specific objective is to identify ADP equipment for seed bed preparation, timely planting and weeding while at the same time conserving water in the soil and retaining trash as mulch. This will be accomplished through review of relevant literature addressing the following questions:

i. What are the tillage and equipment needs, resources and constraints to increased maize production?

ii. What are the available tillage and equipment options

iii. What limitations do they have?

### *2.1.2 Tillage and equipment needs, resources and constraints for maize production*

***Needs***

Luthenberg (1980) observed that a single family with hand tools cannot operate more than one ha of cultivated field crops. At an average yield not exceeding one tone per ha the food produced was inadequate to meet the needs of one family. Increased population and urbanization prompted intensification and expansion of farming using ADP equipment (Pingali and Binswanger, 1987). With a pair of oxen and a plough a family farm can do up to 4 ha (FAO, 1972).

Over time, continuous shallow ploughing without adequate crop residue recycle has resulted in soil degradation including soil erosion, sub-surface compaction as well as low SOM content and associated low infiltration rate and low water holding capacity. Subsurface soil compaction in the form of a hard pan is observed 10 to 20 cm below the surface (ICRISAT 1987). Therefore in addition to innovative ADP tillage and equipment for efficient and timely land preparation and planting there is need for tractors for the purpose of reclaiming compacted soils through sub-soiling (El Well, 1992; El Swaify *et al*, 1987; Macartney, 1971; Willocks, 1981).

***Resources***

Experience in Eastern Kenya shows that although farmers have access to recommended biochemical inputs (fertilizers, improved seeds, crop spacing and protection) additional recommendations including timely planting, timely weed control, soil and water conservation, and application of organic fertilizers present serious challenges. The reality is that farmers are generally late for land preparation due to subsurface soil compaction or the plough pan which has developed over the years. Late planting competes for labour with the weeding of early planted crop and thus causing late weeding (Nadar. 1984; Steward, 1984). In other words farmers have not been able to benefit from available package of recommended practices due to in adequate labour and farm equipment (Muhammad and Parton, 1992; Audi, 1976). Ability to apply Farm Yard Manure (FYM), prepare land, plant and weed on time depends on farmers' access to appropriate equipment and labour. Basically there are three levels of farm equipment in semi arid Kenya namely hand tools, ADP and TP equipment.

The hand tools consist of the hand hoe and the machete. In a survey of a random sample of 205 households and a more detailed survey of 40 households in Mbeere Division in Embu District, Diana Hunt (1974) found that none of the farmers had oxen or an ox plough. The inventory in the report reveals an acute shortage of tools. Thus on the average each of the case study households owned 1.5 hoes, 2.5 machetes, 1.25 digging sticks and only one in four households had an axe. However, a similar survey in lower Machakos District (Mbithi, Muchiri, Kayongo-Male and Thomas, 1977) showed a different picture. Frequency distribution of the farm tools available on the farms visited shows that about 65 % of farmers had one plough while the hoe and the machete still remained the most common tools on these farms with 68% of farmers interviewed having 2 or less hoes and 80% having 2 or less machetes. Considering the fact that there are two machetes and two hoes per average family of three adults plus three children, it is apparent that even the most inexpensive farm tools are lacking to such an extent as to render 1/3 of the farm labour force redundant at any one time. Next in popularity is the shovel, which is an essential soil conservation tool. However 27% of the farmers reported having no shovel and 53% had only one shovel.

Mutebwa (1979) surveyed labour utilization by farmers and identified labour for land preparation, planting and weeding as a major constraint. Although farmers have access to traditional ADP Victory plough the demand for labour is up to 101 man hours per ha during planting and as high as 230 man hours per ha for weeding. It was also estimated that only 16% of farmers had access to tractors.

The other important resource is maize yield potential. Stewart (1984) measured soil water required for various levels of crop yield using irrigation. The possibility of getting the required soil water from available rainfall was considered. Examining time series data for 26 years, it was concluded that there are three categories of seasonal rainfall:

- 1/3 of the seasons are good
- 1/3 of the seasons are medium
- 1/3 of the seasons are low (crop failure)

A process of identifying the type of seasonal rainfall by monitoring the precipitation of the first month of rains onset was developed. With this information, the necessary adjustments for maize spacing and fertilizer application were made in order to minimize loses and maximize the benefits. The adjustments were based on expected maize yield for that season. The existing general recommendations for early planting and early weed control were endorsed; management of inputs being adjusted according to expected rainfall. The limitation with this process is the fact that farmers do not have access to rainfall data and associated capacity to analyse and apply it as necessary.

With inadequate information on the effect of time of planting and time of weeding farmers are not guided with regard to the benefits of mechanization inputs. This is one of the reasons why efforts to apply simulation models in agricultural research in Eastern Kenya can be considered a breakthrough. In this regard, Keating, *et al* (1992) simulated 63 long rains (L.R) and short rains (S.R) seasons and estimated the mean maize yields for delays in planting of 0 to 25 days from rains onset at the National Dryland Farming Research Station, Katumani. Maize yields for the L.R. declined from 2060kg to 1150kg per ha (Figure 3.1). They also estimated that a 20-day delay in planting was likely to lead to crop yield losses of 80% and 60% of L.R and S.R. seasons respectively. These yield losses worked out at 1.2% of grain yield per day delay in the S.R. and 2.5% per day delay in the L.R.

The effect of delay in weeding is similar to the effect of the delay in planting because the weeds also compete with the crop for nutrients and water resources (Ofori, 1993; Stewart, 1984). Makatiani (1971) conducted substantial weeding trials in 1970 and 1971. Although much of the trials were primarily concerned with the method of weeding some of the observations showed significant losses due to delay in weeding over five weeks.

Available information indicates that subject to meeting standard recommendations for improved seed, plant nutrients, plant population and plant protection, farmers can increase crop yields through timely land preparation, planting and weeding. This is partly due to early access to soil moisture and nutrients and reduced competition with weeds. Ofori (1993) observed that '*The soil moisture content and the rate at which soil solution is moving through the soil determine the efficiency at which solutes are redistributed. Crop responses to fertilizers are therefore greatly dependent on the rooting pattern and root distribution, water regime in the rooting zone and nutrient availability within this zone'*. Therefore there is a need to estimate the combined effect of the delay in planting and weeding from available secondary data in order to quantify the effect of tillage and equipment for timely land preparation, planting and weed control on crop yield. Potential increase in yield is therefore a major resource that farmers have not yet exploited.

**Constraints to efficient and timely operations**

In addition to early planting and early weeding, tillage equipment is needed for soil and water conservation. Anderson (1980) reported the Indian experience whereby the bullock drawn traditional equipment consisting of Desi plough, bukhar blade and two or three row seeder with wooden furrow openers and funnel into which seed is metered by hand, were used for optimum soil and water management based on narrow ridge and furrow system. However the ridges tended to slump during the rainy season and when high intensity rainstorms came late, they would bleach causing considerable erosion down-slope. In other words: Attempts to use ADP ridge and furrow cultivation in semi arid areas of India have significant limitations according to Thierstein (1979). He noted that

*"While it was possible to perform all the operations with locally available animal drawn implements, the time required for tillage operations was high and planting precision was poor. It was also difficult to make uniform beds with indigenous machinery"*

The main tillage and equipment constraints to efficient and timely land preparation, planting and weeding are soil compaction and poor rainfall distribution. The latter can be addressed by selection of drought evading or resistant crops which is not within the scope of this study. Soil compaction is the major constraint for farming not only in Eastern Kenya but in most semi arid Eastern, Central and southern Africa.

### *Causes and effects of soil compaction*

Soil compaction is a soil condition which develops in Alfisols and related soils which are common in semiarid areas. The two main soil types in the semi arid areas are Vertisols and Alfisols. Vertisols are clay soils which contain montimorillonite clay minerals commonly known as black cotton soils. They swell when wet and shrink when dry developing deep cracks which render ploughing for soil loosening unnecessary. Alfisols and related soils are sandy clays and sandy loams which contain kaolinite minerals.

According to Charreau (1977), Alfisols over time develop a subsurface compact layer due to the leaching of clay particles when wet. Under low SOM content, the leaching process is exacerbated by continuous soil disturbance during ploughing and associated hoof and wheel tramping (Hudson, 1961; Charreau, 1977; Unger, 1989; Thomas, 1997). The result is well developed compact layer with relatively high density, low porosity and associated low rate infiltration. The roots tend to spread horizontally in the shallow soil layer which is subject to soil erosion when the rains fall and desiccation when the weather dries. Thus root development is handicapped such that the plant utilizes only the top 100 mm of soil whereas the soil depth may be up to one metre deep. Soil compaction is therefore the major constraint to timely land preparation and planting and thus affecting maize yields significantly. It is the main factor determining identification of appropriate tillage and equipment for smallholder maize production (Jonsson, Singisha, and Mbise, 2000).

Past efforts to solve the problem of soil compaction in small-holder semi-arid areas include: (i) multi-farm use of tractors to carry out sub soiling, ii) improved ADP equipment and (iii) crop rotation including planting of crops whose roots can penetrate through the hard pan. The latter is not within the scope of this study. The problem of access to tractors was in early sixties and seventies addressed through various schemes for multi-farm use of tractors such as government supported tractor hire service (THS) as well as through private contractors. However there are few schemes still remaining due to poor support infrastructure and too small economies of scale (Stout, 1971; Downing, 1976; Binswanger, 1978; Pingali and Binswanger, 1987). The role of tractor mechanization in smallholder agriculture is discussed in Section 2.2. In the following paragraphs ADP tillage and equipment options and available alternatives are discussed.

### *2.1.3 Available ADP tillage and equipment options*

In addressing the problem of soil compaction there are both short term and long term measures. In the short term compacted soils may be reclaimed through sub soiling which means sub surface soil loosening with no inversion leaving the trash on surface and roots in the soil. As mentioned above sub soiling is not necessary every year but may be repeated at 3 to 4 years intervals. In the meantime surface runoff is controlled by shallow chiselling and creation of a rough surface, planting the crop along the contour and leaving some trash on surface (FAO, 1971 and 1984).

***Short–term measures***

***Zonal cultivation***

Zonal cultivation may be practiced by creating separately crop management and water management zones in cases where surface runoff control is necessary. Typical techniques include strip tillage and ridge and furrow systems. Strip tillage means loosening soil in the crop zone leaving the inter-row space undisturbed for the purpose of water harvesting into the crop zone. At the same time trash is left on surface to reduce evaporation. Where water drainage is required ridges and furrows are built so that the crop is planted on the ridge whereas the furrow provides water drainage or retention as the case may be. Normally strip tillage and ridge and furrow systems are repeated every season.

Broad bed is a short-term zonal cultivation practice with semi permanent qualities. This is an elevated soil bed one metre wide separated by half a metre furrow along the contour (ICRISAT 1979 and 1987). All the traffic is restricted to the furrow leaving the elevated bed compaction free crop zone. The furrow provides the function of drainage or water retention as the case may be. While the broad bed lasts (3 to 4 years) the necessary seasonal operations can be done by ADP equipment.

In place of locally available and well adopted Desi plough a French-made multi-purpose and wheeled tool carrier known as a "Tropiculteur" was imported. Some of the desirable features of the "Tropiculteur" designed by Jean Nolle (1994) include infinite wheel-track adjustment on the cross beam (from 60 to 180cm), pitch adjustment on the pulling pole to allow for variation in bullock height and vertical clearance of 65cm under the frame for inter-row cultivation. These features earned it the name of "bullock tractor". For equipment requiring rotary power, such as sprayer pumps or mowers, a small engine can be mounted.

However this tillage and equipment system which is technically appropriate for the management of semi arid soils has not been widely adopted because of two main reasons namely: (i) high cost of the imported implement, Tropiculteur at 600 US dollars whereas the locally made (Ard) Desi plough costs 30 US dollars, and (ii) the system demands high precision in operations whereby the draft animal must learn to walk consistently along a permanent furrow (Thierstein, 1979 and Bansal, 1987).

***Shallow chisel ploughing***

Charreau (1977) and EL Well (1992) have suggested that sub soiling can be done at 3 to 4 years intervals whereas shallow cultivation equipment caters for the necessary seasonal operations. Chisel tines have been considered as an alternative to mouldboard plough in order to eliminate inverting the soil and thus minimize soil pulverization and associated runoff and soil erosion. Animal drawn Parabana ripper (Bwalya, 1999 and Rockstrom *et al*, 2009) and the West African Sine Hoe (Jean Nolle, 1994) have chisel tine attachments designed to penetrate through crusted and compacted soil to loosen it without too much disturbance. At the same time a rough surface layer mixed with trash is created to protect the soil from erosion and high temperatures. Therefore the main objectives of conservation tillage namely: to conserve, water, nutrients, soil structure and energy can be achieved in the short-term. Other measures for alleviating soil hard pan formation in conservation farming are discussed in Gitau *et al*, 2004.

***Long term measures***

In the long term increased water infiltration and deep root development produce increased crop yield including biomass. Thus increased SOM and associated physical and chemical fertility of the soil is sustained. If the soil can be kept compaction free by having adequate SOM the need for tillage is minimised or eliminated altogether to give way to no-till practice which is the typical long term conservation tillage strategy in semi humid Alfisols or in semi arid Vertisols where sub surface compaction is not a major problem (Lal, 1986). In the long term the soil can realize adequate and sustainable physical and chemical fertility if and only if adequate crop residue recycle can be achieved (Uri, 1981; Lal, 1975; Okwach, 2002).

The four mechanical soil treatments against soil compaction namely: sub soiling below 25cm, broad beds, ridge and furrow and shallow chisel ploughing, have short-term (3-4 years) or single season effect (in case of the latter two) and have to be repeated at set intervals. They need to be complemented with long term SOM management in terms of vegetative cover and crop rotation. Yu *et al.* (1981) in Lal (1986) observed that fungi, actinomycetes, ammonifying bacteria, N-fixing bacteria and potassium bacteria in mulched plots increased 58.3%, 25.8%, 47.3%, 56.3% and 56.1% more, respectively, than in the unmulched control. The long term benefits of conservation tillage are well documented by other researchers (Lal, 1975; Wang, 2006; Okwach, 2002). Okwach (2002) showed that hand hoeing with mulch cover, high crop density and high application of crop nutrients (high management) can reduce run-off by 58.8% compared with low maize crop density without mulch. However, it was observed that increased runoff by 6.5% due to this same high management treatment but with zero till compared to conventional hand hoe tillage for low maize density (low management) without mulch. This fact underscores the importance of mulch combined with tillage. Wang (2006) also compared conservation tillage (including crop residue application) and conventional tillage (ploughing 22-25 cm deep) after spring maize harvest followed by harrowing twice. Conservation tillage showed superior benefits in form of protection from wind erosion, reduced water loss as well as increased crop yield of up to 22%.

From the discussion above the main ADP tillage and equipment options for maize production system are for minimizing (not sub soiling) soil compaction in the short-term and adequate crop residue recycle to restore physical and chemical fertility in the long-term. Available tillage and equipment options discussed above have many limitations with regard to adoption as reviewed in the following paragraphs.

### *2.1.4 Limitations of available ADP tillage and equipment options*

Rockstrom *et al* (2009) have reported 4 years of conservation farming (CF) on farm trials in Eastern and Southern Africa including Ethiopia, Kenya, Tanzania and Zambia. The success achieved in terms of farmers' ability to use innovative equipment such as chisel rippers is a significant step in the innovative technology adoption scale. Compared with conventional practices the high increase in yields reported is an indication of benefits that can be gained from single or combined effects resulting from breaking of the land with rippers such as increased soil moisture and root growth. It can also be a result of added chemical fertilizers. Therefore there is need to continue these experiments and confirm improved physical and chemical fertility under long-term and greater experimental controls. The fact that none of the trials reported significant crop residue retention as mulch (due to competing uses) poses a fundamental limitation to sustainability of improved performance.

Knowler and Bradshaw (2009) have reported on farmer's adoption of conservation agriculture (CA) globally. Through extensive review and synthesis of information from 31 analyses drawn from 23 publications, they attempted to identify those universally accepted independent variables that regularly explain adoption, and thereby facilitate policy prescriptions to augment adoption. They found that once various contextual factors (e.g. locale or method) are controlled, there are few such variables (sustainable yields and associated profitability) that regularly explain the adoption of CA across past analyses. Therefore they concluded that efforts to promote CA will have to be tailored to reflect the particular conditions of individual locales. Uri (1998) for example, identified a strategy to promote conservation tillage that began with regional policy makers identifying whether its adoption generally provides a positive or negative net return to potential adopters.

The benefits attributed to CA and the basis on which it is being recommended as a panacea to agricultural problems in the tropics have been questioned by Giller *et al* (2009). Taking what they call heretics view, they have argued that claims of substantial increase in yield do not indicate which variables are responsible for the increase. Whereas researchers' demonstration plots may have the benefits of the full package including fertilizers, herbicides and improved seeds, the farmers' control plots will often have none of the external inputs. The cause of increased yield may not be CA but herbicides or fertilizers which farmers do not use and cannot afford. On the other hand the increase in yields could be because of rain water productivity due to deep tillage (Rockstrom *et al* 2008) or reduced tillage. Considering several factors and evaluating various trade-offs including mulching, short-term and long-term yield gains, labour savings, SOM content, added fertilizer, legume rotation, reduced soil erosion, enhanced below-ground biological processes and the potential for adoption by small farmers, Giller *et al* (2009) arrived at a simple conclusion that under present circumstances CA is inappropriate for the vast majority of resource constrained smallholder farmers and farming systems. In agreement with Knowler and Bradshaw (2009) referred to above, Giller *et al* (2009) suggested that research should be focused on identifying situations where CA can offer major benefits taking into account that CA is but one of the options in the 'basket' for addressing the critical problem of raising agricultural productivity in SSA and that there is no case for promoting CA as a panacea.

### *Summary*

*The purpose for this part of the review was to identify appropriate tillage and equipment for timely land preparation, planting and weeding while at the same time conserving soil water, nutrients and structure. The three questions addressed were: i) What are the tillage and equipment needs, resources and constraints? ii) What are the available tillage and equipment options? iii) What are their limitations? Given that the restricted time available for planting is a consequence of the dry land rainfall regime, the two main constraints are soil compaction and inadequate crop residue recycle. The former is a result of continuous shallow cultivation with ADP equipment whereas the latter is a result of competition with alternative uses including livestock feeding. Therefore, increased yields and associated biomass production is essential for sustainable CA.*

*In absence of a significant rate of adoption of available tillage and equipment options there is a need to consider location specific research under controlled long-term experiments in order to measure more accurately the performance of available options. It was concluded that reliably predicted quantification of the effect of tillage and equipment on production will influence policy decisions on appropriate investment for support infrastructure.*

## 2.2 Effect of Tractor Mechanization on Production in Semi-arid smallholder agriculture

### *2.2.1 Introduction*

According to FAO, agricultural mechanization is the application of human, animal, engine, electricity, solar or wind powered equipment in agricultural development and rural industrialization. It is one of the main inputs in modern farming. Other inputs include seeds, fertilizers and chemicals for pests and disease control. Butterworth and Nix (1983) estimated that the capital valuation of farm power and equipment is over 40% of annual working capital for a tenant farmer. A farm energy survey was carried out in Tunisia to compare the value of increased production versus the cost of increased input use between projected and the current levels of mechanization and other inputs (Myers, 1983). It was shown that the value of increased cost of the main inputs (mechanization, fertilizers and pesticides) of rain-fed durum wheat production was 8.7% of the value of increased production. The fact that 43% of this input value was diesel fuel for tractors underscored the importance of mechanization as a catalyst for increased production. On per ha basis Myers (1983) showed that mechanical power units consume half of the total energy input at the highest yield level while the other half went to fertilizers and pesticides. There is a need to isolate the effect of mechanization on production for a given farming system in order to justify heavy investment on support infrastructure such as roads, repair workshops and agro-service stations. The purpose of this section is to show that there is a need to develop a methodology for quantifying the effect of mechanization on production in semiarid smallholder agriculture. In this section the following questions will be addressed namely:

- What are the current tractor mechanization problems?
- What has been done about these problems?
- Does mechanization have quantifiable benefits?

For the purpose of this review it is assumed that conservation tillage constitutes the main mechanization input in typical semiarid smallholder agriculture.

### 2.2.2 *Current tractor mechanization problems*

Although the modern tractor is the prime mover for agricultural development in developed economies, the transfer of conventional tillage (mouldboard and disk ploughing followed by several harrowing operations) to the tropics caused severe soil degradation (Russell, 1960; Hudson, 1971; FAO, 1984). The fine seedbed is also ideal for soil erosion under intensive raindrops. Wind erosion is significant according to American experience in the Mid West and Western USA Therefore conservation tillage techniques have been developed and adopted for large-scale conservation farming in South Western USA, Australia and parts of Southern and Eastern Africa. They are characterized by high-powered and high capacity equipment justified by the strict timeliness requirements and economies of scale to eke out a profit from low potential land (FAO, 1971; Thiagalingam *et al.*, 1996). Therefore this technology has made little impact in semiarid smallholder agriculture where farmers still use the traditional animal drawn ploughs.

Due to increased population density and associated demand for food over time, the environmentally sustainable shifting cultivation in the less developed countries has given way to continuous cultivation by the animal draft powered plough, which has also accelerated soil degradation. The characteristic shallow ploughing and grazing of stubble has led to low soil organic matter content, and attendant surface and subsurface compaction, low infiltration rate and low water holding capacity (Wang, 2006; ICRISAT, 1987;). Soil compaction is therefore one of the causes of poor land preparation, late planting and weeding. Appropriate mechanization is therefore needed for conservation tillage in semiarid smallholder agriculture.

Various policies and strategies have been pursued in an attempt to solve these problems in small scale farming. Public sector managed tractor hire service is one of such attempts. However there are few public sector tractor hire services that succeeded for various reasons including: inadequate training of operators and technicians, high ownership costs due to low capacity utilization, high operation costs due to inadequate backup services, and inadequate technical performance due to the diversity of field conditions created by land fragmentation (Ministry of Agriculture, 1994; Pingali, 1987; Stout and Downing, 1976).

Stout (1971) argued that the benefits of tractor mechanization in terms of increased production were compromised by lack of support infrastructure; the root cause of failure of public sector managed tractor hire service in small scale farming areas. Economists argued that tractors displaced labour and wasted foreign exchange (Gimmell and Eicher, 1973). These arguments and counter arguments underscored the importance of quantifying the effect of mechanization on production and employment which was expressed in a FAO panel meeting held specifically to debate this issue (FAO, 1975). The conclusion from the panel meeting was that there was inadequate farm level data to justify conclusive analysis.

### *2.2.3 What has been done about these problems*

Although many short-term socio-economic studies have been subsequently undertaken to address the data problem, divergent views and opinions still persist since no consensus has been reached (McRota, 1997; Panesar, 1995; Pingali, 1987; Sorokon, 1986; Farington, 1982; Binswanger, 1978). It is not the purpose of this study to contribute to the ongoing debate on the effect of mechanization on production and employment in less developed countries but rather to suggest a methodology that can facilitate consensus among interested scientists from various disciplines.

From the outset it is necessary to clear a fundamental confusion in the literature on the interpretation of the effect of tractor mechanization on production. In the strict scientific sense, farm equipment hardware does not affect crop yield directly. Crop yield depends on biological processes that are directly affected by access to radiation, soil water, nutrients, pests and diseases. Farm equipment simply facilitates access to soil, water and nutrients and control of weeds, pests and diseases. In the case of irrigated farming for example, delays in time of planting and low cropping intensity that can be improved by mechanization are inconsequential so long as the farmer is achieving optimum water use efficiency (Stewart, 1984). Therefore the indirect effect of farm equipment for conservation tillage on production can best be measured under long-term controlled field experiments designed specifically for this purpose (Unger 1989; Lal, 1986; FAO, 1976; FAO, 1975,). Four to eight years conservation tillage research in Northern Australia reviewed by Thiagalingam *et al.* (1996), for example, is considered short-term. This is because increased organic matter content and water holding capacities, which are the main factors that affect crop yield directly, are unlikely to change significantly in short periods. As an alternative, crop scientists have suggested crop production simulation models using long-term series agro-climate data (McCown *et al*, 1994; Keating *et al*, 1992). Otherwise application of short-term survey data creates serious methodological problems. Two examples are sufficient to highlight the flaws in short-term data application.

Using extensive but short-term two year tractor use survey data agricultural economist Binswanger (1978) concluded that;

***'Tractor surveys fail to provide evidence that tractors are responsible for significant increase in intensity, yields, timeliness and gross returns on small farms in India, Pakistan and Nepal.'***

Agricultural engineer, Sorokin (1986) analyzed equally short-term tractor utilization survey data on 815 farms in fourteen districts of seven states of India. It was found that 69% of tractor utilization is on custom hire. He also found that the tractor has a significant influence on crop yield and the resulting farm income. The value of crop output per hectare on farm utilizing tractors was on average 63% higher than on farms utilizing bullocks while per hectare crop yield increase did not exceed 25%. These findings contradict the findings of Binswanger (1978) who used equally short-term farm survey data.

Short-term economic analysis has failed to explain massive tractor power adoption in the Punjab State of North India. In 1997 a population of 22 million with 4 million farmers cultivating 4 million ha at 183% crop intensity produced 69% and 54% of all Indian centrally marketed wheat and rice respectively (PAU, 1998). Actual mechanization inputs included: 350,000 tractors, 235,000 power tillers, 725,000 electrical pump tube wells, 175,000 Diesel pump tube wells and 4,700 combines. This is probably as a result of long-term policy and strategy to invest in infrastructure for irrigation (90% of cultivated land), research and development and local manufacture of tractors, post harvest processing and marketing, adequate access to sources of power (i.e. immigrant labour, draft animals, tractors and electricity).

Therefore use of short term social costs and benefits as the major criteria for determining appropriateness of tractors to a community of farmers is questionable. Although the need of tractors for specialized tasks such as deep tillage is conceded, little effort has been made to quantify the associated benefits. Therefore, what some researchers disagree with is not that tractors have superior technical performance but that the superior performance is the reason for farmers' adoption of tractors (Pengali and Binswanger, 1987; Farrington, 1985; Binswanger, 1978).

Pingali and Binswanger (1987) and Holtkamp (1990) observed that mechanization does not necessarily precede agricultural intensification and associated increase in production and it is often a consequence of it. Therefore farmers may invest on mechanization for several reasons including: elimination of drudgery, farm transport, reduction of crop failure risks, expansion of cultivated land, efficient operations, crop intensification, timeliness of operation and deep tillage. The first four factors do not necessarily affect crop yield whereas the last four are likely to do so. What is required is to address a fundamental data problem by carrying out technical performance tests under controlled field experiments. This will provide accurate short-term data which is an input into relevant models for crop production prediction in the long-term

### *2.2.4 Does mechanization have quantifiable benefits?*

Doty and Reicosky (1978) demonstrated a comparison between mechanization and irrigation. Their highly controlled experimental work carried out in the U.S.A Southern coastal plains is summarized as follows:

"Millet and sweet corn were grown on a varina sandy loams with a compact A 2 horizon disrupted by chiselling to a depth of 38 cm. Yields were compared from different water management schemes: irrigation, natural rainfall and droughts imposed by artificial means. Chiselled soil produced yields comparable with irrigated non-chiselled soil. As much as 12 cm (ET) more water was used by plants on the chiselled than on ploughed (non-chiselled) treatment during the growing season. Chiselling the soil to disrupt the compact A 2 horizon will sustain millet and sweet corn production from 8 to 24 days longer under drought conditions than mould board ploughing or shallow disking and harrowing. Chiselling the soil to a depth of 38 cm to disrupt the compact A 2 horizon tended to alleviate short-term drought with net return greater, even with droughts of 26 and 31 days, than on conventionally ploughed soils that were irrigated. Since most droughts in the U.S.A. coastal plains are short-term, less than 20 days in length, chiselling may be as effective as supplying water by irrigation on the crops sweet corn and millet". Thus in dry land farming, soil and water conservation may be an alternative to irrigation.

El Well (1992) has observed the need for mechanical tillage to eliminate the common plough pan in Zimbabwean sandy loam and sandy clay soils. In addition tied ridges were proposed for Zimbabwe to control runoff and water infiltration. The mechanically constructed tied ridges can be kept for up to four years. In the meantime crops are planted and harvested; ridges being maintained by hand tools and ADP equipment. The study also suggested integrated pest management combining both biological and chemical means. In other words there is a way to integrate no-tillage and mechanical tillage methods of soil, water and organic matter management to improve both productivity and sustainability.

The need for a form of mechanical tillage operations was seen, as an absolute necessity for Botswana's mostly sandy soils underlain with ferruginous concretionary horizon. Willcocks (1978 and 1981) showed the need to reduce the high bulk density by mechanical tillage and by periodic sub-soiling operations.

Macartney *et al*, (1971) as quoted by Lal (1986) observed a complete failure of a maize crop under no-tillage on a compacted Alfisol with a bulk density of 1.52 $g/cm^3$. The initial high infiltration rate, caused by ploughing, disking and harrowing, decreased drastically over 2 to 3 seasons due to structural deterioration and surface sealing. It was suggested that soil tillage be limited to the row (seed) zone only. It was further suggested that dead weed and crop residue mulch be retained between rows to improve infiltration.

It is therefore evident that some short-term factors, which influence farmers' decisions to select farm power and equipment such as difficult soil conditions or timeliness requirements, have quantifiable effect on production. According to Srivastava *et al*, (1995) the following short-term factors constitute the conventional criteria for the farm equipment selection namely: owning costs, operating costs, field capacity and timeliness.

In the long term farmers must face the need for backup services and R&D support infrastructure, which determine sustainability. This is the experience in Kenya, Ghana, Nepal and India (Ministry of Agriculture, 1994; Loos, 2002; Pengali and Binswanger, 1987; Farrington, 1985; Binswanger, 1978; Pariyar *et al*, 1999). In other words the costs associated with the short term criteria must in the long term be written off by the benefits of increased production both at farm level as well as at national level. It is often assumed that the necessary support infrastructure is in place. This is a valid assumption in developed economies but not so in less developed countries. China is an exception to this. A survey by Li (2005) as reported by Wang (2006) shows that in Shanxi province in a dry semi humid area a village with 400 ha farmland increased its tractor population from 1 in 1973 to 4 in 1983 and 28 in 1993. He also showed a 75 fold increase in tractor numbers from 1970 to 2003 from data for all China. This level of mechanization is similar to Punjab state in North India mentioned earlier. The common denominator in the two cases is a heavy investment on the back up service infrastructure. China for example has Ministry of Agricultural Machinery separate from the Ministry of Agriculture. Following the increase of tractor mechanization, China has also invested heavily on conservation tillage as shown in Wang (2006).

### *Summary*

*Although researchers agree on the need for quantification of the effect of tractor mechanization on production there is no consensus with regard to methodologies used or the conclusions reached. Studies reviewed show tangible benefits of tractor mechanized tillage which is targeted at specified constraints such as soil compaction and timeliness requirements. Examples of successful mechanization such as Punjab in Northern India are accompanied with heavy investments on infrastructure. It is argued that these benefits can form the basis for quantification of the effect of tillage equipment on production. This information can in turn be used not only to guide the selection of machinery for multi-farm use but the allocation of resources for investment on the necessary support infrastructure as well.*

## 2.3 Quantifying the Effect of Tillage and Equipment on Small Holder Maize Productivity

### *2.3.1 Introduction*

Animal draft power (ADP) and tractor power (TP) tillage and equipment options for maize production in semiarid small-holder agriculture and associated limitations are reviewed in Sections 2.1 and 2.2. The purpose for the review in this section is to consider available options for quantifying the effect of tillage and equipment on maize production in case it is adopted and well utilised.

In quantifying the effect of farm equipment for tillage on maize productivity, there is a need to address the problem of timeliness of land preparation, planting and weeding. The optimum time period for farm operations depends on crop growth requirements and on the machine workable time limited by the weather, soil and crop conditions (Van Elderen, 1977 & 1978; Portiek, 1975; Tulu, 1973; Cervinka & Chancellor, 1972; Audsley, 1984; Sorensen, 2003). If the farmer wants to be 90% sure to get the job done, then the number of hours must be assumed likely at 90% probability. In order to enhance machine performance, one must select labour and machinery with enough capacity to accomplish the operations on time within the limited time.

Farm operation scheduling models have been developed to select machines for specific timeliness requirements (Srivastava et al, 1995). Except in certain harvesting and sometimes planting situations (Cervinka & Chancellor, 1972; Van Elderen, 1977), few timeliness functions relating loss in yield or revenue to the time of a particular operation have been developed. An example of the few situations where the effect on crop growth is considered is demonstrated by Audsley (1984). Using a dynamic programming model, the benefits of using gantry instead of a tractor which is likely to compact soil under wet conditions and thus reduce crop yield was evaluated. Compared to a tractor a gantry (a structure of steel beams to support moving machines) is capital intensive. The implication is that the economy of scale allows large capital investments to guarantee timeliness and minimum soil compaction under adverse weather conditions.

In general, the machine selection and scheduling models have been designed to meet exact timeliness requirements at minimum cost (Srivastava *et al* 1995). This is justified in developed economies where power is generally not limiting (Audsely, 1984; Hunt 1974; Buchele 1969). Therefore, such rigid timeliness requirements are relevant to large economies of scale with relatively high profit margins. The other possible reason for not considering less than timely alternatives is that, in developed countries farming is relatively profitable and generally timely. The problem often addressed is that of selecting a machine and scheduling of farm operations to guarantee timeliness at the time of adverse weather conditions. In other words, models in developed economies are used to optimize the mechanization selection minimizing investment on machinery and maximizing profit.

In the Less Developed Countries (LDCs) especially in semi arid small-holder agriculture, operations are generally untimely and farming is seldom profitable. The main reasons for this are that the soil conditions are too difficult for the available human and animal power to till and the design of implements are inadequate (Muchiri, 1984). Furthermore, labour bottlenecks are experienced not only during land preparation and planting but also during the subsequent weeding and even harvesting. Thus, early land preparation of a relatively large area to take advantage of limited rainfall may create labour bottlenecks during early weeding and may nullify the benefits of early planting (Muchiri, 1976). Spread-out planting (i.e. allowing some late planting deliberately) may make it possible for the farmer to take care of early germinating weeds while planting and delay the weeding operation to a time when there is no labour bottleneck (Nadar, 1984). In this way, better labour utilization may be achieved. The problem arises when early weeding requirements coincide with late planting and the farmer cannot easily determine the optimum labour allocation (Muchiri, 1976). There is a need to allocate labour and machine time optimally during the critical time of planting and weeding.

The other important point is that increased yield and associated production does not arise from one operation but a set of operations such as land preparation, planting and weeding (Keating *et al* 1992). The opportunity cost for carrying out a single operation is meaningless in this case. What is required is an optimization model in which timeliness requirements are included as constraints over the cropping season. Moreover, for the purpose of sustainability, there is a need to simultaneously minimize energy use as well as environmental damage. In this study linear and goal programming are applied to achieve the necessary optimization.

Based on the above realizations, the main objective of this study is to apply goal algorithm models in quantifying the effect of tillage and equipment on maize production and energy consumption. The specific objectives are as follows:

1. Apply linear programming model in optimization of maize production.
2. To optimize energy consumption in maize production using the goal programming algorithm.

### *2.3.2 Linear Programming Modelling Techniques*

Linear programming applies to optimization models in which the objective and constraint functions are strictly linear (Taha, 2003). The technique is used in a wide range of applications, including agriculture, industry, transportation, economics, etc. In agriculture for example linear programming (LP) techniques have been used to examine the effect of technological innovations on productivity (Low, 1975; Heyer, 1971; Hardaker 1979: Kinsey, 1980; Mutebwa, 1979; Mc Carl and Nuthall, 1982; Mc Rota, 1997). Low (1975) used a farm level LP model to test the effect of new technologies including tractor mechanisation, improved cropping system, storage and credit on small Ghanaian farms. While observing that the farmers' resource allocation was near optimum, he conceded that there is a need for technological interventions. Neither tractor mechanization, which solves the labour problem during land preparation but creates another at weeding time nor high yielding but drought evading (hence risky) maize variety were appropriate. However, incorporating storage facilities to guarantee subsistence in adverse years improved cost benefit ratio considerably.

Hadarker (1979) identified three general criticisms against linear programming applications to farm level problems namely; assumption of certainty when the pervasiveness of risk is widely appreciated assumption of linearity whereas reality is invariably non-linear, and use of single goal instead of multiple goal objective functions which are closer to reality. Anderson et al (1977) observed that the problems of non-linearity and programming under risk are connected with the additional computational load. The extra effort is therefore likely to be ignored in project development. Anderson and Hadarker (1979) in their comprehensive review of economic analysis in design of new technologies for small holder agriculture have recognized the general complexity of small farm enterprise and that any attempt to include all the possible activities and constraints encountered would to computational problems. It was suggested that a new technology could be classified into one of the following three categories; notional technologies which are analyzed through models only, preliminary technologies which are analyzed for certain target groups, and developed technologies which are well tested and require communication to the target group for adoption. In this study consideration is given to technologies, which are well developed and require communication to farmers.

### *2.3.3 Multi-criteria Modelling Techniques*

By using single criterion objective functions the models are unable to examine other equally important objectives, which may be conflicting, or having different units of measurements. The purpose of this section is to review multi-criteria models, which might be applicable to small farm technology analysis.

Alocilia and Ritchie (1993) have argued that existence of multiple objectives in agriculture is a rule rather than an exception; profitability being only a part of the overall concern for agricultural sustainability. They presented an analytical structure, validation results and applications of simulation multi-criteria optimization software designed to optimize two conflicting objective functions simultaneously. It was a tool to help identify a non-inferior fertilizer nitrogen application schedule in maize production, such that profit is maximized and nitrate leaching is minimized, subject to constraints in physical and biological resources and the natural environment. Effects of weather factors, soil properties, genetic properties and cultural management practices are simulated through the CERES-Maize model (Keating, 1992). Yield and amount of nitrate leaching are output of the simulation. Yield is converted into revenue and profit is calculated. Optimization is conducted to find the best trade-off between fertilizer N application schedule with respect to profit and nitrate leaching. The use of this model has demonstrated that a set of feasible and efficient fertilizer N application schedules, which is an optimal compromise between maximum profit and minimum nitrate leaching can be identified.

Van Latesteijn (1993) discussed 'A methodological framework to explore long term options for land use'. He showed how quantitative relations between a number of self-contained technical development processes in agriculture, socio-economic and environmental policy objectives can be modelled. A dynamic crop simulation model and a geographical information system that comprise soil characteristics, climatic conditions and crop properties were used to calculate regional yield potentials for indicator crops. Next, a linear programming model that contains several policy derived objective functions is applied to calculate optimal regional allocation of land use. Different restrictions can be put to the objective functions.

For the purpose of validation he used crops research data. By looking at factors like steepness, salinity and stoniness of the soil the suitability for mechanized farming is assessed. In other words, the model proposed by Van Latesteijn (1993) is simply a mathematical instrument to explain the relationship between policy objectives and technical performance at farm level. Thus, the model assists the policy makers to understand and select strategies that can achieve policy objectives, subject to the potential limits fixed by socio-economic and physical environment.

In the centre of the methodology, a linear programming (LP) model is used in conjunction with 'Interactive Multiple Goal Programming' (IMGP). An LP-Model is generally used to optimize a single objective function. The IMGP procedure makes it possible to optimize a set of objective functions in an interactive process. Naturally the computational load is substantial and for that reason multi-criteria modelling techniques are not widespread. As discussed below, goal programming is a simplified form of multi-criteria modelling techniques

### *2.3.4 Goal Programming*

Taha (1997) reported several examples of situations where it is impossible to find a single solution that optimizes the conflicting objectives. In such situations, a compromise solution based on the relative importance of each objective is all that can be achieved. The principal idea in goal programming is to convert the original multiple objectives into a single goal. The resulting model yields what is usually referred to as an efficient solution because it may not be optimum with respect to all the conflicting objectives of the problem.

Bhattacharya (2005) developed a goal programming model to predict the yield of sugarcane three months before harvest. The biometric characteristics used were plant height, girth of the cane, number of canes per plot and width of third leaf from the top. Goal programming was compared with the conventional multivariable regression analysis. Although some of the characteristics were correlated, regression analysis is based on the assumptions of normality, independence and homoscedasticity. After demonstrating that both have equal level of accuracy, goal programming was recommended for predicting sugarcane yield three months before harvesting in situations where the assumptions of conventional regression analysis are violated.

Sharma et al (2007) developed 'Fuzzy' goal programming for optimum allocation of land under cultivation and development of an annual plan for different crops. Goals such as crop production, net profit, and machine requirements were modelled as fuzzy. The study showed that the fuzzy goals were transformed to linear constraints by introducing tolerance variables. He showed that the model allows tolerances in the allocation of resources in order to fit the prevailing circumstance of the analysis.

More recent work by Jafari *et al* (2008) and Khan *et al* (2011) indicate that goal programming is an essential tool for understanding real world problems where a compromised solution for multiple goals is imperative. Thus goal programming is a simplified form of multi-criteria modelling. This is the technique adopted in this study and it is discussed in detail in section 3.0 below

***Summary***

*Past works on timeliness effects on crop yield has been reviewed. Studies that quantify productivity using linear programming (LP) multiple-criteria and goal programming models are also reviewed. It was concluded that LP models suffer serious limitations due to assumptions of linearity, certainty and use of single goal whereas reality is non-linear, is risky and multiple goaled. Multiple goal models impose serious complexities in data collection, analysis and interpretation. Goal programming was therefore recommended because of its simplicity. Existing timeliness models were also found to be inappropriate due to the fact that timeliness costs are assigned to each of the operations separately. In Semi arid small holder agriculture timeliness costs for land preparation, planting and weeding are incurred collectively and must be analyzed as such*

## 2.4 Effect of Tillage and Equipment on Production: Problem analysis

### *2.4.1 Introduction*

According to the review in Section 2.1, there are four short term and one long term constraint(s) to identification of appropriate tillage and equipment for timely land preparation planting and weeding: i) inadequate power to break the hard pan, ii) inadequate management of broad beds iii) inadequate ridge and furrow practice, iv) inadequate shallow chisel ploughing which is complementary to sub soiling and, v) inadequate crop residual management (long term). Technical options for addressing them are discussed below.

***Sub soiling***

The review in Section 2.2 shows that multi-farm use of tractor powered equipment can offer the necessary tractor services for sub soiling provided it is well managed as a tractor hire service (THS) and supported with the necessary infrastructure for distribution and maintenance. However implementation of the necessary policy decisions demands a reliable benefit cost analysis which makes it imperative to quantify the expected effect of tillage and equipment system on production.

***Broad beds***

To slow hard pan formation compaction free broad beds may be constructed after sub soiling. However successful and sustainable adoption of broad bed system of tillage implies a paradigm shift from poorly managed smallholder to highly controlled traffic farming (CTF) based on ADP equipment. In order to facilitate allocation of adequate resources to empower semi arid smallholder farmers to achieve this level of precision farming, it is imperative that benefit cost analysis be carried out.

***Ridge and Furrow practices***

Ridge and furrow practices using ADP equipment are practiced for either conserving runoff in the furrow when rainfall is inadequate or draining excess water when soil profile is saturated. It is usually preceded by chisel ploughing to loosen the soil. Thus it is energy intensive, disturbs soil and is often repeated annually. Traditional ADP equipment is not appropriate for this system as observed by Theirstein (1979).

***Shallow ploughing.***

ADP shallow chisel ploughing to facilitate timely planting can be done with or without sub soiling having been done by tractor. The tool bar has attachments for ploughing, planting and weed control. Moreover ADP direct seeders which can insert seed through mulch cover are also available (Ribeiro, 2000). Like tractor sub soiling and broad bed equipment, ADP tool bar package also requires heavy investments on support infrastructure for R & D, manufacture, distribution and maintenance. Therefore the necessary policies must be based on reliable benefit cost analysis. In other words the four options can complement each other to bring in a total paradigm shift in semi arid small holder agriculture. The cause and effect relationships in the adoption process is illustrated in the problem tree (Figure 2.1)

***Crop residue management***

Inadequate crop residue management, the other constraint, is partly due to competition with feed for livestock, firewood and other uses of residue. The problem can best be addressed by production of adequate biomass to meet the competing demands. It can therefore be addressed through associated increased production. This is because increased crop yield is accompanied with increase in biomass production.

***Limitations***

On the one hand, there are proponents of CA who believe that it is the panacea for African agricultural development (Rockstrom *et al* 2009). On the other hand, there are others who have analyzed available information globally and concluded that there are no universally accepted independent variables to support policy prescriptions to augment adoption (Knowler and Bradshaw, 2009). Yet others have taken the heretics view that CA is not appropriate for small farmers in Africa (Giller *et al*, 2009). However there is consensus that location specific research and development should be conducted in areas where CA benefits are likely to be significant so that the necessary prescriptions for supporting adoption can be justified. The main challenge is that short term conservation tillage data is not conclusive because changes in the soil physical and chemical fertility are long-term. This study has proposed a methodology for model development to predict the effect of tillage and equipment on production. The cause and effect relationships in the system is shown in the problem analysis tree (Figure 2.1)

### *2.4.2 Problem Analysis*

The above findings are summarized in the problem tree shown in Figure 2.1. Thus the development problem (which overall goal addresses) is manifested in food insecurity, low income and unemployment in the rural areas. The main causes are low food production and associated lack of raw materials for rural industrialization. Low production is a result of poor farm husbandry practices including late planting, late weed control as well as inadequate recycle of crop residue including Farm Yard Manure (FYM). The main cause of these problems is inadequate utilization of farm equipment for conservation tillage. In other words low adoption of conservation tillage practices has led to inadequate utilization of farm equipment for conservation tillage resulting in late land preparation and associated delay in planting. Moreover inadequate crop residue recycle including FYM has resulted in low soil organic matter content, associated soil compaction and low soil fertility. Low utilization of farm equipment for conservation tillage is caused by inadequate adoption of conservation tillage practices largely because of poor planning, poor system design and inadequate backup services. The root cause of the problem is therefore inadequate investment on support infrastructure of roads, repair workshops, manufacturing, R&D, and training institutions. Inadequate utilization of farm equipment for conservation tillage is therefore the core problem which is caused by poor selection. The relevant interventions are shown in the corresponding objective analysis tree (Figure 2.2). The project purpose is to facilitate adoption and utilization of farm equipment through investment on the necessary support infrastructure.

Objectives of this study are generated from objective analysis chart (Fig. 2.2) and are as outlined in Section 1.7. It is assumed that one way to influence decision makers in investment priority setting is to carry out cost benefit analysis and the rate of return on investment. The starting point for this analysis is a reliable prediction of the production potential based on adoption of currently available package of recommended practices. **Lack of a methodology to predict effect of innovative farm equipment for conservation tillage on production is the research problem for this study.**

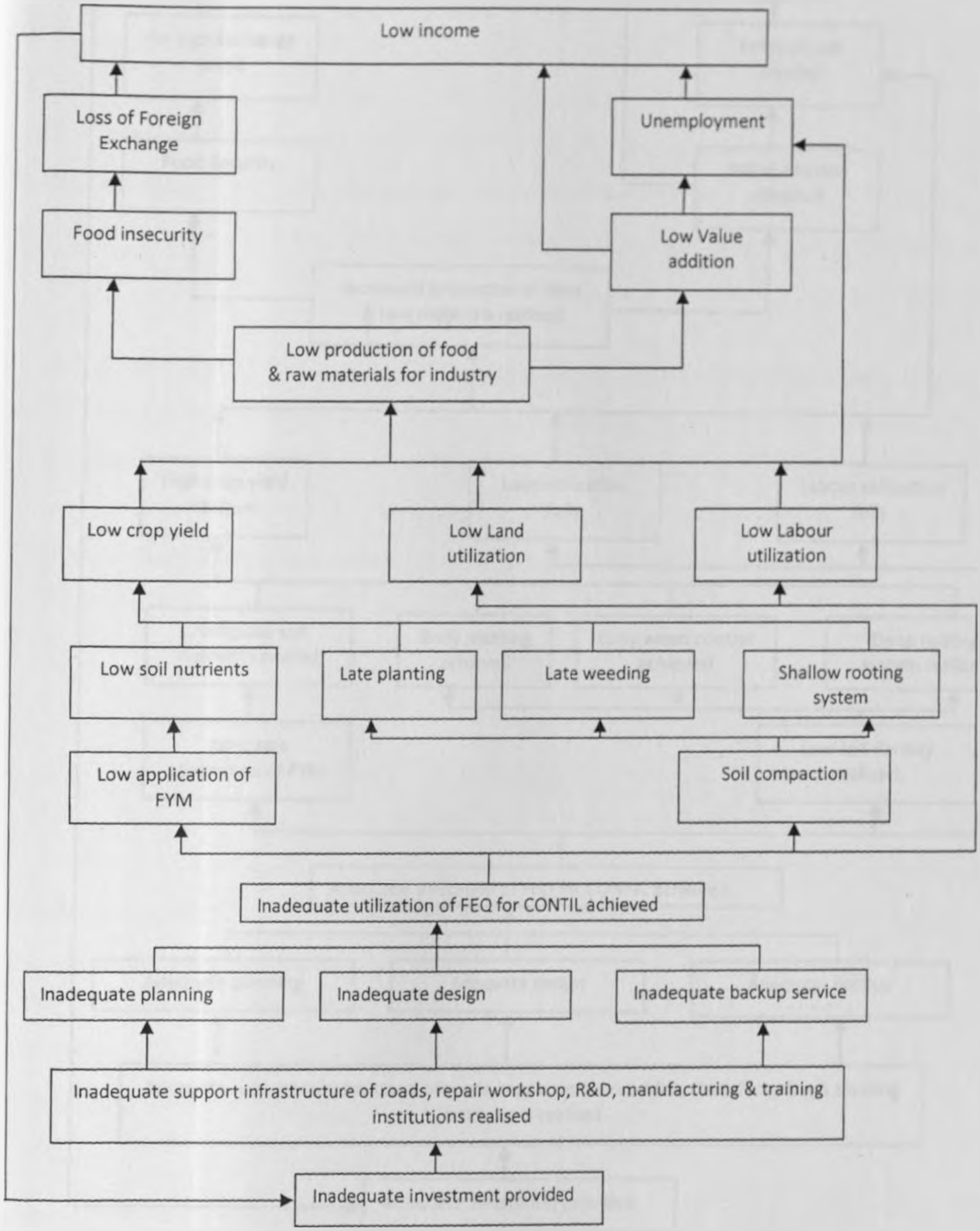


**Figure 2.1 Problem analysis on inadequate utilization of farm equipment – the core problem**

*Source: Adopted from Ministry of Agriculture (1994)*

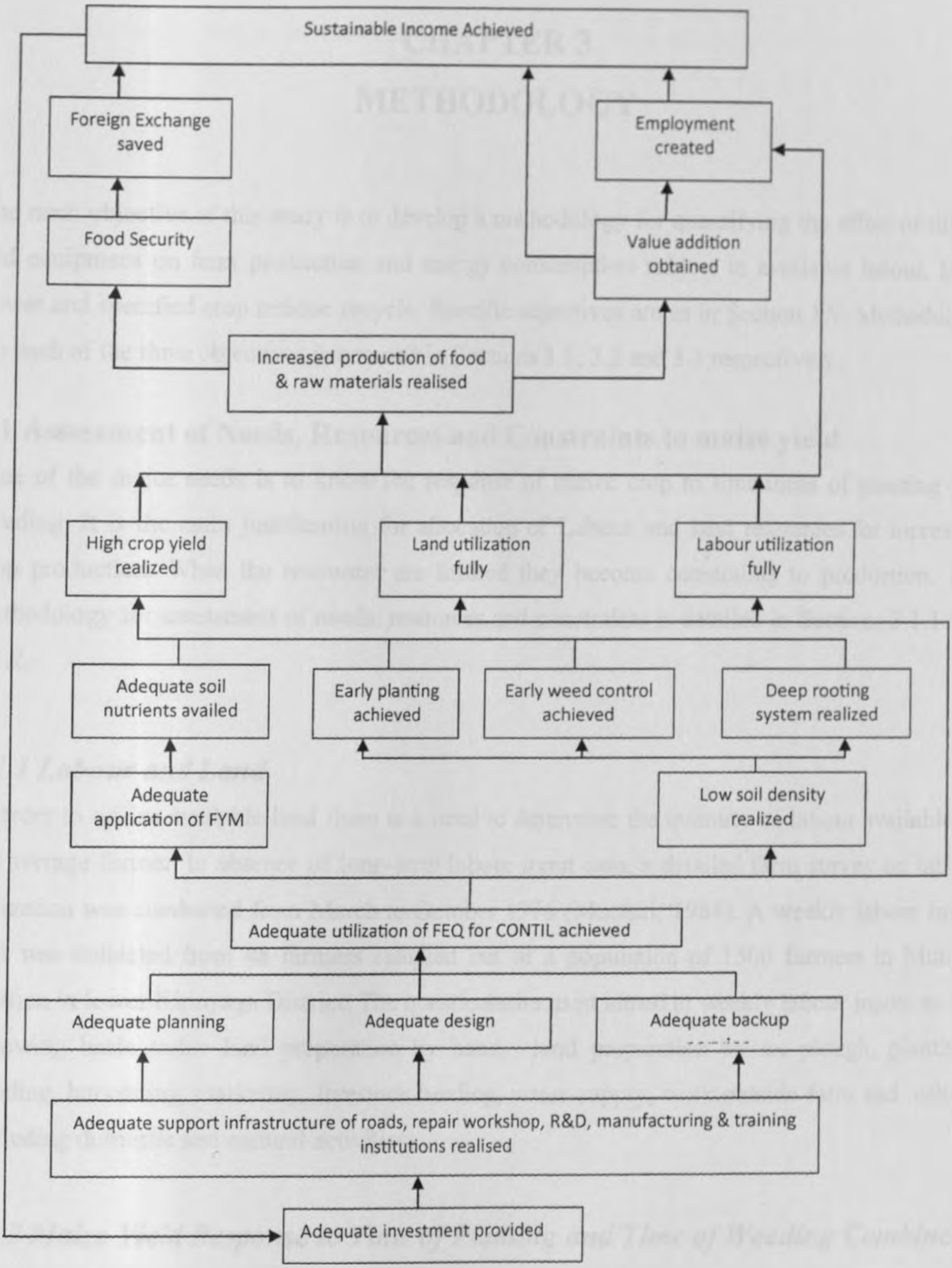


**Figure 2.2 Objective analysis on the project purpose – adequate utilization of farm equipment**

*Source: Adopted from Ministry of Agriculture (1994)*

# CHAPTER 3
# METHODOLOGY

The main objective of this study is to develop a methodology for quantifying the effect of tillage and equipment on farm production and energy consumption subject to available labour, land, power and specified crop residue recycle. Specific objectives are as in Section 1.7. Methodology for each of the three objectives is covered in Sections 3.1, 3.2 and 3.3 respectively.

## 3.1 Assessment of Needs, Resources and Constraints to maize yield

One of the major needs is to know the response of maize crop to timeliness of planting and weeding. It is the main justification for allocation of Labour and land resources for increased crop production. When the resources are limited they become constraints to production. The methodology for assessment of needs, resources and constraints is detailed in Sections 3.1.1 and 3.1.2.

### *3.1.1 Labour and Land*

In order to utilize available land there is a need to determine the quantity of labour available to the average farmer. In absence of long-term labour input data, a detailed farm survey on labour utilization was conducted from March to October 1976 (Muchiri, 1984). A weekly labour input data was collected from 48 farmers sampled out of a population of 1500 farmers in Mutithi location in lower Kirinyaga District. The questionnaire used aimed at weekly labour inputs to the following basic tasks: land preparation by hand, land preparation by ox plough, planting, weeding, harvesting, marketing, livestock herding, water supply, work outside farm and others (including domestic and cultural activities).

### *3.1.2 Maize Yield Response to Time of Planting and Time of Weeding Combined*

Factors that affect maize yield were reviewed (Section 2.1) from reports on rural surveys, on station crop research trials and computer modelling experiments. The most relevant data on the effect of delays in planting on maize yield was obtained from modelling by Keating *et al* (1992). Data on the effect of delays in weeding on maize yield was obtained from Makatiani (1971). The two sources will be used to estimate the combined effect of both delays in planting (Fig. 3.1) and weeding (Fig. 3.2). From Figure 3.1 the effect of delays in planting during the long rains can be expressed by a linear function of the form;

$$Y_n = Y_0 - b_p n \qquad 3.1$$

Where:

$Y_n$ = expected yield for maize planted n weeks late

$b_p$ = slope of the approximated linear curve

$Y_o$ = expected yield of maize planted before the rains onset

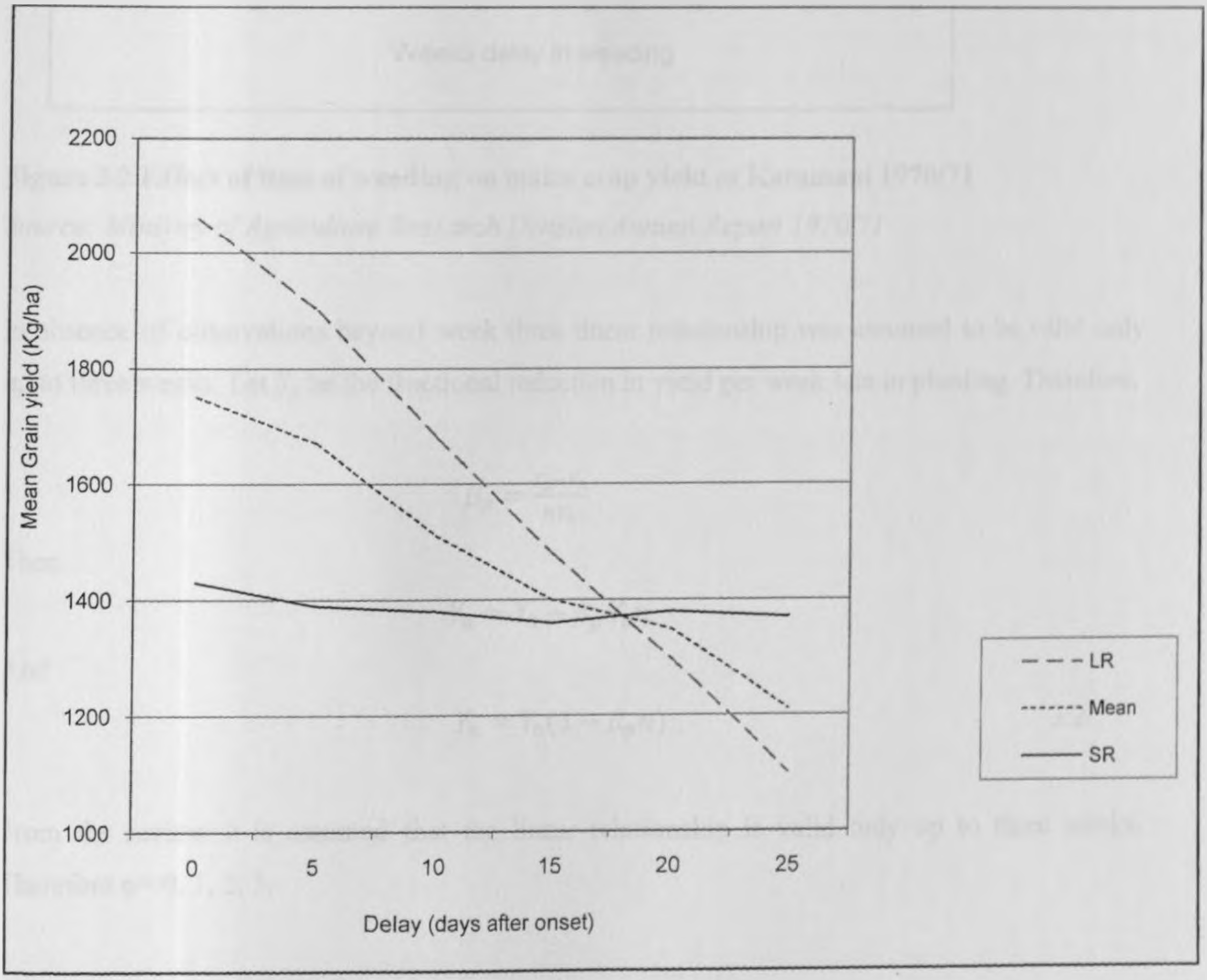


**Figure 3.1 Effect of delay in planting on maize yield**

**Source: Keating *et al* (1992)**

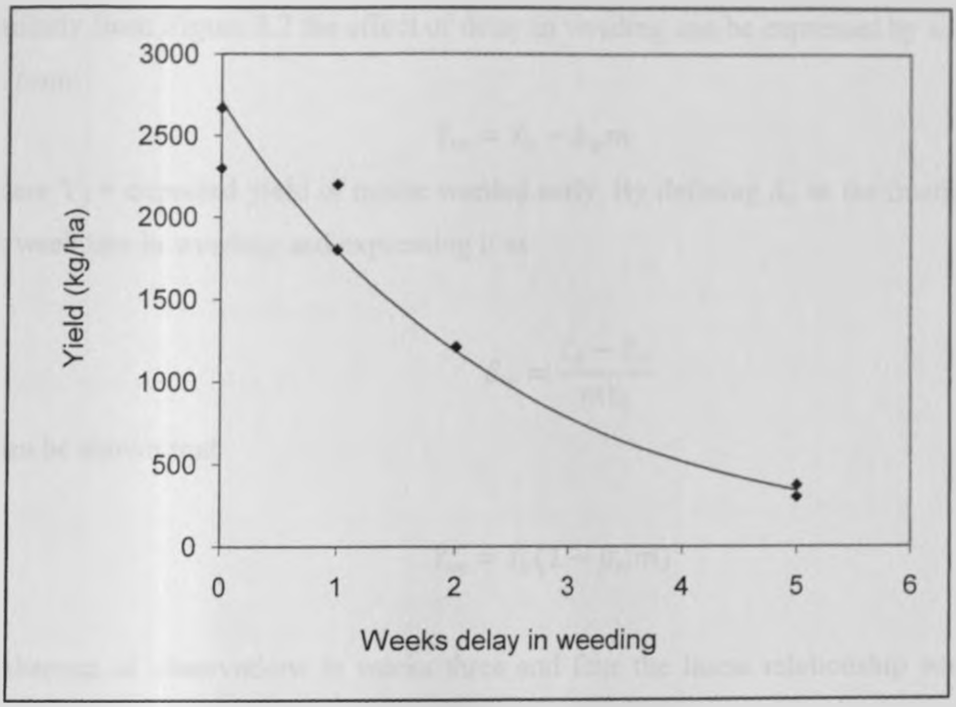


**Figure 3.2 Effect of time of weeding on maize crop yield at Katumani 1970/71**

*Source: Ministry of Agriculture Research Division Annual Report 1970/71*

In absence of observations beyond week three linear relationship was assumed to be valid only up to three weeks. Let $\beta_p$ be the fractional reduction in yield per week late in planting. Therefore,

$$\beta_p = \frac{Y_0 - Y_n}{nY_0}$$

Then

$$Y_n = Y_0 - \beta_p Y_0 n$$

And

$$Y_n = Y_0(1 - \beta_p n) \qquad 3.2$$

From the review it is assumed that the linear relationship is valid only up to three weeks. Therefore n= 0, 1, 2, 3.

Similarly from Figure 3.2 the effect of delay in weeding can be expressed by a linear function of the form:

$$Y_m = Y_0 - b_w m \qquad 3.3$$

Where $Y_0$ = expected yield of maize weeded early. By defining $\beta_w$ as the fractional loss in yield per week late in weeding and expressing it as

$$\beta_w = \frac{Y_0 - Y_m}{mY_0}$$

It can be shown that

$$Y_m = Y_0(1 - \beta_w m) \qquad 3.4$$

In absence of observations in weeks three and four the linear relationship was assumed to be valid only up to three weeks late. Therefore m = 0, 1, 2, 3.

Setting n = 0 for early planted crop

$$Y_{0m} = Y_{00}(1 - \beta_w m)$$

Similarly setting m = 0 for early weeded crop

$$Y_{n0} = Y_{00}\,(1 - \beta_p n)$$

Rearranging Equation 3.2 and 3.4,

$$1 - \frac{Y_n}{Y_0} = n\beta_p \qquad 3.5$$

and

$$1 - \frac{Y_m}{Y_0} = m\beta_m \qquad 3.6$$

Considering that the effects of planting and weeding are additive, the combined fractional effect of both factors can be expressed by

$$\frac{Y_{00}-Y_{nm}}{Y_{00}} = \beta_{nm} \quad \text{Or} \quad 1-\frac{Y_{nm}}{Y_{00}} = \beta_{nm}$$

And

$$1-\beta_{nm} = \frac{Y_{nm}}{Y_{00}}$$

Also,

$$m\beta_w = \frac{Y_{n0}-Y_{nm}}{Y_{n0}} = 1-\frac{Y_{nm}}{Y_{n0}}$$

From the above equation

$$1-m\beta_w = \frac{Y_{nm}}{Y_{n0}}\frac{Y_{00}}{Y_{00}} = \frac{Y_{nm}/Y_{00}}{Y_{n0}/Y_{00}}$$

Therefore,

$$1-m\beta_w = \frac{1-\beta_{nm}}{1-n\beta_p}$$

And

$$(1-m\beta_w)(1-n\beta_p) = (1-\beta_{nm})$$

This can be expressed in terms of $\beta_{nm}$ as follows

$$\beta_{nm} = n\beta_p + m\beta_w - m\beta_w \times n\beta_p \qquad 3.7$$

$$Y_{nm} = Y_{00}(1-\beta_{nm}) \qquad 3.8$$

The fractional loss in yield due to delay in planting was given by Keating *et al* (1992) as 2.5 % per day. Therefore,

$$\beta_p = \frac{Y_0 - Y_n}{nY_0}$$

Substituting,

$$\beta_p = \frac{2.5 \times 7\ days}{100} = 0.175$$

Available data on the effect of time of weeding on maize crop yield fitted a linear curve of the form of Equation 3.4.

$$Y_m = Y_0(1-\beta_w m)$$

Therefore $\beta_w$ was calculated from Figure 2 as follows:

$$\beta_w = \frac{2485 - 1210}{2485 \times 2\ weeks} = 0.256$$

The combined effect of time of planting and weeding is given by Equation 3.8.

## 3.2 Field Capacity and Runoff Control of Conservation Tillage and Equipment under Controlled Field Experiments

### *3.2.1 Locations*

The semi arid area referred to in this paper includes lower Muranga, lower Kirinyanga, lower Embu, lower Meru, lower Machakos and central Kitui. However most of the research data was collected at Katumani Dry land Agricultural station and its environs. A limited number of experiments were conducted in heavy clay soils of the Rhine basin in Holland.

### *3.2.2 Climate*

Katumani has bimodal rainfall ranging between 625 and 855 mm annually split almost equally between the long rain (March – June) and the short rain (October –January). The 20 year data which was available adequately described the climate as shown in Figure 3.3. The bimodal rainfall which averages 685 mm per annum shows that only in 4-ten days periods in April and November, does rainfall exceed crop water requirements. Rainfall in December, March and May is likely to meet crop water requirements, two in seven years for December and one in five years for March and May (M' Arimi, 1977).

### *3.2.3 Soils*

The soils are mainly derived from basement complex rocks except in Murinduko and Kindaruma areas where the soils have developed on volcanic rocks. There are significant pockets of black cotton soils occurring in plains and broad depression within the area. The soils derived from basement complex are friable clays, sandy clay loams and loamy sands. They tend to harden when dry but are friable when wet. They are deep and well drained in the wetter areas but tend to be shallow in the drier areas due to presence of petroplinthite (Murram) horizons (M'Arimi, 1977). At National Dry Land Farming Research Station (NDLFRS) Katumani the soils are ferro-chronic Alfisols (luvisols under FAO classication), deep, well drained dark reddish brown sand clay and clay loam (Mbuvi and Van de-weg, 1975; Barber *et al*, 1979). If left bare they have a pronounced tendency to crust under rainfall impact. A compact layer develops approximately 100 mm below the surface due to clay movement and soil moisture depletion.

### *3.2.4 Cropping System*

The crops grown in these areas are maize, beans, pigeon peas, cowpeas, bulrush millet, sorghum, sweet potatoes and cassava. Cotton and tobacco have recently been started. Allan (1971) identified six factors that affect crop yield namely late planting, late weeding, low quality seeds, low fertility, low plant population and inadequate plant protection. For maize crop, appropriate and feasible recommendations are available for the last four factors (M'Arimi, 1977). They can be implemented easily using the currently available equipment. However without timely planting, weed control and soil and water conservation, other improvements (although easier to adopt) have little pay-off.

### *3.2.5 Labour*

Available family labour is about three adults per holding, but it is sometimes supplemented by casual labour during the peak seasons of early land preparation and weeding. However due to high labour costs, late planting and late weeding are common causes of low yields; appropriate mechanization could alleviate the problem.

### *3.2.6 Existing mechanization*

There are three levels of mechanization in semi-arid areas of Kenya, namely hand tools, ox-cultivation and tractor equipment. Hand tools are too slow and tractor mechanization too expensive and not suitable for these small and steep sloping plots. Ox-cultivation was introduced about 60 years ago and has reached more than 70% adoption (Mutebwa, 1979) in some restricted areas. It was adopted because of its superiority in soil loosening, rate of work and above all labour saving.

The only available implement has been the mouldboard plough, which under the hard dry condition, has a relatively high draft requirement which cannot be supplied by the pair of bullocks that are not in a physically fit condition after the long drought. This has resulted in delayed planting and subsequent weeding operations (Stewart, 1984).

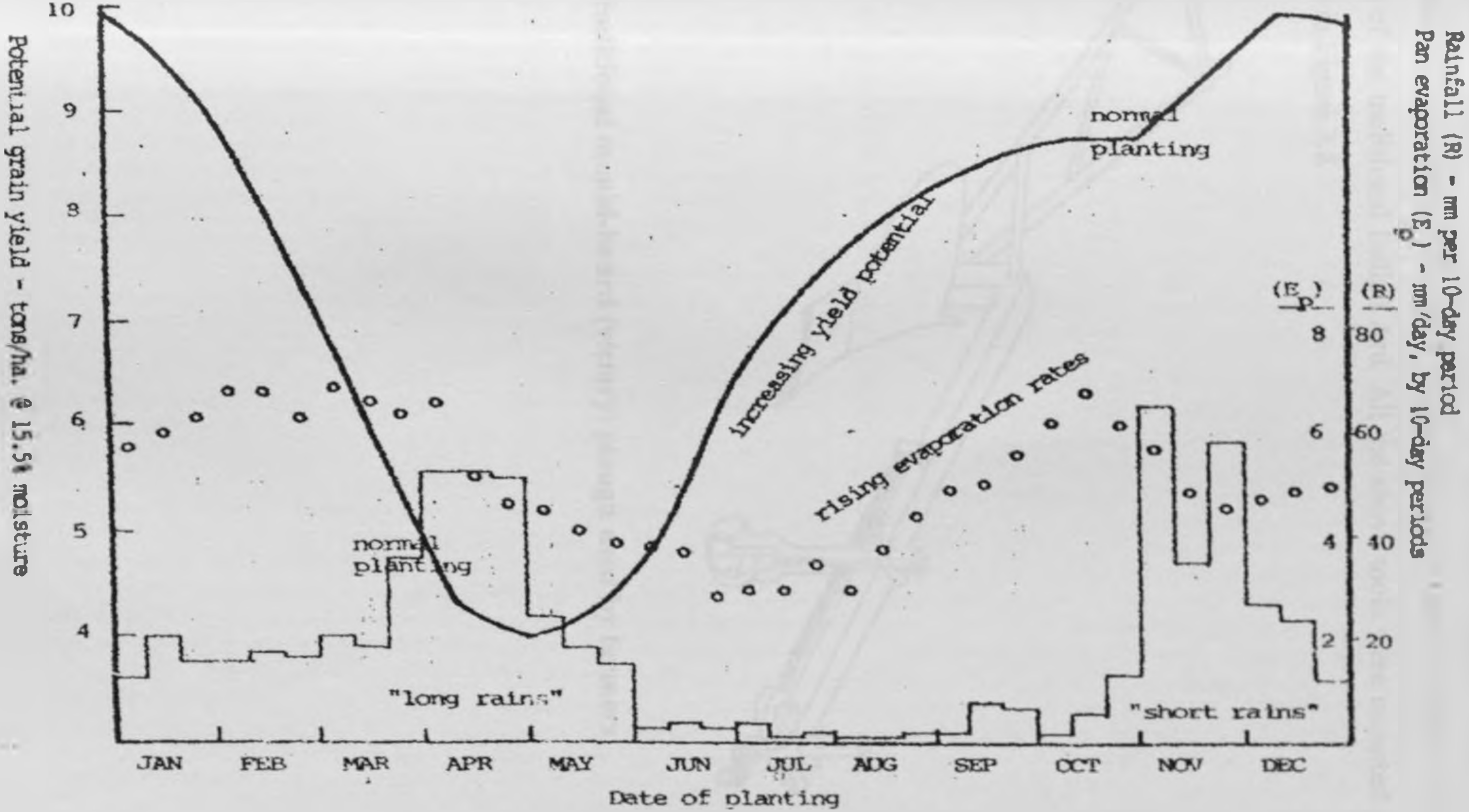


**Figure 3.3 20-year average rainfalls at Katumani**

*Source: Stewart (1980)*

### *3.2.7 Tillage Implements*

The following pieces of tillage equipment were tested under field conditions to evaluate their performance in land preparation and planting: mouldboard plough (Figure 3.4), chisel share (Figure 3.5and 3.6), A – shares (Figure 3.7), Desi plough (Figure 3.9 and 3.10). Desi plough is a modification of the traditional Indian Ard. All the above tools were mounted on Sine Hoe tool bar as shown in Figure 3.8.

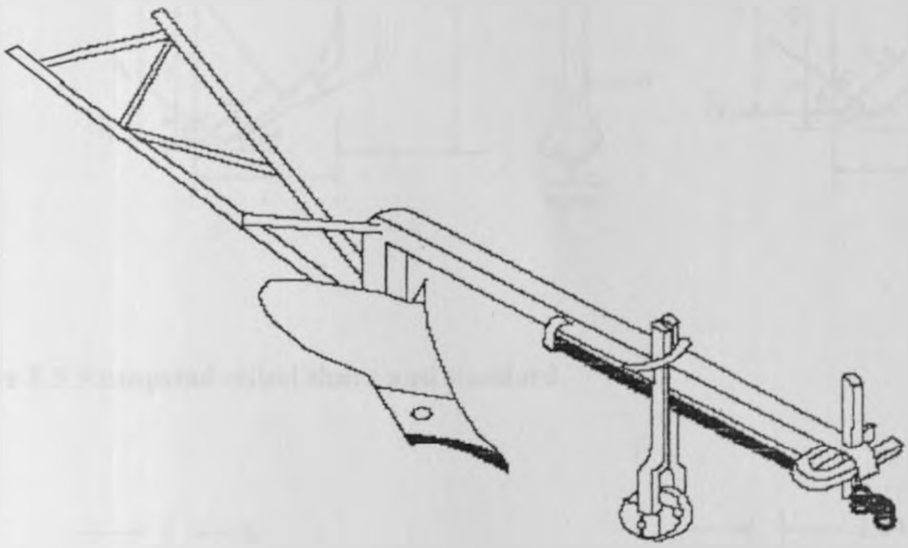

**Figure 3.4 Traditional mould-board (victory) plough used by farmers**

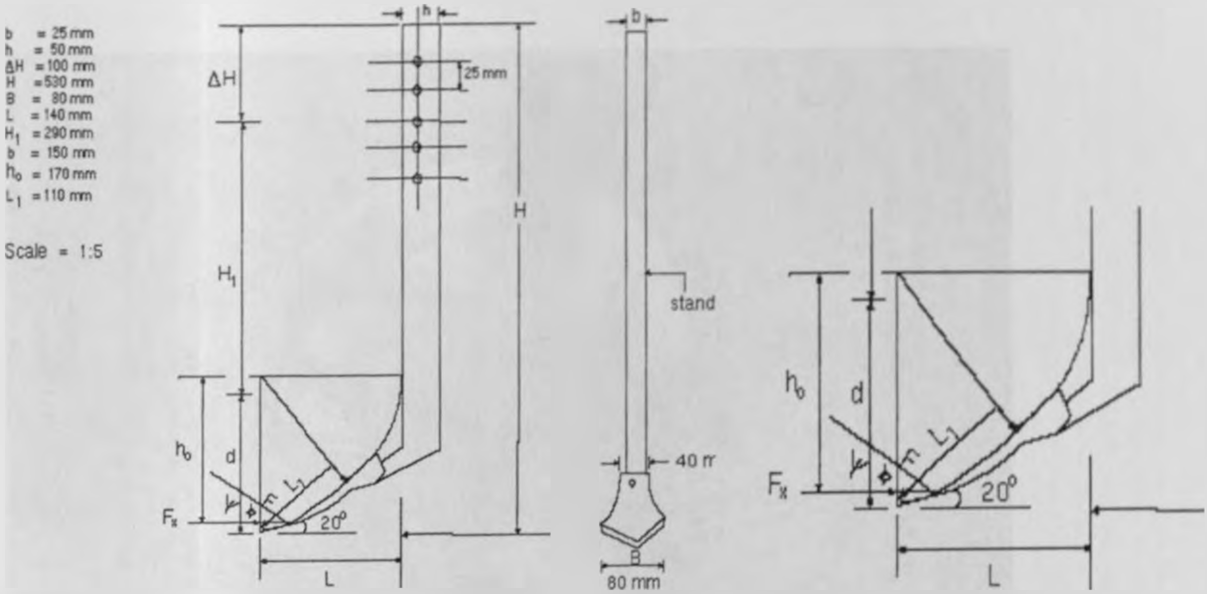


**Figure 3.5 Rumpstad chisel share and standard**

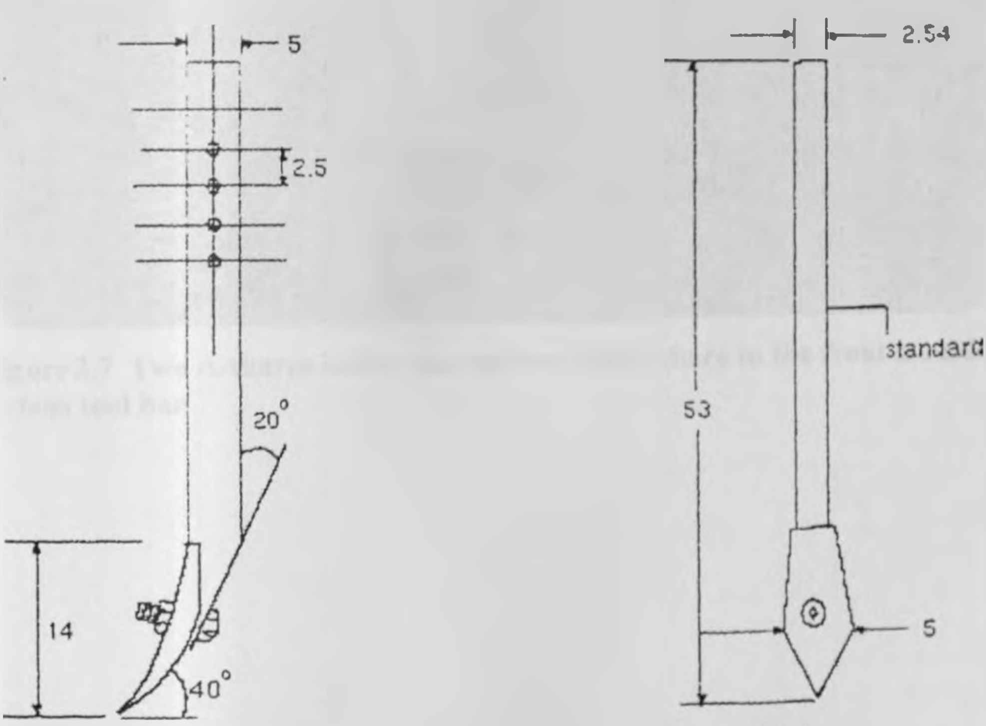


**Figure 3.6 Ariana chisel share mounted on standard**

**Figure 3.7 Two A-shares in the rear and one chisel share in the front moulded on the Ariana tool bar**

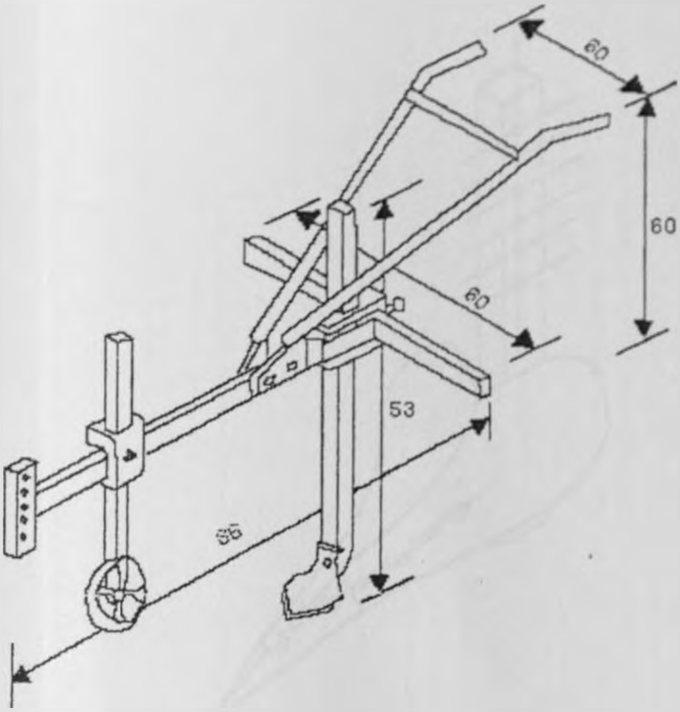


**Figure 3.8 Sine Hoe tool bar assembly (dimensions in cm)**

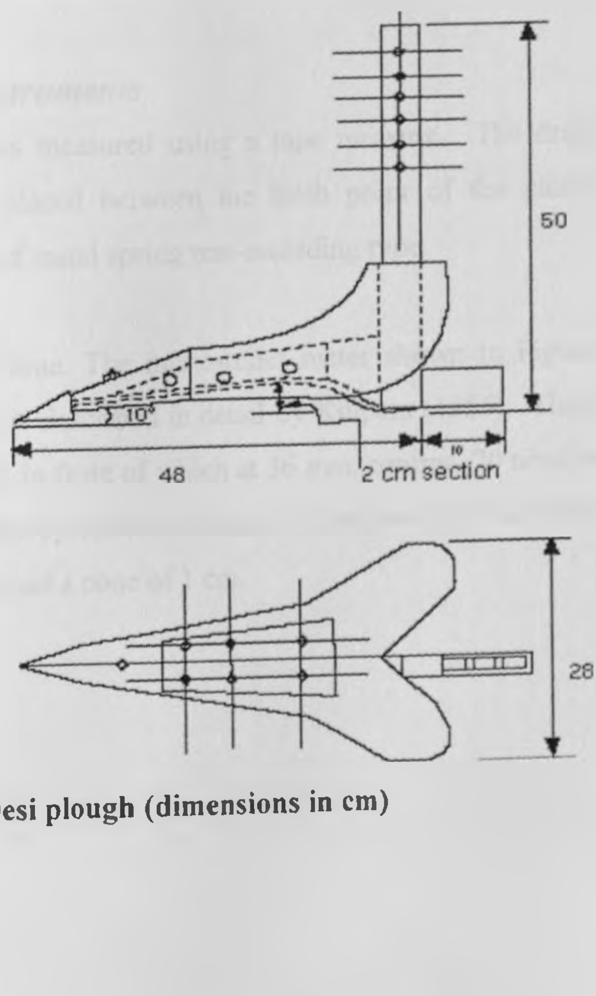


**Figure 3.9 Modified Desi plough (dimensions in cm)**

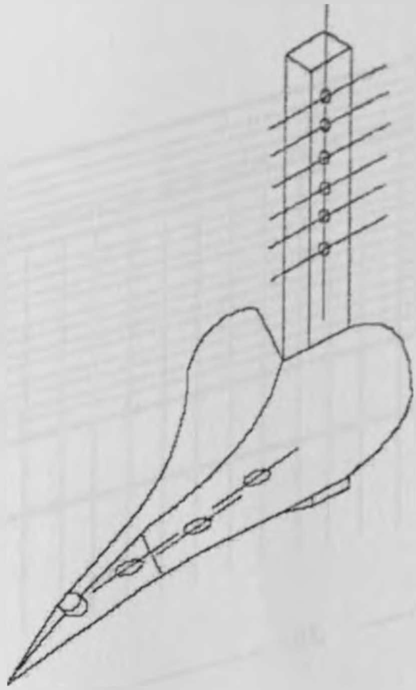

**Figure 3. 10 Modified Desi plough with standard**

### *3.2.8 Measuring Instruments*

The depth of tillage was measured using a tape measure. The draft was measured using a drawbar dynamometer placed between the hitch point of the plough and the chain. The dynamometer used was of metal spring non-recording type.

A stopwatch measured time. The micro-relief meter shown in Figure 3.11 measured surface roughness. This method is described in detail by Kuipers (1956). The relief meter consists of a board with a scale in cm. in front of which at 36 mm. centres, 20 needles are placed; each needle being divided into 4 parts by different colours. The cone type recording penetrometre, used for measuring soil hardness had a cone of 1 cm.

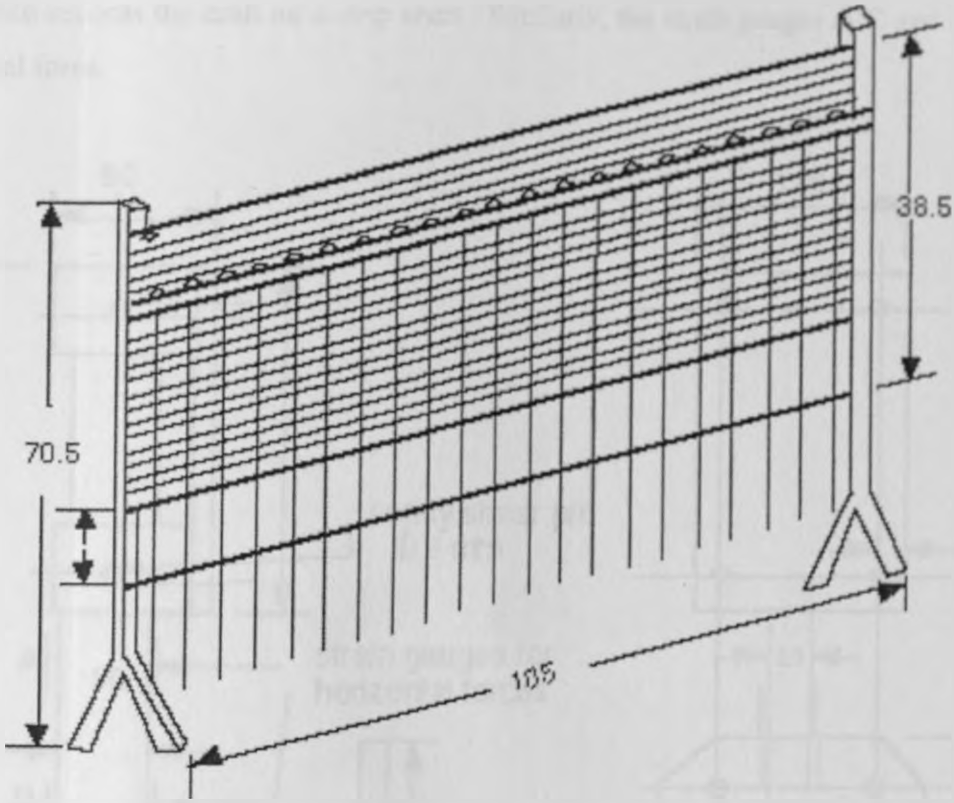


**Figure 3.11 Drawing of the micro relief meter (dimensions in cm)**

Soil shear strength was determined using a torque meter. The maximum torque at soil failure was recorded. On very hard soils, the shear devise blades did not penetrate and the torque could not be measured.

**Strain Gauge Transducer**

A strain gauge transducer for draft force measurements was designed and fabricated jointly by the Institute of Agricultural Engineering and the Department of Agricultural Engineering of the University of Wageningen, The Netherlands. Figure 3.12 and 3.13 show the various components of the transducer. At both A and B is mounted a set of strain gauges which measure the stress due to the bending moment caused by the draft force, F. The distance between A and B is fixed. Since the point of action of F depends on the depth of operation and is therefore not fixed, the strain gauges are arranged such that only the difference between the stresses at A and B is measured. This is then calibrated to measure the draft force F to which it is proportional. The output from the strain gauge is measured in electrical current, which is amplified to actuate a point which records the draft on a strip chart. Similarly, the strain gauges at C and D measure the vertical force.

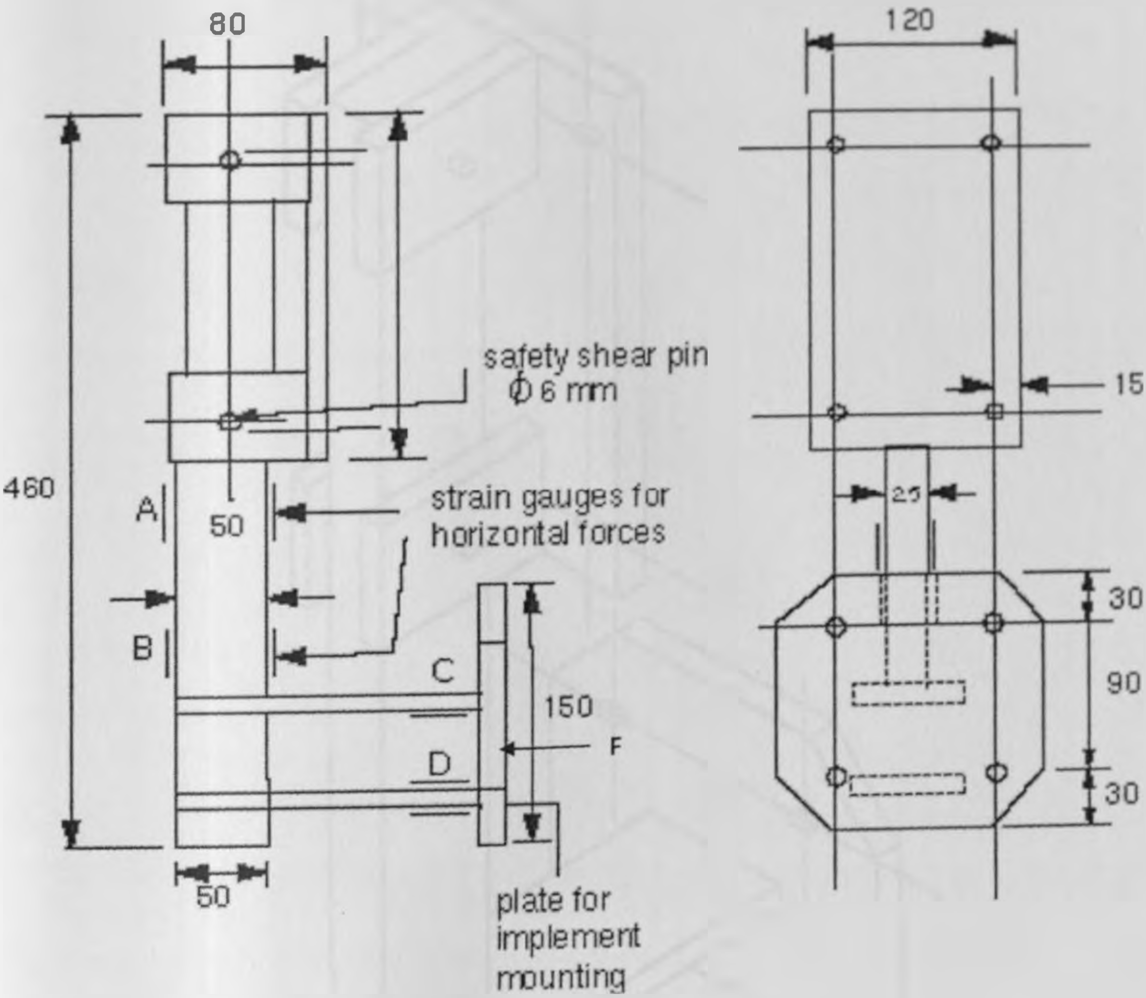


**Figure 3.12 Strain gauge transducer for horizontal and vertical force sensing (dimensions in mm)**

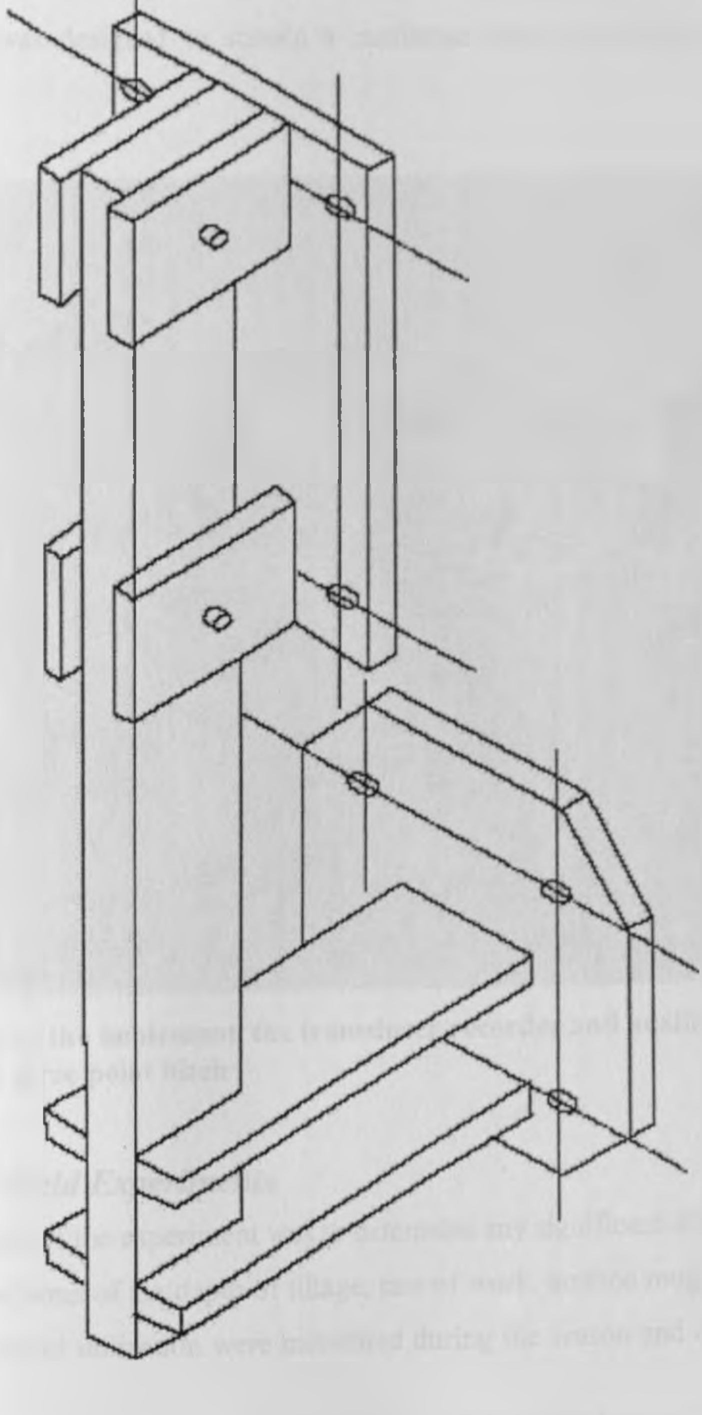

**Figure 3.13 Strain gauge transducer for horizontal and vertical force sensing**

The layout of the implement, the transducer, recorder and auxiliary power source all mounted on three point hitch of a 45 horse-power tractor is shown in Figure 3.14. As a safety measure the transducer, which was designed to sustain a maximum force of 500 Kg., a shear pin was installed.

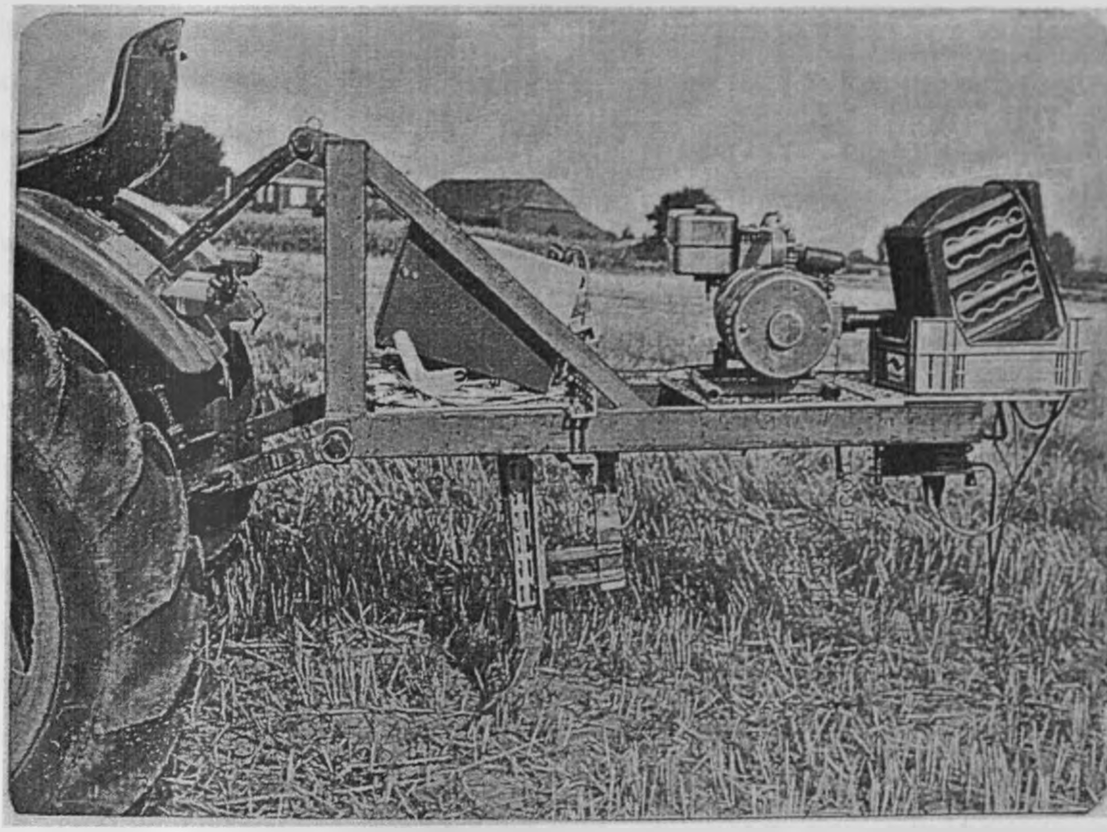

**Figure 3.14 Layout of the implement, the transducer recorder and auxiliary power source all mounted on the three point hitch**

### *3.2.9 Design of Field Experiments*

The primary objective of the experiment was to determine any significant difference between the tillage equipment in terms of the depth of tillage, rate of work, surface roughness, and the draft. Soil moisture and labour utilization were monitored during the season and crop yield was taken at harvest.

In order to collect realistic field data that might have some relevance to farm level operations, large plots (20×8 and 30×7 metres) were used. In addition turning space of not less than 5 meters was required for the oxen. Because of large variation expected, several (at least 4) replications were considered necessary. All these considerations made it necessary to use a large field of 300 metres by 50 metres (1.5 ha.) hence there was a large variation from one end of the field to the other. Land slope varied from 5% to 15%. It was also observed that soil texture, depth and fertility varied considerably. Thus, uniformity usually necessary for yield-targeted experiments did not exist. As discussed in detail in Section 3.1 yields were estimated from secondary sources (Keating *et al*, 1992). The calculations are based on the analysis given in Section 3.2.

The experiments were therefore concentrated on the factors that cause lateness in planting and weeding. Thus, the draft requirement and the corresponding depth of tillage and rate of work were important indicators of the ability to prepare land and plant when dry. The rate of ox weeding was also a good indicator of how timely weeding should be done. All these operations require at least two people at any one time, one to guide the oxen while the other guides the implement. Other factors namely: quality of seed, application of fertilizer, plant population and plant protection were kept constant as far as possible. The overriding question of soil and water management was dealt with through the measurement of micro-relief created in each method of tillage. Effectiveness of micro relief in controlling runoff was assessed using estimates drawn from secondary sources (Kijne, 1980) as discussed in Appendix G.

Figure 3.15 shows the plot layout for the 1978/79 short rains (S.R). It is a split plot design where hand and mechanical weeding are allocated to the main plots and the four tillage methods are allocated the split plots. However, since the methods of planting and weeding did not affect the primary tillage method and were in fact subsequent to it, the design could be treated as a randomized complete block design as far as the parameters measured before planting are concerned. Thus, depth of tillage, rate of primary tillage, micro-relief, and draft requirement were analyzed in accordance with the latter design.

In the 1979 long rains (L.R) a similar split plot Design was used to compare two methods of planting namely: mechanical planting using funnel and tube method and hand planting and two methods of weeding namely mechanical and hand weeding.

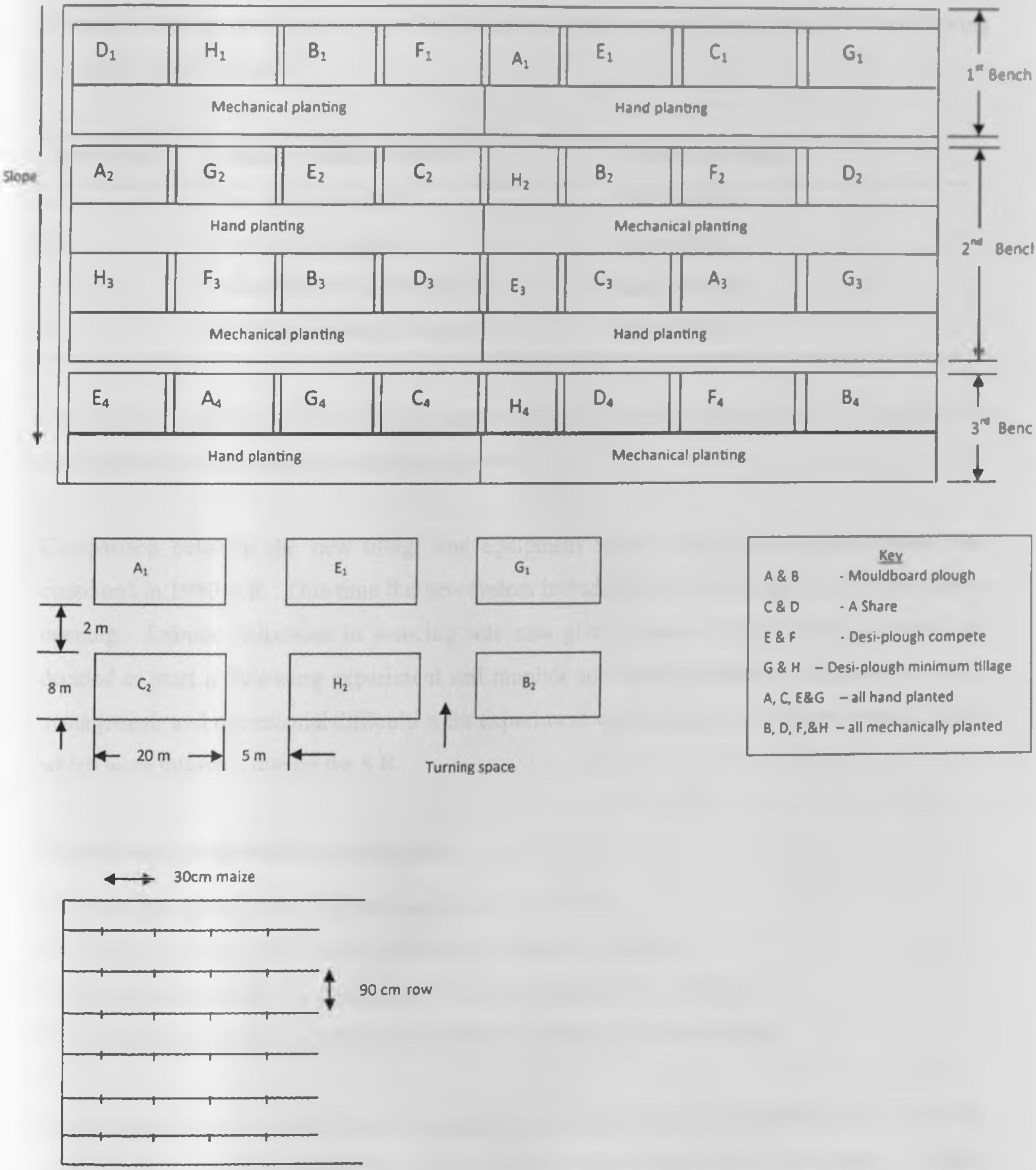


**Figure 3.15 Experimental plot lay-out**

For the 1979/1980 S.R. it was felt necessary to cross check the results of the previous S.R. through further comparison between the Desi plough and the mouldboard plough. The following treatments were included:

| Treatment | Primary tillage method | Weeding method |
|---|---|---|
| A | Desi strip ploughing | Hand weeding |
| B | Desi strip ploughing | Ox weeding |
| C | Mouldboard strip ploughing | Hand weeding |
| D | Mouldboard strip ploughing | Ox weeding |

All plots were planted by the tube and funnel mounted on the Sine Hoe tool bar. It was done at the same time as the furrows were being opened.

Comparison between the new tillage and equipment system and the traditional system was continued in 1980 L.R. This time the new system included the chisel plough before Desi furrow opening. Labour utilization in weeding was also given a major consideration. It was also decided to start a fallowing experiment and monitor soil moisture regime. In order to reduce management and operational difficulties the experiment was restricted to 32 plots overall, half of which were fallowed during the S.R.

The following treatments were compared:

A - Chisel ploughing, Desi furrow opening and ox weeding;
B - Chisel ploughing, Desi furrow opening and hand hoe weeding;
C - Mouldboard ploughing, mouldboard furrow opening and ox weeding;
D - Mouldboard ploughing, mouldboard furrow opening and hand weeding.

Chisel ploughing before Desi furrow opening was repeated during the 1980/81 S.R. to test the value of this operation under the harder conditions prevailing during this season. Further observation on effectiveness of weeding was also made.

Some experiments were carried out in Holland to establish the benefits of chisel ploughing before the Desi-furrow opening in terms of soil loosening and draft requirements. At the same time, the Desi plough was also compared with the Rumpstad potato lister while the Ariana chisel share was compared with a Rumpstad chisel. All the tools were mounted on a three-point hitch of a tractor. Instrumentation for measuring the horizontal and vertical forces and the furrow were as described in Section 3.2.8.

Finally, the Rumpstad single unit chisel ploughing was tried behind the farmer's bullock's at Katumani in the long rains of 1981. This was followed by Desi furrow opening and hand seed planting.

## 3.3 Effect of Tested Conservation Tillage and Equipment on Farm Production

A review of methodologies for quantifying the effect of technologies on small farm production which focused on linear and goal programming is given in Section 2.3. It was concluded that linear and goal programmings are appropriate for this purpose (Taha, 1997). The conceptual model is discussed in Section 3.3.1.

### *3.3.1 The Conceptual Model*

Linear programming (LP) is used mainly for comparing alternative activities in terms of quantified output performance given limited resources. In other words, LP is a mathematical tool used to compute the optimum production subject to a specified resource allocation. A typical sample can be drawn from a farming business. A farmer has limited land to which allocated various cropping enterprises. To grow the crops he uses labour, fertilizer, machines, which are available in fixed quantities over the season. The expected profit margin is also fixed. The requirement for resources for each enterprise is also known. The LP model computes the best combination of enterprises that yield the overall optimum. In our case the alternative enterprises are a combination of time of planting and the time of weeding to achieve an expected yield.

The purpose of the conceptual model is to show the range of information that was required as inputs into the models used. Details on how data was collected and the mathematical formulations used for analysis are given in Section 3.3. A linear programming model was used to compute the optimum maize grain production, the priority goal, of an average farmer who adopts innovative farm equipment successfully. This formulation was then modified into a goal programming model to compute the optimum energy consumption without violating the optimum production already achieved. For the purpose of sustainability the model recycled a specified quantity of crop residue.

Figure 3.16 illustrates input data and the expected outputs. The inputs data required include (i) expected maize yield (ii) available labour (iii) available land for cultivation (iv) field capacity of tested equipment innovations and (v) Specified crop residue recycle.

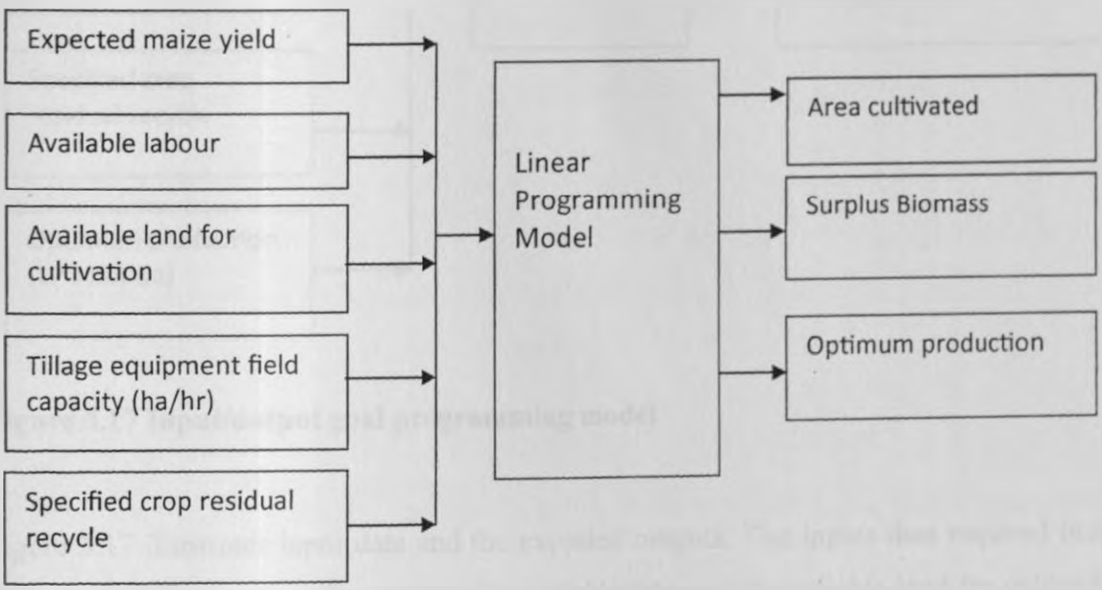


**Figure 3.16 Input/Output linear programming model**

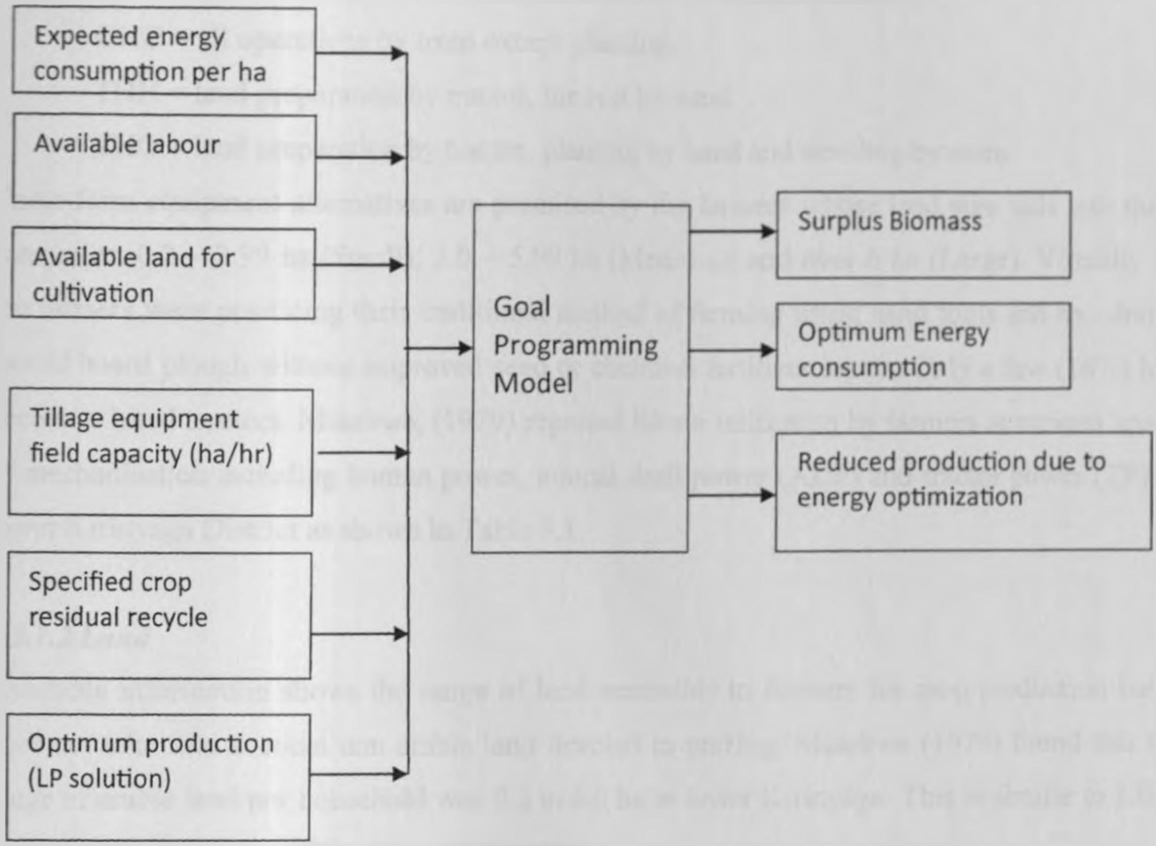


**Figure 3.17 Input/output goal programming model**

Figure 3.17 illustrates input data and the expected outputs. The inputs data required include (i) expected energy consumption per ha (ii) available labour (iii) available land for cultivation (iv) equipment field capacity (v) optimum productivity (LP solution) and (vi) specified crop residue recycle.

### *3.3.1.1 Labour*

Mutebwa (1979) determined the levels of mechanisation with respect to farmland size and labour in semi arid Kenya. He surveyed 56 farmers over two seasons. From the survey data he categorized farm equipment subsets into five alternatives depending on whether the farmers use one of various combinations of: hand tools, ox equipment or tractor for land preparation, planting or weeding, thus:

HHH = land preparation, planting and weeding by hand.

OHH = land preparation by oxen, planting and weeding by hand.

OHO = all operations by oxen except planting.

THH = land preparation by tractor, the rest by hand

THO = land preparation by tractor, planting by hand and weeding by oxen.

These farm equipment alternatives are practiced by the farmers whose land size falls into three categories: 0.2 – 2.99 ha (Small); 3.0 – 5.99 ha (Medium); and over 6 ha (Large). Virtually all the farmers were practicing their traditional method of farming using hand tools and ox- drawn mould board plough without improved seed or chemical fertilizer inputs. Only a few (16%) had access to hired tractors. Mutebwa, (1979) reported labour utilisation by farmers at various levels of mechanisation including human power, animal draft power (ADP) and tractor power (TP) in lower Kirinyaga District as shown in Table 3.1

***3.3.1.2 Land***

Available information shows the range of land accessible to farmers for crop production but it does not take into account non arable land devoted to grazing. Mutebwa (1979) found that the range of arable land per household was 0.2 to 6.0 ha in lower Kirinyaga. This is similar to 1.0 to 6.0 ha found by Audi (1996) in lower Machakos.

***3.3.1.3 Power***

ADP equipment performance was generated under controlled field experiments as detailed in Section 3.2.

***Tractor Power***

Some areas had access to Tractor Hire Service (THS) whereas other areas did not have access to any form of tractor power (TP). Mutebwa, (1979) found that 16% of farmers in the lower parts of Kirinyaga District had access to tractors for general land preparation but not necessarily for sub soiling. Access to THS is subject to farmers' ability to pay. The actual performance is shown in Table 3.1. The model formulation is detailed in Section 3.3.2.

**Table 3.1 Labour (by hand, oxen or tractor equipment) used in hours per hectare for maize as a function of different mechanization levels**

| | | Levels of Mechanisation | | | | |
|---|---|---|---|---|---|---|
| Activities | Levels | HHH Hand | OHH Hand Oxen | OHO Hand Oxen | THH Hand Tractor | THO Hand oxen Tractor |
| Ploughing | Low | 230 | 42 | 43 | 5 | 4 |
| | Average | 377 | 51 | 49 | 6 | 6 |
| | High | 524 | 60 | 55 | 7 | 8 |
| Planting | Low | 62 | 34 | 32 | 74 | 79 |
| | Average | 80 | 50 | 49 | 88 | 84 |
| | High | 98 | 66 | 66 | 102 | 89 |
| Weeding | Low | 166 | 200 | 22 | 224 | 20 |
| | Average | 234 | 230 | 25 | 226 | 25 |
| | High | 302 | 260 | 28 | 228 | 30 |
| Harvesting | Low | 200 | 150 | 208 | 210 | 220 |
| | Average | 220 | 222 | 218 | 219 | 221 |
| | High | 240 | 294 | 228 | 238 | 222 |

*Source: Mutebwa (1979). Lower Kirinyaga District*

Key:

| | **Ploughing** | **Planting** | **Weeding** |
|---|---|---|---|
| HHH | hand | hand | hand |
| OHH | oxen | hand | hand |
| OHO | oxen | hand | oxen |
| THH | tractor | hand | hand |
| THO | tractor | hand | oxen |

### 3.3.2 Energy Use for Crop Production Activities

#### 3.3.2.1 Tractor power

According to Panesar (1993), total energy (EI) consumption for a soil-working tool is given by:

$$EI = \frac{(D+MRP)v \times e \times T}{\eta_c \times \eta_t \times (1-s)} + \frac{MRP \times K_1 \times v \times (1-e)}{\eta_c \times \eta_t \times (1-s)} + \frac{RP \times T + PLP \times T}{\eta_c \times \eta_t} \qquad 3.9$$

Where

| | | | |
|---|---|---|---|
| $D$ | = draft; | $k_l$ | = constant; |
| $v$ | = speed; | $MRP$ | = rolling resistance; |
| $T$ | = total time; | $e$ | = field efficiency; |
| $\eta_t$ | = traction efficiency; | $s$ | = wheel slip; |
| $RP$ | = rotary power requirement at P.T.O; | $\eta_c$ | = engine efficiency; |
| $PLP$ | = power requirement for accessories; | | |

In a heavy non-rotary tillage operation RP=0 and PLP is negligible. The second of the two remaining components is the energy consumption during non-working period. The fuel consumption during time T is given by:

$$FC = \frac{EI}{\lambda} = \frac{(D+MRP)v \times T \times e}{\lambda \times \eta_c \times \eta_t \times (1-s)} + \frac{MRP \times v \times T \times (1-e)}{\lambda \times \eta_c \times \eta_t \times (1-s)} \qquad 3.10$$

Where $\lambda$ = fuel calorific value

For simplicity it can be assumed that the energy requirement during non-working period is the same as that during working period considering the following:

- Stops and starts
- Turns out and back into the field
- Engine speed increases as soon as load is reduced and lowers as the load is applied.

Under these circumstances the field efficiency, $e$, can be assumed to be equal to unity. Thus both the energy used when the implement is in the soil and that used when it is out of the soil (turning etc) is accounted for equally. Accordingly it is assumed that fuel used and traction efficiencies remains the same and that energy used per unit time is the same during total time T. The Equation 3.10 can therefore be reduced to the form:

$$FC = \frac{(D + MRP)v \times T}{\lambda \times \eta_c \times \eta_t \times (1 - s)} \quad 3.11$$

Therefore the rate of fuel consumption is given by

$$RFC = \frac{FC}{T} = \frac{(D + MRP)v \times T}{\lambda \times \eta_c \times \eta_t \times (1 - s)} \quad 3.12$$

Alternatively the rate of fuel consumption is given by

$$RFC = SFC \times BP \times \frac{Area}{v \times w \times e} \times Loading\ factor \quad 3.13$$

Where RFC is the rate of fuel consumption, SFC is specific fuel consumption and BP is brake power.

The alternative method of calculating the F.C. is convenient because SFC and BP for common tractors are published periodically. The relevant loading factors are also published periodically, by ASAE. The calorific value of the diesel fuel was taken from Liljedahl *et al* (1989). Diesel number 2-D with density of 0.847kg/l has high heating value of 39020 kJ per litre. A 60 Hp (45 kW) tractor was assumed.

### *3.3.2.2 Animate Energy Consumption*

Energy consumption from human beings and animals depends on several factors including: body weight, physical condition, type of work, motivation and experience. It is normally estimated by oxygen consumption and pause rate. Binning, Pathak and Panesar (1984) published 'Energy Audit of Crop Production Systems' in which they have standardised methods of analysis using data from various researchers in India. They found that energy for labour varied from 0.18 to 2.04 MJ/man-hour. For the purpose of this study a wighted average figure of 1.96 MJ/man-hour undertaking heavy agricultural tasks such as tillage is assumed.

In a similar manner, they analysed data on energy output from draft animals. They found that the range for oxen varies from 2.68 to 31.40 MJ per bullock hour. For the purpose of this study a weighted average of 10.1MJ per bullock hour has been used as recommended by Binning et al (1984) referred to above.

### *3.3.3 Machinery Performance*

When a group of farmers have adopted a form of farm power and equipment, the degree of adoption is measured for example in the form of how many hectares are being ploughed per season. The gross benefits associated with the selected schedule of planting and weeding are estimated from the list of alternative production schedules determined in Section 3.1. The seasonal cost of ploughing per ha is estimated in terms of owning costs and variable costs. Custom hire service rates are good indicators of the cost of mechanization of the relevant operations.

In order to estimate the cost of machine hours or man-hours, accurate measurements of machine hours and/ or labour inputs per season for each of the operations were carried out. Alternatively available secondary data on machine utilization were used in estimating the relevant field capacity, field efficiency, labour requirement, and associated costs. Definitions used here are based on ASAE standards namely: S495 on uniform terminology, EP496 on machinery management and D497 on machinery management data (Srivastava, Goering and Rohrbach, Engineering Principles of Agricultural Machines and Efficiency ASAE (1995).

#### *3.3.3.1 Field Capacity*

On an area basis field capacity is given by:

$$C_a = \frac{SWe}{10} \qquad 3.14$$

Where

$C_a$ = field capacity

S = actual travel speed (Km/h)

W = machine working width (m)

e = field efficiency (decimal)

The term theoretical field capacity is used to describe ideal conditions when full working width is used and when no interruptions in the form of turns or idle time take place. Under such circumstances the field efficiency is deemed to be equal to 1.

#### *3.3.3.2 Field efficiency*

Theoretically, time required to perform a given operation varies inversely with the theoretical field capacity and can be calculated with the following equation

$$T_t = \frac{A}{C_{at}} \qquad 3.15$$

Where

$T_t$ = time theoretically required to perform an operation (h)

$C_{at}$ = theoretical field capacity (ha/h)

A = area to be processed (ha)

The actual time required to perform the operation will be increased due to overlap, time required for turning on the ends of the field, time required for loading or unloading materials etc. Such time losses lower the field efficiency below 100%. The following equation can be used to calculate the field efficiency:

$$\eta = \frac{T_t}{T_e + T_h + T_a} \qquad 3.16$$

Where

$T_e = T_t / K_w$ = effective operating time (h)

$K_w$ = fraction of implement width actually used

$T_a$ = time losses that are proportional to area (h)

$T_h$ = equals time losses that are not proportional to area

### *3.3.3.3 Machinery costs*

Machinery cost consists of ownership and operations including penalties for lack of timeliness.

***Ownership Costs***

The total annual ownership costs can be expressed as in Equation 3.17 by Srivastava (1995).

$$C_{os} = \frac{C_{oa}}{P_u}(1 - S_v)\left(\frac{I_r(1 + I_r)^{\tau_l}}{(1 + I_r)^{\tau_l} - 1}\right) + \frac{K_{tis}}{100} \qquad 3.17$$

Where

$C_{os}$ = specific annual ownership costs (1/yr)

$C_{oa}$ = total annual ownership costs (Kshs/yr)

$P_u$ = purchase price machine (Kshs)

$\tau_l$= economic life of the machine

$S_v$ = salvage value as fraction of purchase price

$I_r$ = real annual interest rate (decimal)

$K_{tis}$ = annual cost of taxes, insurance and shelter as percentage of Purchase price

The real interest rate, as defined by Bartholomew (1981) is:

$$I_r = \frac{I_p - I_g}{1 + I_g} \qquad 3.18$$

Where

$I_p$ = prevailing annual interest rate

$I_g$ = general inflation rate

*Operating Costs*

Operating costs are associated with use of machine. They include the costs of labour, fuel and oil, repair and maintenance.

### *3.3.4 Workable Time*

Kijne (1980) showed that the basic infiltration rate for Katumani Alfisols is 20 mm rainfall per hr. Therefore 40 mm would take over 2 hrs. It was therefore considered prudent to allow unworkable time as follows:

- **One day** was considered unworkable if 20-40 mm rainfall was received within 24 hours
- **Two days** were considered unworkable if more than 40mm rainfall was received within 24 hours

The linear programming model was run for each of the 19 years using actually available workable days per week assuming a maximum of 5 working days per week. For instance, for 2 AME (adult men equivalent) whose weekly labour input is 50 man-hours, only 40 hours were taken if one working day was lost.

From these runs, it was determined that the difference between the average output of the 19 year runs and the output of one run using the average workable time for each week over the season was negligible. Therefore, all subsequent runs were done using 19-year averages of workable time during the season.

The data collection procedures are shown in Appendix A, input data processing methodology in Appendix B and worked out examples for input matrices in Appendix C.

### *3.3.5 Linear Optimization Rationale*

The linear optimization model considered for the analysis of farm production attempts to maximize the area of land planted and weeded as early as possible utilizing all the available resources. Therefore the model selects area units of land planted and weeded at specified timeliness subject to available labour, land and power during the critical cropping season. For each of the area units (variables) there is a corresponding expected yield. Farm production is therefore the sum of selected area units (ha) times the corresponding yield (kg. of maize grain).

For each variable there is a specified number of operations that must be carried out according to a given time schedule in order to attract the corresponding yield. The tillage subsystem is defined by the nature of operations that are specified. Each operation is carried out by a tillage equipment subset which consists of operation schedule, equipment hardware, field capacity, and number of men and women.

Therefore for each variable the number of subsets in the subsystem defines the tillage that is applied. The purpose of this model is not to optimize the allocation of resources in a particular farm unit but rather to quantify the optimum production of typical farm size units for the purposes of corporate planning of a mechanization scheme. Therefore actual labour or land resources in a particular farm setting are not necessary.

For these reasons, family specific socio-economic and cultural factors, which affect access to labour, land and power, are not considered. The model considers a range of labour, land and power utilization and computes the corresponding farm production. In addition to farm production, the model attempts to minimize energy consumption. The model also recycles a specified amount of crop residue to contribute to building up of organic matter content.

*3.3.5.1 Single Objective Linear Programming*

Farmer's production is the sum of the product of the cultivated area units and associated expected yield of each of the selected timeliness crop production schedules (variables).

The general Linear Program (LP) is;

Maximise

$$z = \sum_{J=1}^{n} c_j x_j \qquad 3.19$$

Where $C_j$ is the price of the commodity per unit and $x_j$ is the number of units in activity $j$ respectively.

Such that

$$\sum_{J=1}^{n} a_{ij} x_j \quad \leq b_{ij}, \qquad 3.20$$

And subject to $x_j \leq b_i,\ i = 1,2,\ldots,\quad x_j \leq b_i,\quad i = 1,2,\ldots,m$

$x_j \geq 0,\ j = 1,2,\ldots,n \quad x_j \geq 0,\ j = 1,2,\ldots,n$

Farmers' gross production is the sum of the product of the cultivated area units multiplied by the corresponding crop yield to the selected timelines crop production schedules. This analysis is confined to three weeks from rains onset.

The variables are defined as;

$x_{nm}$= *Area of the maize activity planted n weeks late and weeded m weeks late for n, m=0, 1, 2, 3.*

$y_{nm}$ = *the expected yield corresponding to the timeless schedule nm.*

Therefore the objective function becomes

$$z = \sum_{n=0}^{3}\sum_{m=0}^{3} x_{nm} y_{nm}$$

3.21

The problem has four constraints

1. The number of hours available from each power unit during the critical (week) period of 10 weeks cannot be exceeded. Given that $b_{(i,j,t)}$ is the number of hours available for $i^{th}$ crop operated by the power unit $j$ during working period $t$.

Given that $H_{(i,j,k,t)}$ = hours per ha required for $i^{th}$ crop in $k^{th}$ operation powered by $j^{th}$ power unit in the week period $t$, then the constraint becomes

$$\sum_{n=0}^{3}\sum_{m=0}^{3} x_{nm} \sum_{k=1}^{k} H(i,j,k,t) \le b_{(i,j,t)} \qquad 3.22$$

For $i=1; j=1, 2, 3; t=1, 2 \ldots 10.$

For animal draft power (ADP), $j=1$; tractor power (TP), $j=2$

2. The number of man hours available during the critical (week) period cannot be exceeded. Where $M_{(i,j,k,t)}$ is the man hours per ha required for $i^{th}$ crop in the $k^{th}$ operation by $j^{th}$ power unit during working period $t$.

   So the second constraint becomes;

$$\sum_{n=0}^{3}\sum_{m=0}^{3} x_{nm} \sum_{k=1}^{k} M(i,j,k,t) \le b_{(i,j,t)} \qquad 3.23$$

3. The model recycles a predetermined quantity of crop residue regardless of the quantity produced. If necessary the model draws from uncultivated land. The constraint equation to ensure residue recycle is given by

$$\sum_{n=0}^{3}\sum_{m=0}^{3} x_{nm}(B - C_r Y_{nm}) \le 0 \qquad 3.24$$

   B is the specified crop residue recycle in kg per ha and $C_r$ is crop residue / maize grain ratio.

   The accessible land for cultivation ranges from 2 ha to 4 ha per farmer. So the fourth constraint becomes;

$$\sum_{n=0}^{3}\sum_{m=0}^{3} x_{nm} \le h \qquad 3.25$$

4. The non-negativity constraint where $x_{nm}$ cannot assume negative values.

   $x_{nm} \ge 0, \; n = 0, 1, 2, 3; m=0, 1, 2, 3.$

Thus the overall linear programming model becomes

Maximise

$$Z = \sum_{n=0}^{3}\sum_{m=0}^{3} x_{nm} y_{nm} \qquad 3.21$$

Subject to;

$$\sum_{n=0}^{3}\sum_{m=0}^{3} x_{nm} \sum_{k=1}^{k} H(i,j,k,t) \leq b_{(i,j,t)} \qquad 3.22$$

$$\sum_{n=0}^{3}\sum_{m=0}^{3} x_{nm} \sum_{k=1}^{k} M(i,j,k,t) \leq b_{(i,j,t)} \qquad 3.23$$

$$\sum_{n=0}^{3}\sum_{m=0}^{3} x_{nm} (B - C_r Y_{nm}) \leq 0 \qquad 3.24$$

$$\sum_{n=0}^{3}\sum_{m=0}^{3} x_{nm} \leq h \qquad 3.25$$

With $x_{nm} \geq 0$, $n=0, 1, 2, 3$; $m = 0, 1, 2, 3$.

For the purpose of maximizing net production the net crop yield can be substituted for the gross crop yield where the net crop yield is given by

$$\Delta y_{nm} = y_{nm} - y'_{nm}$$

And, $y'_{nm}$ is the break even yield.

The LP model given by Equation 3.21 was used to carry out estimates of net production per farm unit.

$$H_{(i,j,k,t)} = \frac{10(np \times r)_{(i,j,k,t)}}{(v \times e \times w)_{(i,j,k,t)}} = \frac{(np \times r)_{(i,j,k,t)}}{C_{a\,(i,j,k,t)}} \qquad 3.26$$

$$M_{(i,j,k,t)} = \frac{10(np \times nm \times r)_{(i,j,k,t)}}{(v \times e \times w)_{(i,j,k,t)}} = \frac{(np \times nm \times r)_{(i,j,k,t)}}{C_{a(i,j,k,t)}} \qquad 3.27$$

Where: ***np*** is the number of power units operating together, ***nm*** the number of men per power unit, ***r*** the number of replications per operation, ***v*** the speed in km/h, ***e*** efficiency

***w*** = width in meters and

$$C_a = \frac{v \times e \times w}{10} \qquad 3.28$$

### 3.3.6 Goal Programming

The purpose for agricultural development is to achieve high but sustainable profit. Therefore the following goals must be achieved concurrently namely:

- Increased production
- Optimum energy consumption
- Residue bio-mass recycle

Goal formulation was as follows:

Maximize net production

$$Z = \sum_{n=0}^{3}\sum_{m=0}^{3} x_{nm}\Delta y_{nm} \qquad 3.21$$

Since the high priority goal values of $Z$ were determined by the single objective LP formulation discussed above, energy goal was optimized as follows:

Minimize energy requirements

$$EIG = \sum_{n=0}^{3}\sum_{m=0}^{3} X_{nm}(EIP)_{nm} \qquad 3.29$$

Where $(EIP)_q$ is the energy requirement per hectare and $EIG$ is the gross energy requirement.

Subject to

$$\sum_{n=0}^{3}\sum_{m=0}^{3} x_{nm}\Delta y_{nm} + S_1^{+} - S_1^{-} = Z \text{ (Production Goal)} \qquad 3.30$$

$$\sum_{n=0}^{3}\sum_{m=0}^{3} x_{nm}(B - C_r Y_{nm}) + S_1^{+} - S_1^{-} = 0 \text{ (Residue recycle goal)} \qquad 3.31$$

$$\sum_{n=0}^{3}\sum_{m=0}^{3} x_{nm} \sum H_{(i,j,k,t)} \le b_{(i,j,t)} \qquad 3.22$$

$$\sum_{n=0}^{3}\sum_{m=0}^{3} x_{nm} \sum_{k=1}^{k} M(i,j,k,t) \le b_{(i,j,t)} \quad 3.23$$

$$\sum_{n=0}^{3}\sum_{m=0}^{3} x_{nm} \le h \quad 3.25$$

$$x_1, x_2, \ldots\ldots\ldots, x_q, S_1^+, S_1^- \; S_2^+, S_2^- \ge 0 \quad 3.32$$

The optimum solution was obtained by TORA, goal programming software (Taha, 1997). The single objective LP model, Equation 3.21, defined optimum production subject to the constraints of the farming system also defined by Equations 3.22, 3.23, 3.24 and 3.25 as shown above. In goal programming, the optimum production (already determined above) was set as the priority goal, which is achievable. The corresponding objective function was then formulated as a constraint Equation 3.30 to ensure that the production goal already achieved is not violated when energy consumption is being optimized. If the system produced less than the previous optimum, this was considered a violation of production goal and the model estimated the degree to which this goal was violated. In the same way, biomass to be recycled was set as an achievable goal. A corresponding constraint Equation 3.31 was formulated with a restriction that a certain amount of the biomass must be recycled. The model quantified any surplus biomass after recycling specified amount. In short the same objective function for single goal was maintained for optimization of energy use. The coefficients now became the energy consumption instead of maize yield equivalent; other constraints remaining the same.

The data collection procedures are shown in Appendix A, input data processing methodology in Appendix B and worked out examples for input matrices in Appendix C.

# CHAPTER FOUR

# RESULTS AND DISCUSSION

Results and discussion for the study are given in Section 4.1, 4.2 and 4.3. Detailed procedures for data collection, processing, worked out examples for model input matrices, and detailed outputs are given in appendices A, B, C and D respectively. Background information on equipment design criteria, description of equipment tested and evaluation of tillage performance in controlling runoff is given in appendices E, F and G.

## 4.1. Needs, Resources and Constraints to Maize Yield Response to Delays in Planting and Weeding

The combined effect of time of planting is given by Equation 3.8. The results are shown in Table 4.1Yield of 2060 kg/ha was the mean of the 63 L.R simulated timely planted seasons by Keating *et al* (1992); all other crop requirements being met.

Yields for early-weeded crop reduced to 980 kg/ha, which is a typical farm level average yield. Further delays produce yields below farmers' average and can be expected from poor adopters. The need for farm equipment to facilitate timely land preparation, planting and weeding is underscored by the potential to double the yields if these operations are timely. Table 4.1offers alternative schedules for maize planting and weeding operations using available tillage equipment. Taking farm level yield as a benchmark, Table 4.1 indicates the tillage timeliness options that the farmer can consider. From this table it is clear that subject to adoption of biochemical inputs (seeds, fertilizers and pesticides) farmers need to improve timeliness of planting and weeding in order to increase maize yield. Before planting they must apply a specified amount of farm yard manure (FYM) as well as break the land before the rains.

However oxen were often not in good physical condition at the end of the dry season when a high demand for power was imposed by hard soil conditions (Mutebwa, 1979). Moreover the farmers' plough is not appropriate for breaking a compacted surface and sub surface layer. Inadequate capacity to break the hard soil surface implies equally inadequate surface roughness to control runoff. It was therefore recommended that farmers be empowered to access tillage equipment innovations to carry out timely and efficient operations in order to realize increased yields. Access to labour and land is a necessary precondition for increased production. Results of labour surveys are given in Table 4.1.

**Table 4.1 Expected maize yield in kg/ha as affected by delays in planting and weeding**

| Weeks delay in weeding | Weeks delay in planting | | | |
|---|---|---|---|---|
| | 0 | 1 | 2 | 3 |
| **0** | 1260 | 1700 | 1340 | 980 |
| **1** | 1530 | 1260 | 1000 | 728 |
| **2** | 1010 | 829 | 653 | 478 |
| **3** | 478 | 394 | 311 | 227 |

### *4.1.2 Labour*

The results of the survey are shown in Table 4.2. Second to livestock, weeding required the largest labour input. A close observation of a typical farm situation is shown in Figure 4.1. The salient points are discussed below.

The main reason for the survey on labour utilization was to give an indication of the feasible labour inputs. It was apparent that depending on the number of adults available on the farm, labour inputs varied from 42 to 160 man-hours per week. From Table 4.2, land preparation, planting and weeding used 792 (474 +319) man-hours over five weeks on an average of 133 hours per week. This figure offers a fair indication of how much labour is available during peak labour demand period.

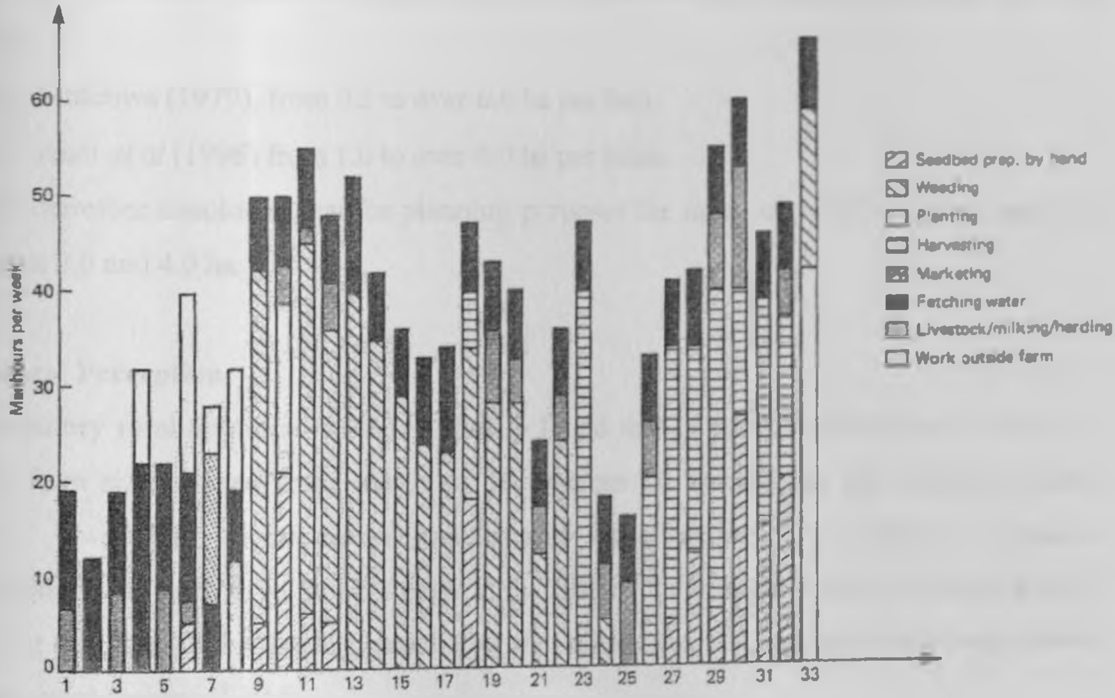


**Figure 4.1 Labour input calendar March to October, 1976, lower Kirinyanga, Kenya**

**Table 4.2 Man hours for various activities by a sample 48 farmers in lower Kirinyaga, 1976**

| Activity | L.R. average (Man hrs) | % | S.R. average (Man hrs) | % |
|---|---|---|---|---|
| Land preparation and planting | 319 | 14 | 142 | 17 |
| Weeding | 474 | 20 | 119 | 14 |
| Marketing | 128 | 5 | 11 | 1 |
| Livestock keeping | 952 | 40 | 449 | 53 |
| Water carrying | 269 | 12 | 109 | 13 |
| Others* | 202 | 9 | 16 | 2 |
| Total | 2344 | | 846 | |
| Total for the year | | | 3190 | |

*Others included harvesting and work outside farm only and did not include other domestic activities

### *4.1.3 Land*

Available land resources were derived from the secondary data in Section 2. It is apparent that while the average farm size may have changed over time the range changed very little.

Thus the researchers observed similar ranges in different places and at different times as shown;

- Mutebwa (1979), from 0.2 to over 6.0 ha per farm
- Audi *et al* (1996) from 1.0 to over 6.0 ha per farm

It was therefore concluded that for planning purposes the range of ADP cultivated land lies between 2.0 and 4.0 ha.

**Farmers' Perception**

Participatory rural appraisal (PRA) workshop found that in parts of Machakos (Audi *et al*, 1996) farm sizes ranged from one to six ha whereas the family size lies between six and twelve. Ownership of ox-drawn plough and wheelbarrow was confined to middle management or innovative farmers only. Only 20% of the villages surveyed managed early planting and thus 80% villages planted after the rains onset. All farmers adopted application of farm yard manure (FYM).

### *4.1.4 Conclusion and Recommendations*

Although farmers have accepted early planting and weeding, the results show that their average yield is half the expected bio-chemical potential had the current recommendations been implemented fully. The farmer's yields are equivalent to those planted three weeks late and weeded early (Table 4.1). The same yield is realised for a crop planted early and weeded two weeks late. This means that farm equipment capacities for both timely planting and weeding are inadequate.

It can be concluded that farmers' willingness to adopt current recommendations including timeliness of planting and weeding, application of improved seed, organic and inorganic fertilizers and crop protection are frustrated by inadequate access to improved tillage equipment for dry land breaking. It is recommended that i) multi-farm use of both ADP and TP equipment for tillage be explored. It is further recommended that policy makers consider creating the necessary support infrastructure for selection, testing and maintenance of appropriate ADP and tractor powered equipment.

## 4.2 Tillage and Equipment test results under Controlled Field Experiments

The results of controlled experiments in the 1978/79 S.R. are summarized in Tables 4.3 to 4.9. The results of four blocks planted by funnel and tube included in these tables illustrate the performance with regard to the main parameters of interest namely: depth of tillage, rate of work, speed, surface roughness and draft.

**Depth of tillage**

Table 4.3 shows that all treatment differences are significant at 5% level. Desi strip tillage achieved over 50% greater depth than chisel share.

**Rate of work**

Table 4.4 shows that there is no significant difference in the rate of work except, when the Desi plough was used for strip tillage in which case, the rate of work is 2.5 to 3 times greater than the rest. For continuous cultivation, mouldboard had 25% lower rate of work probably due to poor penetration, which interrupted the process. The main factor that influenced rate of work was speed and effective width; field efficiencies being not significantly different.

**Speed**

Table 4.5 shows the speed observed for the four tillage methods. Clearly, there is a significant difference between the Desi plough and mouldboard plough. The reduced speed by the Desi plough is most probably due to its greater depth of cultivation.

**Table 4.3 Results of average depth (cm) (1978 short rains)**

| | BLOCKS | | | | | |
|---|---|---|---|---|---|---|
| | I | II | III | IV | Treatment Total | Mean |
| Treatment: | | | | | | |
| Mouldboard | 5.80 | 4.85 | 5.70 | 6.55 | 22.9 | 5.7 |
| A-Share | 8.15 | 7.70 | 7.30 | 7.65 | 30.8 | 7.7 |
| Desi Plough | 9.15 | 9.10 | 9.25 | 9.30 | 36.8 | 9.2 |
| Desi Strip Tillage | 10.80 | 11.15 | 12.55 | 11.50 | 46.05 | 11.5 |
| Block Totals | 33.90 | 32.80 | 34.80 | 35.05 | 136.55 | |
| Mean | 8.50 | 8.20 | 8.70 | 8.80 | 8.50 | |

| | D of F | SS | Variance | F |
|---|---|---|---|---|
| Total | 15 | 75.19 | | |
| Blocks | 3 | 0.8 | 0.26 | 0.8 |
| Treatments | 3 | 71.61 | 23.87 | 77.0 |
| Error | 9 | 2.78 | 0.31 | |

LSD = 0.88 Studentised Range D = 1.70

**Table 4.4 Results of average effective rate of work M2/s x $10^{-2}$ (1978 short rains)**

| | BLOCKS | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Treatment | I | II | III | IV | Treatment total | Mean | Ha/ hr | Eff % |
| Mouldboard | 9.5 | 9.0 | 8.5 | 9.0 | 36.0 | 9.00 | .03 | 77 |
| A-Shares | 12.5 | 11.5 | 11.5 | 13.5 | 49.0 | 12.25 | .04 | 78 |
| Desi Plough | 12.5 | 10.5 | 9.5 | 8.5 | 41.0 | 10.25 | .04 | 76 |
| Desi Strip Tillage | 29.5 | 27.0 | 29.5 | 29.5 | 115.0 | 29.0 | .10 | 83 |
| Block Totals | 64.0 | 58.0 | 59.0 | 60.0 | 241.0 | | | |

**Table 4.5 Results of average speed m/s x $10^{-2}$**

| Treatment | BLOCKS I | II | III | IV | Treatment Totals | Mean |
|---|---|---|---|---|---|---|
| Mouldboard | 59.0 | 56.0 | 55.5 | 55.5 | 226.0 | 56.6 |
| A-Shares | 45.0 | 43.0 | 41.5 | 48.0 | 177.5 | 44.4 |
| Desi Plough | 53.0 | 43.0 | 46.0 | 40.0 | 182.0 | 45.5 |
| Desi Strip Tillage | 42.0 | 38.0 | 42.0 | 44.5 | 166.5 | 41.7 |
| Block Totals | 199.0 | 180.0 | 185.0 | 188.0 | 752.0 | |
| Means | 50.0 | 45.0 | 46.3 | 47.0 | 47.0 | |

Anova

| Total | D of F | SS | Variance | F |
|---|---|---|---|---|
| Blocks | 15 | 666.0 | | |
| Treatments | 3 | 48.5 | 16.16 | 1.4 |
| Error | 3 | 513.12 | 171.04 | 15.6* |
| | 9 | 98.38 | 10.93 | |

LSD = 10.6

Studentised range, D = 20.6

**Roughness Coefficient**

Table 4.6 shows the roughness coefficients (R). It is evident that Desi plough used as strip tillage tool has much greater surface roughness coefficient than either the A-share or the mouldboard plough.

Four blocks were planted by funnel and tube at the same time the furrows were opened. Table 4.7 shows the results of the four blocks planted by the funnel and tube method. The Desi strip tillage had the highest plant population although the difference was not significant. All the treatments had a plant population drop of 26 - 43 %, most probably due to the depth of planting and the quality of the seedbed.

Table 4.8 shows soil moisture in percent by volume, which was taken in the middle of the rainfall season when the profile was near field capacity. Although the Desi plough seems to have retained more moisture than mouldboard plough plots, the differences were not statistically significant.

**Table 4.6 Roughness coefficients (1978 short rains)**

| Treatment | BLOCKS I | II | III | IV | Treatment totals | Mean |
|---|---|---|---|---|---|---|
| Mouldboard | 37.41 | 32.79 | 27.22 | 38.32 | 135.74 | 33.93 |
| A-Share | 37.10 | 27.42 | 44.21 | 32.54 | 141.27 | 35.31 |
| Desi Str. Till. | 60.42 | 57.38 | 61.95 | 43.55 | 223.30 | 55.82 |
| Block total | 174.94 | 164.48 | 166.18 | 154.42 | 660.02 | |

ANOVA

| | D of F | SS | Variance | F |
|---|---|---|---|---|
| Total | 15 | 1752.59 | | |
| Blocks | 3 | 54.10 | 18.03 | 0.50 |
| Treatment | 3 | 1376.53 | 458.84 | 12.82* |
| Error | 9 | 321.96 | 35.77 | |

LSD = 9.6

Studentised range, D = 18.7

**Table 4.7 Results of average plant population as a percentage of the desired 37,037 plants per hectare - (all the plots were planted by tube and funnel)**

| Treatment | BLOCKS I | II | III | IV | Treatment total | Mean |
|---|---|---|---|---|---|---|
| Mouldboard | 57.5 | 62.3 | 59.1 | 97.9 | 276.8 | 69.2 |
| A-Shares | 65.7 | 53.4 | 57.1 | 53.5 | 229.7 | 57.4 |
| Desi plough | 64.6 | 85.3 | 62.6 | 84.9 | 297.4 | 74.3 |
| Desi strip tillage | 72.6 | 74.4 | 75.9 | 61.9 | 284.8 | 71.2 |
| Block totals | 260.4 | 275.4 | 254.7 | 298.2 | 1088.7 | |
| Mean | 65.1 | 69.0 | 63.7 | 74.6 | 68.0 | |

ANOVA

| | D of F | SS | Variance | F |
|---|---|---|---|---|
| Total | 15 | 2451.7 | | |
| Blocks | 3 | 283.0 | 94.3 | 0.5 |
| Treatments | 3 | 655.3 | 218.4 | 1.3 N.S |
| Error | 9 | 1513.4 | 168.1 | |

**Table 4.8 Results of average moisture content % by volume**

| Treatment | BLOCKS I | II | III | IV | Treatment totals | Mean |
|---|---|---|---|---|---|---|
| Mouldboard | 25.58 | 25.30 | 26.90 | 24.16 | 101.94 | 25.48 |
| A-Shares | 27.11 | 26.66 | 27.32 | 27.83 | 108.92 | 27.23 |
| Desi plough | 26.26 | 27.66 | 25.96 | 29.60 | 109.48 | 27.37 |
| Desi strip tillage | 27.78 | 30.02 | 27.30 | 27.00 | 112.10 | 28.02 |
| Block totals | 106.73 | 109.64 | 107.48 | 108.59 | 432.44 | |
| Means | 26.7 | 26.7 | 26.9 | 27.1 | 27.0 | |

ANOVA

| | D of F | SS | Variance | F |
|---|---|---|---|---|
| Total | 15 | 32.53 | | |
| Blocks | 3 | 1.22 | 0.40 | 0.2 |
| Treatment | 3 | 14.10 | 4.70 | 2.47 N.S |
| Error | 9 | 17.20 | 1.9 | |

The maize crop was planted without adequate application of fertilizers, plant population (25-43% lower) or plant protection and weeding was 2-3 weeks late. The yields are therefore close to those realized at farm level (Table 4.9). Again Desi strip tillage appears to give higher yields as compared to mouldboard plough by up to 18% but statistically not significant. As explained above the nature of the experiment (large plots) allowed so large variations in slope, soil texture, soil depth, and fertility, that the experimental design could not detect differences in soil moisture or crop yield. Having established that the Desi plough is superior for land preparation to either mouldboard plough or A- share, the following experiments in the 1979 L.R. focused on the method of planting and weeding.

**Table 4.9 Results of average yield x $10^2$ kg/ha**

| Treatment | BLOCKS I | II | III | IV | Treatment totals | Mean |
|---|---|---|---|---|---|---|
| Mouldboard | 8.1 | 4.6 | 6.6 | 14.9 | 32.20 | 8.5 |
| A-Shares | 6.6 | 7.1 | 8.9 | 4.9 | 27.50 | 6.8 |
| Desi plough | 9.1 | 10.3 | 8.9 | 7.9 | 36.20 | 9.0 |
| Desi strip tillage | 10.9 | 12.6 | 7.4 | 9.3 | 40.20 | 10.0 |
| **Block totals** | **34.7** | **34.6** | **31.8** | **37** | **138.10** | **34.3** |

ANOVA

| | D of F | SS | Variance | F |
|---|---|---|---|---|
| Total | 15 | 106.9 | | |
| Blocks | 3 | 1 | 0.33 | 0.03 |
| Treatment | 3 | 21.12 | 7.04 | 0.74 N.S |
| Error | 9 | 84.78 | 9.42 | |

The rain between the 1978/79 S.R. and 1979 L.R. did not have the usual break in February and early March when harvesting and land preparation is done. Hence land preparation with Desi plough was done within two days of the L.R. and the soil was fairly soft. The weeds from the previous season had not dried up because of heavy February rains. Pre-emergence weeding was therefore necessary. Although a split plot experiment had been designed, the analysis was simplified to direct comparisons between mechanical and hand planting on the one hand and between hand and mechanical weeding on the other. There was no reason to expect interaction between planting and weeding. Under fairly soft soil conditions the Desi plough achieved both greater depth and rate of work as shown below.

| | March 1979 | Oct/Nov 1978 |
|---|---|---|
| Average depth, cm | 14.60 | 11.50 (9.20)* |
| Rate of work, ha/hr | 0.15 | 0.10 |

* Average depth achieved by Desi plough during continuous cultivation.

Half of the plots (16) were planted by tube and funnel simultaneously as land preparation. Compared with hand planting the plant population that emerged on the mechanically planted plots had 40% less plants. This was worse than in the previous season. It was confirmed that too great a depth of planting was primarily responsible for this poor emergence. For this reason, tube and funnel planting was discontinued until a proper control of depth of planting can be developed.

Half of the plots were also weeded by A-shares at the rate of 8 hours per ha. In addition, supplementary hand weeding was done within the row. Because of pre-emergence weeding, labour requirements were low. Thus in total, mechanical weeding including supplementary hand weeding required 48 man-hours per ha while pure hand weeding required 104 man-hours per ha on the average.

Previous experiments in the 1978/79 S.R. were repeated in the 1979/80 S.R., this time comparing the Desi plough mounted on a modified Sine Hoe tool bar with the farmer's mouldboard plough. It was possible to compare draft requirements in addition to the depth and rate of work.

Table 4.10 shows draft, depth, speed and rate of work achieved under both dry and wet soil conditions. The short rains started before the mouldboard plough was tested under dry conditions. For Desi plough under dry conditions the average draft and depth were 183 kgf and 9.3 cm. respectively. The work was done by the better-trained Faculty of Agriculture oxen, which could sustain the higher draft requirement. Under wet conditions the draft dropped to about half (87 kgf.) at slightly lower depth of 9.0 cm. The reasons for lower depth under wet conditions were not obvious. The rate of work decreased slightly. Under wet conditions the mouldboard performed almost as well as the Desi plough. Both the draft and depth were about the same as those observed for the Desi plough under similar conditions (Table 4.10 part (c)). The speed was about the same as achieved in the previous S.R.

**Table 4.10 Drawbar draft force, field capacity and depth of cultivation for Desi-plough and farmers mouldboard plough during October-December 1979**

| | Draft, kgf | Speed, m/s | Depth, cm | Rate of work, (hours/ha) |
|---|---|---|---|---|
| **(a)Desi-plough under dry conditions** | 175 | 0.38 | 8.7 | 9 |
| | 207 | 0.40 | 8.6 | 9 |
| | 180 | 0.36 | 9.2 | 10 |
| | 187 | 0.44 | 7.3 | 8 |
| | 178 | 0.37 | 9.0 | 10 |
| | 203 | 0.40 | 8.6 | 9 |
| | 187 | 0.36 | 9.0 | 8 |
| | 173 | 0.50 | 11.6* | 5 |
| | 162 | 0.5 | 11.7* | 5 |
| | 167 | 0.83 | 12.6* | 4 |
| | 167 | 0.85 | 12.8* | 4 |
| **Mean** | **183** | **0.41** | **9.3*** | **8.1** |
| **S.D** | **14.3** | **0.06** | **1.43** | **1.9** |
| **(b) Mould-board plough under wet conditions** | 75 | 0.50 | 8.7 | 8 |
| | 78 | 0.38 | 9.6 | 10 |
| | 108 | 0.42 | 8.8 | 9 |
| | 88 | 0.50 | 9.2 | 8 |
| | 88 | 0.44 | 8.6 | 8 |
| **Mean** | **87** | **0.45** | **9.0** | **8.6** |
| **(c) Mould-board ploughunder wet conditions** | 91 | 0.39 | 8.1 | 9 |
| | 76 | 0.45 | 8.0 | 10 |
| | 76 | 0.39 | 7.9 | 9 |
| | 94 | 0.39 | 8.0 | 10 |
| | 96 | 0.42 | 9.0 | 8 |
| | 77 | 0.46 | 7.8 | 9 |
| | 93 | 0.59 | 10.0 | 8 |
| | 88 | 0.36 | 9.5 | 8 |
| | 74 | 0.32 | 7.7 | 8 |
| | 80 | 0.36 | 7.8 | 8 |
| | 103 | 0.34 | 8.2 | 10 |
| **Mean** | **86** | **0.41** | **8.4** | **9.4** |
| **S.D** | **99** | **0.09** | **0.78** | **1.7** |

**Variations in slope, soil structure and relative tiredness of oxen cause large differences*

With these results, it became quite obvious that any reasonable depth under dry conditions was going to demand a high draft, which two bullocks cannot sustain for an extended period. It was also construed that the Desi plough had no relative advantage over the farmers' plough in terms of depth of operation and draft requirements under wet soil conditions.

To overcome the problem of high draft requirements realized in the previous season, a chisel ploughing operation to precede Desi ploughing was incorporated in the 1980 L.R.

experiments. When the rains started on 3rd April, all the chiselling and mouldboard ploughing had been completed except 3 plots, which were chiselled under slightly wet conditions. Furrow opening by both Desi and mouldboard ploughs were done under wet conditions.

Table 4.11 shows the performance of the land preparation and planting equipment. The chisel plough achieved an average depth of 7.1 cm. The large effective width realized a relatively high rate of work of 0.12ha/hr. Subsequently furrow-opening operation by the Desi plough under wet conditions achieved a depth of 12.4 cm. at a draft requirement of 102 kg and a rate of work of 0.15 ha/hr. The greater depth was made possible because the early rains had softened the ground. In contrast, the mouldboard plough under dry conditions broke the ground to a depth of 8.5 cm. at a draft requirement of 101 kg but at a low rate of work of 0.08 ha per hour.

**Table 4.11 Land preparation with chisel plough, Desi plough and Mouldboard plough in 1980 long rains**

| | **Chisel plough** | | | **Desi plough** | | | **Mouldboard plough** | | |
|---|---|---|---|---|---|---|---|---|---|
| | Draft work, kgf | Depth, cm | Rate of work, ha/hr | Draft work, kgf | Depth, cm | Rate of work, ha/hr | Draft work, kgf | Depth, cm | Rate of work, ha/hr |
| | 88 | 9.3 | 0.06 | 111 | 12.0 | 0.12 | 101 | 9.8 | 0.08 |
| | 90 | 8.8 | 0.08 | 115 | 12.7 | 0.18 | 106 | 8.3 | 0.10 |
| | 86 | 8.1 | 0.12 | 103 | 12.3 | 0.14 | 103 | 8.8 | 0.08 |
| | 91 | 7.4 | 0.08 | 95 | 13.0 | 0.22 | 103 | 9.1 | 0.10 |
| | 95 | 7.2 | 0.05 | 96 | 11.5 | 0.13 | 104 | 8.9 | 0.09 |
| | 100 | 5.7 | 0.17 | 102 | 15.3 | 0.13 | 81 | 7.8 | 0.10 |
| | 104 | 6.5 | 0.17 | 104 | 13.3 | 0.11 | 83 | 11.1 | 0.07 |
| | 100 | 6.3 | 0.15 | - | 11.1 | 0.14 | 85 | 7.4 | 0.15 |
| | 103 | 5.9 | 0.14 | 106 | 11.5 | 0.15 | 93 | 8.0 | 0.06 |
| | 104 | 6.8 | 0.15 | 113 | 12.7 | 0.16 | 128 | 9.4 | 0.06 |
| | 106 | 6.5 | 0.15 | 99 | 12.7 | 0.14 | 93 | 7.5 | 0.07 |
| | 103 | 6.7 | 0.12 | 91 | 9.7 | 0.14 | 102 | 11.3 | 0.06 |
| | 102 | 8.9 | 0.07 | 77 | 12.3 | 0.22 | 106 | 8.4 | 0.07 |
| | - | 5.7 | 0.10 | 110 | 12.8 | 0.11 | 103 | 7.6 | 0.06 |
| | 106 | 7.1 | 0.14 | - | - | - | 108 | 8.0 | 0.08 |
| **Mean** | **98** | **7.1** | **0.12** | **102** | **12.4** | **0.15** | 94 | 7.6 | 0.06 |
| **SD** | 7 | **1.06** | - | **10.4** | **1.16** | **0.034** | 114 | 7.1 | 0.07 |
| | | | | | | **Mean** | **101** | **8.5** | **0.08** |
| | | | | | | **SD** | **12.3** | **1.29** | **0.23** |

| **Note:** | **Implement** | **Soil conditions** |
|---|---|---|
| | **Chisel plough** | **dry** |
| | **Desi plough** | **wet** |
| | **Mouldboard plough** | **dry** |

The new system disturbs the soil less and achieved greater depth of cultivation than the traditional method, which in any case disturbs the soil too much. As has already been mentioned, the traditional system is not at all effective under dry soil condition.

Of great interest was the labour utilization by the new system of cultivation. Since the farmer's plough is not suitable for early mechanical weeding because of burying the seedlings, early hand hoe weeding is usually done. The new system offers a relatively fast early weeding alternative using A-shares or sweeps, thus reducing weeding labour considerably. Table 4.12 shows the labour utilization. For instance ox-weeding plus supplementary intra-row weeding used 52 man-hours per ha compared to the first hand hoe weeding which used 287man-hours per ha. Thus, there was a considerable saving on labour. The fact that early weeding is feasible makes it unnecessary for the farmer to delay his planting in order to spread out weeding.

**Table 4.12 Performance comparison of various ox-drawn implements and the hand hoe (1980 long rains)**

| Implement | Operation | Rate of work (ha/hr) | Hours per ha. | Man hours per ha. | Supplementary hand operation | Man hours per ha. |
|---|---|---|---|---|---|---|
| Chisel plough | Ox-chiselling | 0.12 | 8.3 | 16.6 | - | - |
| Desi plough | Ox-planting | 0.15 | 6.67 | 13.3 | Seed and fertilizer dropping & covering | 26.6 |
| A-share | 1st ox-weeding | 0.17 | 6 | 12 | Intra-row weeding | 40 |
| Desi plough with wings | 2nd ox-weeding cum hilling | 0.15 | 6.67 | 13.3 | Intra-row weeding | 36 |
| Hand hoe | 1st hand weeding | - | - | 287 | - | - |
| Hand hoe | 2nd hand weeding | - | - | 204 | - | - |

NB: All the ox-drawn implements were mounted on the Sine Hoe toolbar (Figure 3.7)

The yields received during this season averaged 2000-kg per ha ranging between 833 and 3518 kg per ha. .

The value of chisel ploughing before Desi furrow opening was tested under harder soil conditions during the dry season just before the 1980/81 S.R. Hand planting and mechanical weeding was carried out on the entire plot. Using 3 chisel points the depth averaged 5.2 cm. ranging between 3.6 and 7.0 cm with a standard deviation of 0.73. The draft averaged 93 kg with a standard deviation of 11.3 kg. With two chisels a greater depth of 7.3 cm. was reached. The rate of work averaged 0.06 ha/hr with a standard deviation of 0.02ha/hr.

**Field tests in Holland (Sept/Oct 1980)**

Although very precise measurements on soil-implement interaction are feasible in the artificially prepared soil bins, limitation of space does not offer possibilities for the large number of replications required to arrive at realistic results. The long time usually required to prepare and condition the soil is also a major limitation. In the light of these considerations and the fact that the time available for this work was restricted to 4 weeks, it was decided to carry out experiments in the field rather than in the soil bin.

As described in detail earlier, a strain gauge transducer was installed between the implement and 3 point linkage of a four-wheel tractor of 45-hp. After preliminary trials the horizontal and vertical force on various implements were recorded on a strip chart. Each run was conducted over a ground distance of 40 metres. The cross-sections of the resulting furrow were also sampled.

Table 4.13 shows the comparison of performance characteristics between the Desi plough and the Rumpstad potato lister used on loose wet soil. The Desi plough required about 30% greater horizontal draft than the Rumpstad but achieved 30 % greater depth. The specific soil resistance for the Desi plough was slightly higher (12%) than that observed for the Rumpstad plough. The main differences are that the Rumpstad produced a wider based furrow, which was relatively shallow, while the Desi plough produced a narrow furrow but relatively deeper (Table 4.14). This is due to the Design characteristics. The former is designed to lift the soil and push it side ways without a need for deep penetration while the latter has a bar point with a slightly larger rake angle than the main body primarily to gain penetrating ability. The smooth uninterrupted and well-streamlined double mouldboard of the Rumpstad offers less soil resistance than the interrupted and less streamlined double mouldboard of the Desi. The dipped bar point on the Desi plough is probably the cause for the higher vertical force.

Neither the Desi plough nor the Rumpstad lister was able to penetrate the well-compacted wheel marks without a proceeding chisel breaking operation. The Desi plough was made to back track the chisel plough furrow in order to increase the furrow. Table 4.14 shows the comparison of performance characteristics between the Desi plough after Rumpstad and Ariana chisels. Equal depth of 12 cm. was achieved on rather compacted soil. The draft requirement for the Desi after Ariana was 57 Kg., 36% of what the Desi plough alone required under relatively loose soil. The draft requirement for the Desi plough after Rumpstad was higher than after Ariana chisel and 57% of what Desi plough alone required under relatively loose soil conditions. The specific soil resistance is 42% higher with Desi after Rumpstad than after Ariana. However, the furrow cross-section area in the lower 6 cm. is 39% greater. This is quite evident in Tables 4.15 and 4.16. In other words, the Rumpstad chisel facilitates a well-formed furrow bottom but a higher specific soil resistance.

These results demonstrate the value of a pre-furrow making chisel ploughing operation for the purpose of loosening the soil. Normally, it would not be practical to back track chisel marks with the Desi plough behind animals because the level of precision is not high. Hence, at least two chisel plough runs are necessary to sufficiently loosen the soil for effective furrow making. The relative soil compaction determines final depth of furrow that can be reached after the two operations. A shallow depth of 12 cm was reached on compacted soil compared to 15 cm reached on loose soil.

**Table 4.13 Comparison of performance characteristics between Desi plough and the Rumpstad potato lister on loose soil zone**

| | | Desi plough | Rumpstad potato Lister |
|---|---|---|---|
| Horizontal draft force (kgf): | Range | 61-219 | 88-159 |
| | Mean | 158 | 122 |
| Vertical force (kgf): | Range | 18-80 | 20-49 |
| | Mean | 51 | 38 |
| Furrow cross-section ($cm^2$): | Range | 86-240 | 95-248 |
| | Mean | 171 | 148 |
| Depth (cm): | Range | 9-16 | 9-13 |
| | Mean | 15 | 11.5 |
| Specific soil resistance ($kg/cm^2$) | | 0.92 | 0.82 |

**Table 4.14 Comparison of performance characteristics between Ariana chisel plough and Rumpstad chisel units for soil breaking preceding desi ploughing on compacted soil**

| | | Desi plough after Rumpstad chisel | Desi plough after Ariana chisel |
|---|---|---|---|
| Horizontal draft force (kgf): | Range | 77 – 109 | 23 – 102 |
| | Mean | 91 | 57 |
| Vertical force (kgf): | Range | 29 – 34 | 3 – 24 |
| | Mean | 30 | 14 |
| Furrow cross-section of lower 6 cm ($cm^2$): | Range | 143 – 180 | 100 – 206 |
| | Mean | 160 | 145 |
| Depth (cm): | Range | 10 – 14.5 | 9.5 – 14 |
| | Mean | 12 | 12 |
| Specific soil resistance ($kg/cm^2$) | | 0.57 | 0.40 |

Comparing the two chisels on the basis of the effectiveness of the subsequent furrow making operation, it appears that the Rumpstad facilitates (10%) larger furrow well formed at the bottom but at a greater draft requirement and specific soil resistance than the Ariana.

The separate performance of these tools is now examined. The horizontal forces required by the Ariana and Rumpstad chisels averaged 165 and 134 kg respectively both at a standard deviation of 33. The corresponding vertical forces on the Ariana and Rumpstad were respectively 25 and 33 kg. at a standard deviation of 11 and 9.

These performance differences may be attributed to design differences. The Ariana chisel has a higher rake angle of $40^0$ compared to Rumpstad chisel with $20^0$ rake angle. This may explain the higher horizontal draft required by the Ariana in spite of it being relatively narrow (5cm) compared to Rumpstad (8 cm). The lower rake angle on the Rumpstad facilitates soil lifting as opposed to bulldozing likely to have taken place in front of the Ariana tool. Hence, there was a higher vertical force (33kg) required by the Rumpstad than that required by the Ariana chisel (25kg.), while the horizontal force per unit width required by the Rumpstad was half that required by the Ariana chisel. Both chisels achieved equal depth of about 9 cm. Although the specific soil resistance was not taken, it is quite obvious that it was substantially lower on the Rumpstad because of the greater width. It can therefore be concluded that the Rumpstad chisel is by far superior to the Ariana chisel. The higher draft required by the Desi after Rumpstad is not excessive and is directly related to the wider and higher quality furrow produced.

The Rumpstad chisel (made in Holland) and standard were tested at Katumani in the 1981 L.R. In the previous relatively poor season the rains had stopped around the middle of December 1980. The soil conditions were therefore relatively dry by the middle of February when the chisel ploughing was done. Tables 4.15 and 4.16 show the performance characteristics of the Rumpstad chisel on maize stubble and on previously fallowed land and of the Desi plough after Rumpstad chisel all behind the farmers' pair of bullocks. The maize stubble land had been clean weeded after the rains stopped. The top layer was therefore very friable and easy to penetrate. Heavy weeds covered the fallow. The heavy rooting caused the soil to be fairly loose and easy to penetrate. Both soils had developed a subsurface compacted layer. A similarly compacted layer was observed on the terrace bank. which had been under continuous grass cover for several years.

All the chiselling on fallow and on stubble was done under dry conditions whereas only half of furrow opening was done under wet conditions. Fallowed plots were chiselled twice to completely uproot the weeds and make it easy for furrow opening.

Table 4.15 shows the comparison of performance characteristics of the Rumpstad chisel on the stubble with the performance on the fallow. Chiselling on clean-weeded stubble averaged 11.5 cm. depth at 59-kg draft and 0.09 ha/hr rate of work. The corresponding performance on the fallow was 14.0 cm. and rate of work 0.041ha/hr. The draft for chiselling on the fallow was not recorded, but it was estimated at 120-150 kg. The most important observation here is the very low rate of work achieved on the fallow – one third of that achieved in the previous L.R. (Table 4.12). As expected this is the price to pay for the greater depth achieved without excessive draft when one chisel unit is used. The second chisel ploughing was necessary primarily because of heavy weed cover otherwise one chisel ploughing should have been sufficient. The second chiselling exercise was not necessary on the maize stubble and a high rate of work of 0.09 ha/hr or 11 hours per ha was achieved. This is higher than that achieved in the previous L.R. season but it was mainly because of previous clean weeding.

The time required for chiselling on the stubble and on the fallow was 22 and 48 man-hours per ha respectively. The average of 35 man-hours per ha about double that realized in 1980 LR (16.6 man-hours per ha, see Table 4.12)

The performance characteristics of the subsequent Desi furrow opening on the stubble and on the fallow are shown in Table 4.16. There is no apparent difference between stubble and fallow. It also did not make much difference whether the furrowing was done on wet or dry soil conditions. Thus the chisel ploughing as a pre-furrowing operation was a success.

**Table 4.15 Comparisons of performance characteristics of the Rumpstad chisel plough and subsequent Desi ploughing on the maize stubble and previous fallow 1981 L.R. at Katumani**

| Chiselling on stubble | | | | Chiseling on fallow | | |
|---|---|---|---|---|---|---|
| Plot No. | Rate of work, ha/hr | Depth, cm | Draft, kgf | Plot No. | Rate of work, ha/hr | Depth, cm |
| $D_6$ | 0.045 | 11.2 | 70 | $C_1$ | 0.16 | 12.8 |
| $B_6$ | 0.051 | 11.6 | 64 | $B_1$ | 0.09 | 14.7 |
| $A_6$ | 0.044 | 11.0 | 58 | $D_1$ | 0.08 | 14.4 |
| $C_6$ | 0.038 | 11.5 | 58 | $A_1$ | 0.09 | 14.3 |
| $A_5$ | 0.043 | 11.9 | 60 | $B_4$ | 0.09 | 13.8 |
| $D_5$ | 0.042 | 12.0 | 60 | $A_4$ | 0.09 | 10.8 |
| $B_5$ | 0.036 | 11.3 | 59 | $C_4$ | 0.07 | 13.0 |
| $C_5$ | 0.036 | 11.4 | 61 | $D_4$ | 0.08 | 14.4 |
| $D_3$ | 0.038 | 13.4 | 62 | $C_2$ | 0.10 | 14.6 |
| $C_3$ | 0.040 | 10.8 | 60 | $B_2$ | 0.10 | 15.6 |
| $A_3$ | 0.042 | 10.6 | 57 | $D_2$ | 0.09 | 12.6 |
| $B_3$ | 0.045 | 10.6 | 54 | $A_2$ | 0.10 | 15.2 |
| $C_8$ | 0.039 | 11.6 | 58 | $B_7$ | 0.08 | 15.2 |
| $B_8$ | 0.039 | 11.5 | 55 | $A_7$ | 0.09 | 14.1 |
| $D_8$ | 0.041 | 13.8 | 53 | $D_7$ | 0.08 | 14.4 |
| $A_8$ | 0.044 | 11.1 | 57 | $C_7$ | 0.09 | 13.7 |
| **Mean** | **0.041** | **11.5** | **59** | | **0.09** | **14.0** |
| **S D** | **0.004** | **0.89** | **3.9** | | **0.02** | **1.2** |

**Table 4.16 Subsequent Desi furrow opening**

| Stubble | | | | Fallow | | | |
|---|---|---|---|---|---|---|---|
| Plot no. | Depth, cm | Draft, kgf | Rate of work, ha/hr | Plot no. | Depth, cm | Draft, kgf | Rate of work, ha/hr |
| $D_6$ | 14.8* | 104 | 0.15 | $C_1$ | 15.6 | 111 | 0.18 |
| $B_6$ | 15.9* | 102 | 0.18 | $B_1$ | 14.3 | 105 | 0.19 |
| $A_6$ | 11.6* | 100 | 0.16 | $D_1$ | 14.7 | 95 | 0.19 |
| $C_6$ | 15.3* | 100 | 0.16 | $A_1$ | 14.8 | 100 | 0.12 |
| $A_5$ | 14.5* | 106 | 0.19 | $B_4$ | 15.7 | 107 | 0.11 |
| $D_5$ | 14.5* | 107 | 0.18 | $A_4$ | 14.5 | 109 | 0.18 |
| $B_5$ | 15.7* | 104 | 0.18 | $C_4$ | 15.9 | 112 | 0.19 |
| $C_5$ | 16.0* | 116 | 0.18 | $D_4$ | 15.6 | 105 | 0.15 |
| $D_3$ | 15.0* | 100 | 0.15 | $C_2$ | 15.5 | 104 | 0.19 |
| $C_3$ | 16.5* | 120 | 0.18 | $B_2$ | 16.4 | 108 | 0.18 |
| $A_3$ | 15.3 | 94 | 0.19 | $D_2$ | 13.8* | 146 | 0.14 |
| $B_3$ | 14.0 | 98 | 0.19 | $A_2$ | 15.0* | 112 | 0.16 |
| $C_8$ | 14.0 | 93 | 0.18 | $B_7$ | 15.5* | 104 | 0.16 |
| $B_8$ | 12.7 | 108 | 0.14 | $A_7$ | 15.5* | 105 | 0.16 |
| $D_8$ | 13.7 | 103 | 0.19 | $D_7$ | 15.0* | 103 | 0.15 |
| $A_8$ | 14.5 | 110 | 0.19 | $C_7$ | 16.3* | 108 | 0.16 |
| **Mean** | **14.6** | **104** | **0.17** | | **15.2** | **108** | **0.16** |
| **S.D** | **1.02** | **7.4** | **0.016** | | **0.7** | **11** | **0.025** |

*Plots furrowed under wet conditions do not appear to have had any advantage over those furrowed under dry conditions. This indicates effectiveness of preceding chisel ploughing.

## 4.3 Effect of Tillage and Equipment on Production

### *4.3.1 Maize Grain Production*

It is apparent from Table 4.17 that at 2 adult labour equivalents (2-AME) the traditional hired ADP for land preparation does not increase production when more land is made available unless labour is increased at the same time. When labour constraints are addressed by hiring traditional ADP for weeding, production is increased by 26% (9.4 to 11.9) at all the three levels (2, 3 and 4ha) of access to land for cultivation. If one AME was available instead, production would have increased by 46% (9.4 to 13.7). When THS is made available for land preparation to replace ADP, production is increased by 33% (11.9 to 15.8) at all the three levels (2, 3 and 4ha) of access to land for cultivation. This is less than 51% (11.9 to 18.0) had labour access been increased from 2 to 3 AME instead of THS replacing ADP for land preparation. The obvious reason is that labour and not land is the greater constraint at these levels of mechanization. Moreover access to additional labour has a higher marginal return than either ADP weeding or THS.

However when labour constraints are addressed by introducing hired traditional ADP for weeding combined with additional labour, farmers realize a 31% (13.7-18.0) increase in production at all the three levels (2, 3 and 4ha) of access to land for cultivation. This figure is doubled from 18.0 to 35.5 quintals (qu) when hired tractor is made available for timely land preparation to replace hired ADP. If the farmer hires innovative equipment for land preparation and weed control (NCOHO) there is a substantial increase of 107% (18.0 to 37.4 qu) in production. Therefore tractor hire service (THS) is slightly less profitable than hired innovative ADP equipment.

The impact of THS on farmers, who own ADP equipment (OHO), is negligible at 3.5% (43 to 44.5qu). However if both land and labour are increased to 4 ha × 4-AME at the same time, the THS impact is significant at 24% (43.0 to 53.4). This impact would be doubled at 47% (43.0 to 63.3) if the farmers adopted equipment innovations instead of THS for land preparation. This again underscores the superiority of innovative ADP equipment compared to THS. The following conclusions can be made:

i. For a farmer with 3ha cultivated land and 3-AME but does not own ADP, it makes little difference whether he uses THS or hired innovative ADP equipment for land preparation and weeding. However if the farmer who owns traditional ADP equipment replaced them with innovative ADP equipment he would have extra capacity to increase cultivated land of his own or offer custom hire service to his neighbour who does not own ADP. An increase of up 47% can be realized at 4ha cultivated land.

ii. For the purpose of policy prescription it is apparent that adoption of innovative ADP equipment can cater for both ADP owners and non owners. The need for tractors can therefore be restricted to reclamation of badly compacted soils through sub soiling.

Adoption of innovative ADP equipment and THS (specifically for sub soiling) has implications for investments in the relevant agricultural sector. It means improved rural access roads, development of agro-service centres with repair workshops and distribution centres for fuel and other inputs. It also means better harvesting and post- harvest processing, preservation and storage facilities as well as marketing.

### *4.3.2 Access to land*

Table 4.3.2 gives production increases in quintals of maize grain per farm unit as access to land increases from 2 to 3 ha and 3 to 4 ha with access to labour remaining the same at 3 AME. On the one hand for farmers who do not own traditional animal draft power, COHO there is little to be gained from more land above 2 ha until they adopt tractors (COHOTHO) or equipment innovations (NCOHO) to improve timeliness of planting. Hiring of traditional equipment alone will not improve the situation because it has low rate of work and farmers get it late. This implies that labour is the main constraint. On the other hand farmers who own traditional animal draft power, OHO can increase production by 28% by adding one more ha to reach 3 ha but not beyond that. Benefits of additional one ha are associated with increased rate of work implied in adoption of new equipment NCOHO, NCOHOTHO and NOHO reaching 41%, 39% and 44% respectively. The new animal draft power equipment has high rate of work for land preparation, planting and weed control. The benefits diminish as access to land increase beyond 3 ha even if more labour is available. The tractor hire service which is available for one full day (8 hrs) per season is unlikely to make an impact. It can therefore be concluded that ADP innovative equipment should be promoted in areas where access to cultivated land is between 3 and 4 ha.

**Table 4.17 Model results: Farm unit net production in quintals (100kg D.M) of maize**

| Labour ,AME | | Land , Ha | | |
|---|---|---|---|---|
| | | 2 | 3 | 4 |
| **COHH** | 2 | 9.4 | 9.4 | 9.4 |
| | 3 | 13.7 | 13.7 | 13.7 |
| | 4 | 17.8 | 17.8 | 17.8 |
| **COHO** | 2 | 11.9 | 11.9 | 11.9 |
| | 3 | 18.0 | 18.0 | 18.0 |
| | 4 | 20.5 | 20.5 | 20.5 |
| **COHHTHH** | 2 | 15.8 | 15.8 | 15.8 |
| | 3 | 22.8 | 22.8 | 22.8 |
| | 4 | 27.0 | 28.4 | 28.4 |
| **COHOTHO** | 2 | 28.0 | 28.0 | 28.0 |
| | 3 | 29.1 | 35.5 | 35.5 |
| | 4 | 29.6 | 38.4 | 38.4 |
| **OHO** | 2 | 30.2 | 33.9 | 33.9 |
| | 3 | 33.7 | 43.0 | 43.0 |
| | 4 | 33.7 | 44.7 | 46.4 |
| **OHOTHO** | 2 | 33.2 | 33.9 | 33.9 |
| | 3 | 33.7 | 44.5 | 47.5 |
| | 4 | 35.0 | 48.0 | 53.4 |
| **NCOHO** | 2 | 24.8 | 27.6 | 27.6 |
| | 3 | 26.5 | 37.4 | 41.8 |
| | 4 | 28.3 | 39.2 | 50.1 |
| **NCOHOTHO** | 2 | 30.5 | 41.4 | 48.7 |
| | 3 | 31.1 | 43.1 | 54.0 |
| | 4 | 31.1 | 44.9 | 55.8 |
| **NOHO** | 2 | 31.6 | 42.6 | 48.8 |
| | 3 | 33.0 | 47.5 | 59.3 |
| | 4 | 33.2 | 48.8 | 63.3 |

**Note:** AME = Adult Men Equivalent price in 1990: Kshs. 3/- per kg
(See key after Table 4.19)

**Table 4.18 Model results: Farm unit net income in Ksh. worth maize grain**

| Labour ,AME | | Land , Ha | | |
|---|---|---|---|---|
| | | 2 | 3 | 4 |
| **COHH** | 2 | 2820 | 2820 | 2820 |
| | 3 | 4110 | 4110 | 4110 |
| | 4 | 5340 | 5340 | 5340 |
| **COHO** | 2 | 3570 | 3570 | 3570 |
| | 3 | 5400 | 5400 | 5400 |
| | 4 | 6150 | 6150 | 6150 |
| **COHHTHH** | 2 | 4740 | 4740 | 4740 |
| | 3 | 6840 | 6840 | 6840 |
| | 4 | 8100 | 8520 | 8520 |
| **COHOTHO** | 2 | 8400 | 8400 | 8400 |
| | 3 | 8730 | 1065 | 10650 |
| | 4 | 8880 | 11520 | 11520 |
| **OHO** | 2 | 9060 | 10170 | 10170 |
| | 3 | 10110 | 12900 | 12900 |
| | 4 | 8880 | 11520 | 11520 |
| **OHOTHO** | 2 | 9960 | 10170 | 10170 |
| | 3 | 10110 | 13350 | 14250 |
| | 4 | 10500 | 14400 | 16020 |
| **NCOHO** | 2 | 7440 | 8280 | 8280 |
| | 3 | 7950 | 11220 | 12540 |
| | 4 | 8490 | 11760 | 15030 |
| **NCOHOTHO** | 2 | 9150 | 12420 | 14610 |
| | 3 | 9330 | 12930 | 16200 |
| | 4 | 9330 | 13470 | 16740 |
| **NOHO** | 2 | 9480 | 12780 | 14640 |
| | 3 | 9900 | 14250 | 17790 |
| | 4 | 9960 | 14640 | 18990 |

**Note:** AME = Adult Men Equivalent (Price in 1990, 1 Ksh = 1US $ =Ksh. 22)

(See key after Table 4.19)

**Table 4.19 Increases in net maize production in quintals per farm unit as access to land increases**

| Farm Equipment | Changes in cultivated lands for AME=3 Adult labour | | | |
|---|---|---|---|---|
| | 2-3 ha | % | 3-4 ha | % |
| COHO | 0 | | 0 | |
| OHO | 9.3 | 28 | 0 | |
| COHOTHO | 6.4 | 22 | 0 | |
| OHOTHO | 10.8 | 32 | 3.0 | 7 |
| NCOHO | 10.9 | 41 | 4.4 | 12 |
| NCOHOTHO | 12.0 | 37 | 10.9 | 25 |
| NOHO | 14.5 | 44 | 11.8 | 25 |

**Key**

1. HHH – Land preparation by hand, planting and weeding by hand
2. OHH – Land preparation by oxen, planting and weeding by hand
3. OHO – Land prep. and weeding by owned oxen, planting by hand
4. THH – Land preparation by tractor the rest by hand
5. THO – Land preparation by tractor, planting by hand, weeding by oxen
6. COHH – Land preparation by hired oxen the rest by hand
7. COHO—As 6.0 above except weeding by oxen
8. COHHTHH – As 6.0 above plus 4.0 above
9. COHOTH0 – As 8.0 above except weeding by hired oxen
10. OHOTHH – As 3.0 plus 4.0 above
11. OHOTHO – As 3.0 plus 5.0 above
12. NCOHO – New ADP equipment hired for land preparation & weeding, planting by hand
13. NCOHOTHO – As 12.0 plus tractor hire for land preparation only
14. NOHO – Owned new equipment for land preparation and weeding. planting by hand

### *4.3.3 Is It Animal Draft Power (ADP) or Tractor Power (TP)?*

From Table 4.1 and 4.19, it is evident that access to animal draft power at COHO and OHO makes a big difference for the latter. When the two farmers moved to new ADP equipment namely: from COHO to NCOHO and from OHO to NOHO, the corresponding increases were 108% and 12% respectively. When the THS was added to both namely: from COHO to COHOTHO and OHO to OHOTHO, the increases were 95% (18.0 to 35.5 Qu) and 4% (43.0 to 44.4) respectively. When access to combined new animal draft power equipment and tractor hire services were allowed for farmers who do not own oxen namely: COHO to NCOHOTHO production increased by a total of 139% (18.0 to 43.1 qu/3 ha farm). More detailed comparisons are shown on Tables 4.21 and 4.22. Clearly it is the farmers who do not own oxen who stand to benefit more by access to animal draft power equipment innovations and tractor power *al beit* by custom hire services. This has implications for common infrastructure not only to facilitate easy movement of farm power and equipment from farm to farm, but to carry out R & D, local manufacture and support services as well.

On long-term economic grounds a choice has to be made between moving from OHO to OHOTHO or OHO to NOHO. The latter requires an investment of Sh. 50,000 to cater for two households. The former requires an infrastructure to cater for tractor hire services among several farmers. Due to the fact that more than half of the farmers do not own oxen, NCOHO and NCOHOTHO are good propositions. In other words changes can take place as follows:

| | |
|---|---|
| COHO to NCOHO<br>(18.0 to 37.4) | 108% increase |
| NCOHO to NCOHOTHO<br>(37.4 to 43.1) | 15.0% increase |

The combined increase from COHO to NCOHOTHO (18.0 to 43.1) is 139%. A case can be made for support infrastructure of R & D training and local manufacture of animal draft power innovations. Given the massive infrastructure for access and support services for tractor hire service 15% increase in production cannot justify such an investment. However, it should be noted that the tractor will be needed for deep tillage once in three to four years as discussed in Chapter 2. The merits of investment on infrastructure can be determined after benefit ratio is calculated. It can therefore be concluded that investment in mechanization support infrastructure will benefit many farmers who cannot own ADP or TP.

### *4.3.4 Biomass Recycle Implications*

From Table 4.20 it can be seen that the higher the grain production the greater is the surplus biomass. The extra feed can if necessary support more livestock including draft animals. New equipment even on hire basis also achieved higher yields because the farmer is able to complete planting by the first week due to dry land chiselling and high rate of furrow opening and planting.

**Table 4.20 Surplus crop residue after recycling 25 qu per ha per season on 3 x 3 ha farms**

| | Biomass | Production , qu |
|---|---|---|
| **COHO** | 0.0 | 18.0 |
| **COHOTHO** | 10.5 | 35.5 |
| **OHO*,** | 18.2 | 43.0 |
| **OHOTHO** | 19.0 | 44.5 |
| **OHOTHO,** | 19.0 | 44.5 |
| **NCOHOTHO** | 20.5 | 43.1 |
| **NOHO** | 27.6 | 47.5 |

**Note:** 3×3 farms = 3 AME by 3ha farms

*FPE assumes corresponding values respectively i.e. biomass surplus for OHO = 18.2 qu/farm.

The corollary to this is that better timeliness, which directly increases biomass production, enhances organic matter and associated soil fertility, which is the *sine qua non* for agricultural sustainability. In other words, environmental conservation is achieved.

The same reasoning can explain why NOHO is in its own class at a higher level of both biomass production and productivity. That is timeliness is the answer to both yield increase as well as biomass production. Thus indirectly, the problem of feed for livestock and draft animals in particular is addressed. It should be noted that if the TP was employed to carry out deep ploughing and ridge and furrow forming, soil structure improvement can be carried over three to four years. Thus the additional cost of TP can be amortized over that time.

It is evident that lack of access to adequate farm power and equipment has a direct effect not only on grain production but also on biomass production. Sustainability therefore demands introduction of tractor hire services and new animal draft power equipment.

### *4.3.5 Energy Use Implications*

Basing energy analysis on economic and biomass recycle implications two farm power and equipment subsets deserve to be analyzed namely OHOTHO and NCOHOTHO. Energy optimization was the basis for tractor power and animal draft power selections. It also indicated the optimum combination of tractor and animal draft power in terms of cultivated land in hectares.

From Tables 4.23 and 4.24 it is evident that farmers need to apply both animal draft power and tractor power in order to realize the production potential. The main constraints are labour available during land preparation and weeding in the $6^{th}$ and $7^{th}$ week. The former occurs when there is competition for labour between late planting and early weeding while the latter occurs when demands for weeding are excessive. In conclusion, an important observation was that the farmer can achieve both optimum productivity as well as energy use with negligible violation of the former. This is a small price to pay to remain close to optimum energy consumption.

**Table 4.21 Linear programming objective function value, activities in the solution and the limiting constraints**

| Variables | | | | | | | | | OBJ | Labour constraints. | | | | Land | Biomass surplus |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| FPE | 1 | (2-4) | 5 | (6-8) | 9 | (10-11) | 12 | 13 | | 1 | 5 | 6 | 16 | 18 | 19 |
| NCOHOTHO2 *2 | 16.6 | | 12.02 | | 1.86 | | | | 30.5 | 0 | | 0 | | 0 | 15.5 |
| 2*3 | 16.6 | | 12.02 | | 12.76 | | | | 41.4 | 0 | | 0 | | 0 | 14.2 |
| 2*4 | 16.6 | | 12.02 | | 13 | | 5.89 | 0.86 | 48.4 | 0 | | 0 | 0 | 0 | 5.9 |
| NCOHOTHO3 *3 | 16.6 | | 14.5 | | | | | | 31.1 | 0 | | | | 0 | 16.6 |
| 3*3 | 16.6 | | 19.6 | | 7.44 | | | | 43.14 | 0 | | 0 | | 0 | 17.3 |
| 3*4 | 16.6 | | 19.1 | | 18.34 | | | | 54.04 | 0 | | 0 | | 0 | 16.03 |
| NCOHO2*2 | | | 12.02 | | 12.76 | | | | 24.78 | | | 0 | | 0 | 2.71 |
| 2*3 | | | =do= | | 13 | | 2.54 | | 27.6 | | | 0 | | 0.63 | 0 |
| 2*4 | | | =do= | | =do= | | =do= | | 0 | | | 0 | | 1.6 | 0 |
| NCOHO3*2 | | | 19.1 | | 7.44 | | | | 26.54 | | | 0 | | 0 | 5.8 |
| 3*3 | | | 19.1 | | 18.34 | | | | 37.44 | | | 0 | | 0 | 4.53 |
| 3*4 | | | 19.1 | | 18.44 | | 4.28 | | 41.8 | | | 0 | | 0.4 | 0 |
| NCOHOTHO4 *2 | 16.6 | | 14.5 | | | | | | 31.1 | 0 | | | | 0 | 16.6 |
| 4*3 | 16.6 | | 26.2 | | 2.13 | | | | 44.9 | 0 | 0 | 0 | | 0 | 20.45 |
| 4*4 | 16.6 | | 26.2 | | 13.01 | | | | 55.8 | 0 | 0 | 0 | | 0 | 19.15 |
| NCOHO4*2 | | | 26.2 | | 23.9 | | 0.02 | | 50.1 | | 0 | 0 | | 0 | 6.3 |
| 4*3 | | | 26.2 | | 13.02 | | | | 39.2 | | 0 | 0 | | 0 | 7.6 |
| 4*4 | | | 26.2 | | 2.13 | | | | 28.3 | | 0 | 0 | | 0 | 8.9 |

0 = means the slack is zero or near zero.

The variables selected are 1, 5, 9 &12.

3×3 mean 3 adult men equivalent by 3ha cultivated land.

**Table 4.22 L.P model output showing the variables in the solution and the limiting constraints (✓)**

| File | Obj value | Variables | | | | | | | | | Labour constraints | | | | | | | | | | | | | | | | | Land | Biomass |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 4 | 5 | 7 | 8 | 10 | 11 | 13 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 |
| OHO22 | 30.2 | | | 19.2 | | 4.9 | | 6.2 | | 2.6 | | | ✓ | ✓ | | ✓ | | ✓ | | ✓ | | | | | | | | 0.0 | 13.3 |
| OHO23 | 33.9 | | | 14.9 | | 4.9 | | 6.3 | | | | | ✓ | ✓ | | ✓ | | ✓ | | ✓ | | ✓ | | | | | | 0.6 | 11.8 |
| OHO24 | 33.9 | | | 14.9 | | 4.9 | | 6.3 | | | | | ✓ | ✓ | | ✓ | | ✓ | | ✓ | | ✓ | | | | | | 1.6 | 11.8 |
| OHOTHO22 | 30.2 | | | 19.2 | | 4.9 | | 6.2 | | | | | ✓ | ✓ | | ✓ | | ✓ | | ✓ | | | | | | | | 0.0 | 13.3 |
| OHOTHO23 | 33.9 | 0.02 | | 14.8 | 8.0 | 4.9 | | 6.3 | | | | | ✓ | ✓ | | ✓ | | ✓ | | ✓ | | ✓ | | | | | | 0.6 | 11.8 |
| OHOTHO24 | 33.9 | 0.02 | | 14.8 | 8.0 | 4.9 | | 6.3 | | | | | ✓ | ✓ | | ✓ | | ✓ | | ✓ | | ✓ | | | | | | 1.6 | 11.8 |
| OHO32 | 33.7 | | | 26.2 | | 7.5 | | | | | | | ✓ | ✓ | | ✓ | | | | ✓ | | | | | | | | 0.0 | 19.6 |
| OHO33 | 43.0 | | | 26.2 | | 7.6 | | 8.92 | | 0.30 | | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓ | | | | | | | | 0.1 | 18.2 |
| OHO34 | 43.0 | | | 26.2 | | 7.6 | | 8.9 | | 0.31 | | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓ | | | | | | | | 1.1 | 18.2 |
| OHOTHO32 | 33.9 | 1.13 | | 26.2 | | 6.6 | | | | | | | ✓ | ✓ | | ✓ | | | | ✓ | | | | | | | | 0.0 | 20.0 |
| OHOTHO33 | 44.5 | 2.5 | | 23.7 | 1.7 | 7.6 | | | | | | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | | | | | | | 0.0 | 19.0 |
| OHOTHO34 | 47.3 | 8.7 | | 12.8 | 9.4 | 7.6 | | | | | | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓ | | | | | | 0.6 | 17.6 |
| OHO42 | 33.7 | | | 26.2 | | 7.5 | | | | | | | ✓ | ✓ | ✓ | | | ✓ | | | | | | | | | | 0.0 | 19.6 |
| OHO43 | 44.7 | | | 26.2 | | 9.5 | | 8.9 | | 0.14 | | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | | | | | | | | | 0.0 | 19.1 |
| OHO44 | 46.4 | | | 26.2 | | 9.5 | | 8.9 | | 1.8 | | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | | | | | | | 0.76 | 17.2 |
| OHOTHO42 | 35.0 | 8.8 | | 26.2 | | | | | | | | | ✓ | ✓ | | | | ✓ | ✓ | ✓ | | | | | | | | 0.0 | 23.0 |
| OHOTHO43 | 48.0 | 8.8 | | 26.2 | | 9.5 | | 3.5 | | | | | ✓ | ✓ | ✓ | ✓ | | ✓ | ✓ | ✓ | | | | | | | | 0.0 | 26.0 |
| OHOTHO44 | 53.4 | 8.8 | | 26.2 | | 9.5 | | 8.9 | | | | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | | | | | | | 0.49 | 25.3 |
| NCOHOT4*4 | 50.1 | | | 26.2 | | 23.9 | | 0.02 | | | | | | | ✓ | ✓ | | | | | | | | ✓ | | | | 0.0 | 6.3 |
| NCOHOT4*3 | 39.2 | | | 26.2 | | 13.0 | | | | | | | | | ✓ | ✓ | | | | | | | | | | | | 0.0 | 7.65 |
| NCOHOT4*2 | 28.3 | | | 26.2 | | 2.10 | | | | | | | | | ✓ | ✓ | | | | | | | | | | | | 0.0 | 8.95 |
| NCOHOT3*4 | 55.8 | 16.6 | | 26.2 | | 13.02 | | | | | ✓ | | | | ✓ | ✓ | | | | | | | | | | | | 0.0 | 19.15 |
| NCOHOT3*3 | 44.9 | 16.6 | | 26.2 | | 2.1 | | | | | ✓ | | | | ✓ | ✓ | | | | | | | | | | | | 0.0 | 20.45 |
| NCOHOT3*2 | 31.1 | 16.6 | | 14.5 | | | | | | | ✓ | | | | | | | | | | | | | | | | | 0.0 | 16.6 |
| NCOHOT2*4 | 48.7 | 16.6 | | 12.0 | | 13.0 | | 7.0 | 0.1 | | ✓ | | | | | ✓ | | | | | | | | ✓ | ✓ | | | 0.0 | 6.54 |
| NCOHOT2*3 | 41.4 | 16.6 | | 12.0 | | 12.8 | | | | | ✓ | | | | | ✓ | | | | | | | | ✓ | | | | 0.0 | 14.2 |
| NCOHOT2*2 | 30.5 | 16.6 | | 12.0 | | 1.86 | | | | | ✓ | | | | | ✓ | | | | | | | | | | | | 0.0 | 15.5 |

**Table 4.23 Goal programming model objective function value of activities in the solution and the limiting constraints (✓) (OHOTHOE- energy use)**

| File | Obj values. | Variables | | | | | | | | | Labour constraints. | | | | | | | | | | | | * ha | ** qu | *** qu |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | GJ | 1 | 2 | 4 | 5 | 7 | 8 | 10 | 11 | 13 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | | | |
| OHOTE4*2 | 2.58 | | | 1.85 | | 0.73 | | | | | | | ✓ | ✓ | ✓ | ✓ | | ✓ | | | | | 0.18 | 16.7 | 30 |
| OHOTE4*2 | 3.50 | 0.71 | | 2.35 | | 0.44 | | | | | | | ✓ | ✓ | | | | ✓ | | | | | 0.0 | 20.4 | 34 |
| OHOTE4*3 | 4.18 | 0.20 | | 2.35 | | 0.73 | | 0.90 | | | | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | | | | 0.0 | 19.6 | 45 |
| OHOTE4*3 | 6.0 | 2.50 | | 2.35 | | 0.73 | | 0.45 | | | | | ✓ | ✓ | ✓ | ✓ | | ✓ | ✓ | ✓ | | | 0.0 | 25.0 | 47.5 |
| OHOTE4*4 | 6.79 | 2.80 | | 2.35 | | 0.73 | | 0.92 | | 0.015 | | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | | 0.50 | 24.9 | 53 |
| OHOTE3*2 | 2.87 | | | 2.28 | | 0.58 | | | | | | | ✓ | ✓ | ✓ | ✓ | | | | ✓ | | | 0.4 | 19.1 | 33 |
| OHOTE3*2 | 3.12 | 0.244 | | 2.35 | | 0.53 | | | | | | | ✓ | ✓ | ✓ | ✓ | | | | ✓ | | | 0.0 | 19.9 | 33.8 |
| OHOTE3*3 | 4.36 | 0.50 | | 2.29 | 0.06 | 0.58 | | 0.92 | | | | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓ | | | 0.6 | 19.2 | 44.0 |
| OHOTE3*3 | 4.64 | 0.78 | | 2.16 | 0.2 | 0.58 | | 0.92 | | | | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | | 0.01 | 6.87 | 44.4 |
| OHOTE3*4 | 6.48 | 2.5 | | 1.31 | 1.08 | 0.58 | | 0.92 | | | | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | | 0.69 | 17.8 | 47.4 |

Obj = energy in MJ

* Idle land

** Surplus biomass

*** Production in quintals

**Table 4.24 L.P model objective function value, activities in the solution and the limiting constraints (✓)**

| File | Obj value | Variables | | | | | | | | | *Labour constraints* | | | | | | | | | | | | | | | | | | * ha | ** Qu | *** qu |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | GJ | 1 | 2 | 4 | 5 | 7 | 8 | 10 | 11 | 13 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | | | | |
| NCOHOTE2*2 | 5.91 | 5.43 | | 0.37 | | 0.11 | | | | 0.68 | | | | | | ✓ | | | | | | | | | | | | +0.68 | 0.0 | 14.4 | 30.0 |
| NCOHOTE2*3 | 6.56 | 5.63 | | 0.37 | | 0.53 | | 0.01 | | 0.398 | | | | | | ✓ | | | | | | | | ✓ | | | | +0.40 | 0.0 | 13.4 | 41.0 |
| NCOHOTE2*4 | 7.06 | 5.69 | | 0.37 | | 0.54 | | 0.42 | 0.04 | 0.324 | | | | | | ✓ | | | | | | | | ✓ | | ✓ | | | 0.0 | 5.54 | 48.2 |
| | | | | | | | | | | | | | | | | | | | | | | | | | | | | +0.324 | | | |
| NCOHOTE3*2 | 5.07 | 4.52 | | 0.56 | | | | | | | | | | | | ✓ | | | | | | | | | | | | +0.190 | 0.0 | 15.1 | 30.6 |
| NCOHOTE3*3 | 6..31 | 5.37 | | 0.59 | | 0.35 | | | | 0.76 | | | | | | ✓ | | | | | | | | | | | | +0.76 | 0.0 | 16.1 | 42.6 |
| NCOHOTE3*4 | 6.94 | 5.56 | | 0.59 | | 0.76 | | 0.02 | | 0.49 | | | | | | | | | | | | | | ✓ | | | | +0.49 | 0.0 | 14.9 | |
| | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| NCOHOTE4*2 | 5.07 | 4.52 | | 0.56 | | | | | | 1.90 | | | | | | | | | | | | | | | | | | | 0.0 | 15.1 | 30.6 |
| NCOHOTE4*3 | 6.35 | 5.41 | | 0.81 | | 0.13 | | | | 0.698 | | | | | ✓ | ✓ | | | | | | | | | | | | +0.698 | 0.0 | 19.3 | 44.4 |
| NCOHOTE4*4 | 6.80 | 5.41 | | 0.81 | | 0.58 | | | | 0.698 | | | | | ✓ | ✓ | | | | | | | | | | | | +0.698 | 0.0 | 18.0 | 53.3 |

Obj = energy in MJ

* Idle land

** surplus biomass

*** Productivity in quintals

NCOHOTHOE= New ADP equipment hired for land preparation and weeding plus tractor hire for land preparation only.

# CHAPTER FIVE

# DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS

This study was prompted by the need to inform policy on the development of tillage and equipment for semiarid smallholder agriculture. It was hypothesised that reliable prediction of production attributable to innovative tillage and equipment adoption would enable researchers to carry out the cost benefit analysis as well as estimate the rate of return on investment for the necessary support infrastructure. Therefore the purpose for the study was to develop a specific methodology for predicting the effect of tillage and equipment on farm production. Three objectives were addressed:

1. To assess farm level needs, resources, and constraints to adoption of tillage and equipment for increased maize yield in semiarid smallholder agriculture in Eastern Kenya.

2. To establish the field capacity of selected tillage and equipment for conservation tillage under controlled field experiments.

3. To analyze the effect of the tested tillage and equipment on optimum maize production and energy use subject to available labour, land, power, and specified crop residue recycle.

The reviews in Chapter 2 provided adequate evidence that the main constraint to adequate land preparation, application of manure and early planting in semiarid smallholder agriculture was lack of appropriate tillage and equipment package. In addition farmers do not have access to appropriate tractor powered equipment for sub soiling which is necessary once in 3 to 4 years.

## 5.1 Discussion

The results in Section 4.1 show that farmers need to improve timeliness of planting and weeding to double their current yields from one to two tones per ha using labour and power resources during land preparation, planting and weeding. Although every family has access to

ADP only 16% had access to Tractor Hire Services (THS) for ploughing services. The conclusion was that farmers lacked access to tillage and equipment package which is needed to realize the biochemical yield potential.

Section 4.2 has reported the result of tillage trials comparing the traditional mouldboard plough with innovative chisel plough, Desi plough, and A shares. It was established that land breaking with a single share unit followed by Desi furrow opening before planting provided the necessary seedbed. In addition A-shares provided an effective weed control at low supplementary labour requirements. Draft requirement for each operation done separately could be met by the two well fed bullocks. It was concluded that the new package had adequate field capacity to replace the traditional mouldboard plough. Moreover the micro relief produced in the form of furrows was adequate for the purpose of controlling runoff.

Section 4.3 presents the effect of conservation tillage and equipment on production. The main question addressed was: What is the optimum production and energy use in semiarid smallholder agriculture of Eastern Kenya? The results showed that those farmers who own traditional equipment (OHO) and utilize land and labour at 3 ha and 3 adult men equivalents (AME) irrespectively can achieve increased income of Kshs. 12,900 at 1990 prices when one kg of maize grain cost Ksh. 3 (1 US$=Ksh.22). If they adopt THS the profit margin will increase to Kshs. 13,390 (Table 4.18), which is negligible. If they have access to one more ha of land and additional one AME, THS would raise income to Kshs. 16,020 or 24%. At current price of Ksh. 20 per kg of maize, this would translate into Kshs. 108.000 (1 US$=Ksh.80) per season which is almost double the income of a family currently below poverty line earning less than one dollar per day per person or (80*4-AME*150days) Kshs. 48,000. Moreover increase of surplus biomass production will reach 2530kg per ha which is sufficient to feed the two oxen during the drought having recycled the specified crop residue. In other words proposals for THS must be accompanied with innovative ADP equipment in order to make a significant impact.

**What are the future implications for agricultural development?**

At 2ha × 2-AME, there is little to be gained from adoption of ADP equipment innovations or THS. The benefits are significant at 3ha and 3 AME and substantial at 4ha and 4 AME. However the main contribution comes from access to innovative ADP; much less from access to tractors. The percentage increase in production is much higher with farmers who depend on custom service than those who own ADP. Moreover the increase in biomass surplus is adequate to meet feed requirement for draft animals. Therefore, a strong case can be made for investing on support infrastructure for innovative ADP. Although the benefits of THS are marginal, its role in sub soiling to reclaim degraded land should be considered.

## 5.2 Conclusions and Recommendations

Having achieved the three objectives satisfactorily the following conclusions and recommendations can be made.

### *5.2.1 Conclusions*

1. Access to 3.0ha cultivated land and 3 adult labour equivalent can be implemented and sustain conservation tillage with hired new ADP at an estimated increase in income of

$$\frac{37.4 \times 100kg \times 2000/-}{90(kg/bag)} = Ksh.\ 83{,}111.00 \text{ Per person}$$

This is double the increase in income feasible with the traditional ADP which is

$$\frac{18.0 \times 100 \times 2000}{90} = 40{,}000/-$$

The purchase price for a set of new ADP equipment to cater for two farmers is Ksh. 50,000/= Therefore it can be paid for by the increased production in one season.

2. However the innovative ADP equipment has no capacity for land reclamation involving sub soiling 20-30cm deep and associated land development. Therefore THS should be considered for this purpose.

### *5.5.2 Recommendations*

1. Further controlled tests to be carried out in other semiarid areas in order to identify location specific requirements for ADP equipment.

2. Estimate the cost benefit ratio and associated rate of return on investment in order to inform policy for investment on infrastructure.
3. Feasibility study to be made for a scheme of tractor hire services in order to assist farmers in reclaiming degraded soils while at the same time carrying out land forming for soil and water conservation as well as road construction to access arable land.
4. It is recommended that researchers consider long term quantifiable productivity attributable to farm equipment for smallholders as one of the prerequisite for mechanization selection (as is the case with irrigation technology). This is facilitated by the fact that the model is based on conventional mathematics, statistics, linear and goal programming with software already in the market. This is the main contribution that this thesis has made to the smallholder agricultural development agenda.

### *5.2.3 Recommendation for Further Work*

1. There is a need to extend the use of this model and other relevant systems to a wide spectrum of researchers in agricultural mechanization who may not be conversant with computer modelling.
2. There is a need to compare results from field situations with varied soil and crop conditions. For this purpose it is recommended that standards for field-testing be developed.
3. There is a need to collaborate with specialists in crop production modelling so that the effect of various production factors that require mechanization can be quantified. In particular it is recommended that crop production modelling be expanded to cover the wide spectrum of factors including: *time of planting, time of weeding, farm yard manure (FYM) application, crop residual recycle, harvesting and safe storage*.

### *5.2.4 Contribution to Knowledge*

Methodologies for mechanization selection of small scale farming is lacking in the literature. The impact of introducing, for example, new animal draft power (ADP) equipment is not known. This study has provided a methodology which can be used to estimate the optimum increase in production subject to available labour, land, and power, and a specified crop residue recycle. This methodology quantifies the expected biomass surplus which can be allocated to animal feed. The increase in production and associated income can be used as an input in cost benefit analysis for the purpose of informing policy on the feasibility of investment in the necessary infrastructure for R&D, manufacture, distribution and maintenance of farm equipment.

### *5.2.5 Contribution to Society*

Generally society especially among the young, consider small scale mechanization using animal draft power (ADP) as primitive. Ownership of tractors is associated with modern farming. Consequently, little investment has gone into improved ADP equipment through R&D and associated support infrastructure. Moreover, young farmers are not encouraged to use readily available ADP mechanization resources experience in the management and maintenance of draft animal power. We are oblivious to the fact that use of ADP was the foundation of modern agriculture in Europe and Asia. The methodology developed here can help in quantitative analysis of both ADP and tractor power (TP) in similar farming systems.

A transparent comparative analysis of ADP vis-à-vis TP as well as complimentary utilization of both would have far reaching implication for small scale farming. It would make it possible to evaluate mechanization projects in a way to how irrigation projects are analysed. At the same time it would be possible to evaluate the impact of conservation tillage quantitatively as well as subjectively.

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# APPENDICES

## Appendix A: Data Collection Procedures

In order to realise the necessary outputs the data inputs required include:

- Maize yield
- Schedule of operations
- Tillage field capacities
- Conservation measures
- Weekly labour constraints
- Weekly power constraints
- Land constraints
- Input costs

Each of the data input is briefly discussed below:

### *A.A.1 Maize Yield*

Long term expected mean yields were obtained from a simulation model CM/KEN by Keating et al. 1992. The net yield is the difference between the gross weight of grain output and the weight of grain whose monetary value is equivalent to the cost of recurrent inputs. The data used in the study was adopted from Keating et al 1992.

### *A.A.2 Schedule of operations*

For each crop activity there was a set of critical operations that must be performed at predetermined schedule. The schedule of operations determines the farm equipment subsets that are applicable.

### *A.A.3 Field Capacities*

The field capacities are the rates of work at which power sources were used per unit area of operation. Typical units are:

- Man-hours per ha cultivated
- Ox team hours per ha cultivated
- Tractor hours per ha cultivated

The relevant data was obtained from the following sources:

- Tests under controlled field experiments
- Farm survey information

### A.A.4 Soil and water conservation measures

Establishment of the main soil conservation measures has been adopted by majority of farmers (Thomas et al, 1997). It is therefore accepted as a pre-condition. Tillage operations take place within the well-adopted 'Fanya juu' terraces. The additional soil and water conservation measures imposed, as a constraint, is crop residue recycle. For the purpose of this study it was fixed at 2500 kg dry matter per ha minimum. Ikombo (1984) recommended 2000kg FYM dry matter. The model was designed to calculate the surplus biomass after all the cultivated land gets that amount of biomass recycled.

### A.A.5 Weekly labour constraints

For each week in the cropping season there is a set of operations, which can take place to facilitate cropping activities. These operations compete for available labour during that week. Labour was allocated to each activity according to the relevant technical coefficient (man-hours/ha) subject to the maximum available. Data on labour availability was based on farm surveys discussed in chapter 3.

### A.A.6 Weekly power resources

Farmers had access to animal and tractor power sources during the cropping season. Animal power was combined with labour whereas tractor hire services (THS) did not require labour from the farm. Available power was allocated according to the technical coefficients (ox team hours per ha) subject to the maximum available. Access to tractor power was based on literature reviewed in chapter 2.

### A.A.7 Cultivated land

The farmer allocated cultivated land to all the selected cropping activities up to the maximum available to him according to farm survey (Mutebwa, 1979 and Audi, 1996).

## Appendix B: Input data processing for input matrices

### *Computer Application*

For each cropping system, operations are listed in the order in which they occur and indexed according to the occurrence, crop selection, power source and time period during which operation must take place. The cropping for this model is single maize planted and weeded at various levels of timeliness.

The operations occurrence matrix is structured with the number of columns representing the maize production options. The row corresponding to a particular operation is marked with unity in the columns where it occurs and zero or blank where it does not occur.

The mathematical relationships are given by:

$$\sum_{n=0}^{3}\sum_{m=0}^{3} x_{nm} \sum_{k=1}^{k} H(i,j,k,t) \times Exn \le b_{(i,j,t)} \qquad \text{AB1}$$

Where *Exn* is occurrence matrix; $i=1,2;\ j=1,2,3;\ t=1,2,3,\ldots\ldots\ldots 10.$

$$\sum_{n=0}^{3}\sum_{m=0}^{3} x_{nm} \sum_{k=1}^{k} M_{(i,j,k,t)} \times Exn \le b_{(i,j,t)} \qquad \text{AB2}$$

*M* and *H* are as shown in Equations 3.26 and 3.27.

$j=1,\ 2,\ 3$ animal, tractor and human power respectively.

The software used for LP calculations was TORA developed by Taha (1997). The man hours (M), ox team hours (H) and tractor hours (H) per hectare are the aggregated technical coefficients in the constraints equations. The right hand side (RHS) value is the resource quantity in the particular period of time. In the case of labour it was assumed that each farm has at least two adult men equivalent working full time. Outside the critical periods it was assumed that labour hours are shared equitably among the farm activities. In case of ADP it was assumed that a team of two oxen works six days per week for 6 hours per day. It is assumed that a tractor is available to each farmer for a maximum of 8 working (day) hours during the peak periods i.e. one day 8 hours a day per season. Other constraint equations include land, Equation 3.25 and biomass recycle, Equation 3.24.

### *A.B.1 Traditional System of Cultivation*

The traditional tillage practice was discussed in detail in Chapter 3. The main operations are as follows: a) Ploughing and planting started approximately one week before the long rains have accumulated 30 mm of rainfall in the soil and continued until the 3rd week of the rains depending on the land available and b) early weeding was done by the end of the third week of crop emergence.

Human power, ADP and TP were supplied to these operations over the season as accessible for various activities. Tables AB1, AB2 and AB3 shows the schedule and performance parameters for various operations. The input data matrices are shown in Tables AC3, AC6 and AC7 below.

**Table AB.1 Labour (by hand, oxen or tractor equipment) used in hours per hectare for maize as a function of different mechanization levels**

| | | Levels of Mechanisation | | | | |
|---|---|---|---|---|---|---|
| Activities | Levels | HHH Hand | OHH Hand Oxen | OHO Hand Oxen | THH Hand Tractor | THO Hand , Oxen Tractor |
| Ploughing | Low | 230 | 42 | 43 | 5 | 4 |
| | Average | 377 | 51 | 49 | 6 | 6 |
| | High | 524 | 60 | 55 | 7 | 8 |
| Planting | Low | 62 | 34 | 32 | 74 | 79 |
| | Average | 80 | 50 | 49 | 88 | 84 |
| | High | 98 | 66 | 66 | 102 | 89 |
| Weeding | Low | 166 | 200 | 22 | 224 | 20 |
| | Average | 234 | 230 | 25 | 226 | 25 |
| | High | 302 | 260 | 28 | 228 | 30 |
| Harvesting | Low | 200 | 150 | 208 | 210 | 220 |
| | Average | 220 | 222 | 218 | 219 | 221 |
| | High | 240 | 294 | 228 | 238 | |

Source: Mutebwa (1979)

Key:

| | Ploughing | Planting | Weeding |
|---|---|---|---|
| HHH | hand | hand | hand |
| OHH | oxen | hand | hand |
| OHO | oxen | hand | oxen |
| THH | tractor | hand | hand |
| THO | tractor | hand | oxen |

### A.B.2 Tillage and equipment innovation

Details of farm equipment innovations are given in Chapter 2. Performance parameters are shown in Table AB2 above. Schedule of operations is shown in Table AB3.
Briefly the operations were carried out as follows:

a) Chiselling was carried out as soon as possible after harvesting the previous crop. If the previous crop was maize then on the average a farmer had 3 weeks for dry land preparation and planting before the L.R.
b) Furrow opening cum planting was carried out before and after the onset of the rains.
c) Seeding and basal fertiliser application and covering by hand was be done at the same time of furrow opening (if there is enough labour) or later on.
d) Mechanical weeding was done by the 3rd week of planting. All the plots were mechanically weeded on time. What made the difference was supplementary hand weeding within the row. If not done on time it nullified the effect of mechanical weeding.

All subsequent weeding operations, which were done as necessary, had no direct effect on yield because the crop had already gained advantage over weeds. In any case they were done when labour bottlenecks had been reduced quite considerably. Calculations for the net yields, energy input and available crop residue are shown in Table AC2. Field test performance parameters observed are given in Table AB2 below. Linear programming input matrices are shown in Tables AC4 and AC5

**Table AB.2 Field test comparison of various ox-drawn implements and the hand hoe (1980 long rains)**

| Implement | Operation | Field Capacity (Ha/hr) | Hours per ha. | Man-hours per ha. | Supplementary hand operation | Man-hours per ha. |
|---|---|---|---|---|---|---|
| Chisel plough | Ox-chiselling | 0.12 | 8.3 | 16.6(34)* | - | - |
| Desi plough | Ox-planting | 0.15 | 6.67 | 13.3 | Seed and fertilizer dropping & covering | 26.6 |
| A-share | 1st ox-weeding | 0.17 | 6 | 12 | Intra-row weeding | 40 |
| Desi plough with wings | 2nd ox-weeding cum hilling | 0.15 | 6.67 | 13.3 | Intra-row weeding | 36 |
| Hand hoe | 1st hand weeding | - | - | 287 | - | - |
| Hand hoe | 2nd hand weeding | - | - | 204 | - | - |

*For double chisel ploughing

NB: All the ox-drawn implements were mounted on the Sine Hoe toolbar. *Source: Chapter four*

### A.B.3 Workable Time

In this study actually available workable days were derived from 19 year daily rainfall as follows:

- If 20-40 mm rainfall was received within 24 hours, that particular day was considered unworkable.
- If more than 40 mm rainfall was received in 24 hours, then two days were considered unworkable.

The linear programming model was run for each of the 19 years using actually available workable days per week assuming a maximum of 5 working days per week. For instance, for 2 adult labour equivalents whose weekly labour input is 50 hours only 40 hours are taken if one working day was lost.

From these runs, it was determined that the average output of the 19 year runs was about equal to the output of one run using the average workable time for each week over the season. Therefore, all subsequent runs were done using 19-year averages of workable time during the season. The results are shown in the right hand side columns on labour constraints in all the LP matrices.

### A.B.4 Tillage Equipment Subsets Selected for Model Experimentation

Considering all the feasible farm equipment options for carrying out various operations an inventory of farm equipment subsets was drawn as shown in Table AB3. The subsets that combine to carry out all the operations necessary for a particular maize growing activity is indicated by the matrix on the right side of Table AB3. The relevant net yields and energy used are shown in Table AC2.

The tillage equipment subsets that were tested by the model were drawn from the following combinations:

15. HHH – Land preparation by hand, planting and weeding by hand
16. OHH – Land preparation by oxen, planting and weeding by hand
17. OHO – Land prep. and weeding by owned oxen, planting by hand
18. THH – Land preparation by tractor the rest by hand
19. THO – Land prep. by tractor, planting by hand, weeding by oxen
20. COHH – Land preparation by hired oxen the rest by hand
21. COHO—As 6.0 above except weeding by oxen
22. COHHTHH – As 6.0 above plus 4.0 above
23. COHOTH0 – As 8.0 above except weeding by hired oxen
24. OHOTHH – As 3.0 plus 4.0 above
25. OHOTHO – As 3.0 plus 5.0 above
26. NCOHO – New ADP equipment hired for land preparation & weeding, planting by hand
27. NCOHOTHO – As 12.0 plus tractor hire for land preparation only
28. NOHO – Owned new equipment for land preparation and weeding, planting by hand

## Table AB.3 Input data matrix

| | | | | | | | | | | | | | | | Timeliness Crop Options | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Crop | Power Source | Period | No. of Power units | No. of men | rep | Ca | TPH | ADPH | MH | 00 | 01 | 02 | 03 | 00 | 01 (pw) | 02 | 03 | 10 | 11 | 12 | 13 | 20 | 21 |
| k | Maize crop operations | Wks | i | j | t | np | nm | r | Ha/hr | hr/ha | Hrs/ha | Hrs/ha | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 |
| 1 | Ox-chisel | (1-2) | 1 | 1 | 1 | 2 | 2 | 2 | 0 12 | | 17 | 34 | 1 | 1 | 1 | 1 | | | | | | | | | | |
| 2 | Tractor-plough | (1-2) | 1 | 2 | 1 | 1 | 1 | 1 | | 8 | | | 1 | 1 | 1 | 1 | | | | | | | | | | |
| 3 | Man-plant | (1-3) | 1 | 3 | 2 | 1 | 1 | 1 | | | | 88 | 1 | 1 | 1 | 1 | | | | | | | | | | |
| 4 | Ox-plough | (1-2) | 1 | 1 | 1 | 2 | 2 | 2 | | | | 51 | | | | | 1 | 1 | 1 | 1 | | | | | | |
| 5 | Ox-plough-plant | 3 | 1 | 1 | 2 | 2 | - | 1 | | | | 101 | | | | | 1 | 1 | 1 | 1 | | | | | | |
| 6 | Ox-plough-plant | 4 | 1 | 1 | 3 | 2 | - | 1 | | | | 101 | | | | | | | | | 1 | 1 | 1 | 1 | | |
| 7 | Ox-Desi-plant | 3 | 1 | 1 | 2 | 2 | 6 | 1 | .15 | | 7 | 40 | 1 | 1 | 1 | 1 | | | | | | | | | | |
| 8 | Ox-Desi-plant | 4 | 1 | 1 | 3 | 2 | 6 | 1 | 15 | | 7 | 40 | | | | | | | | | 1 | 1 | 1 | 1 | | |
| 9 | Ox-Desi-plant | 5 | 1 | 1 | 4 | 2 | 6 | 1 | .15 | | 7 | 40 | | | | | | | | | | | | | 1 | 1 |
| 10 | Ox-Desi-plant | 5 | 1 | 1 | 4 | 2 | 6 | 1 | | | | 101 | | | | | | | | | | | | | 1 | 1 |
| 11 | Ox-plough-plant | 6 | 1 | 1 | 5 | 2 | - | 1 | | | | 101 | | | | | | | | | | | | | | |
| 12 | Ox-Desi-plant | 6 | 1 | 1 | 5 | 2 | 6 | 1 | .15 | | | 40 | | | | | | | | | | | | | | |
| 13 | Ox-A Share weed | 6 | 1 | 1 | 5 | 2 | 2 | 1 | | | | 25 | | | | | 1 | 1 | 1 | 1 | | | | | | |
| 14 | Ox-A-share-weed | 6 | 1 | 1 | 5 | 2 | 2 | 1 | 17 | | 6 | 12 | 1 | 1 | 1 | 1 | | | | | | | | | 1 | 1 |
| 15 | Man-weed | 6 | 1 | 3 | 5 | 1 | 1 | 1 | | | | 200 | 1 | | | | | | | | | | | | | |
| 16 | Man-Int -weed | 6 | 1 | 3 | 5 | 2 | 1 | 1 | | | | 40 | 1 | | | | 1 | | | | 1 | | | | | |
| 17 | Ox-weed | 7 | 1 | 1 | 6 | 2 | 2 | 1 | | | | 25 | | | | | | | | | 1 | 1 | 1 | 1 | | |
| 18 | Ox-A-share-weed | 7 | 1 | 1 | 6 | 2 | 2 | 1 | 17 | | 7 | 12 | | 1 | | | | | | | 1 | 1 | 1 | 1 | | |
| 19 | Man-weed | 7 | 1 | 3 | 6 | 1 | 1 | 1 | | | | 230 | | 1 | | | | | | | | | | | | |
| 20 | Man-Int -weed | 7 | 1 | 3 | 6 | 1 | 1 | 1 | | | | 50 | | 1 | | | | 1 | | | 1 | 1 | | | | |
| 21 | Ox-weed | 8 | 1 | 1 | 7 | 1 | 1 | 1 | | | | 260 | | | | | | | | | | | | | 1 | 1 |
| 22 | Ox-A-share-weed | 8 | 1 | 1 | 7 | 2 | 2 | 1 | 17 | | 7 | 12 | | | 1 | | | | | | | | | | 1 | 1 |
| 23 | Man-weed | 8 | 1 | 3 | 7 | 1 | 1 | 1 | | | | 260 | | | 1 | | | | | | | | | | | |
| 24 | Man-Int -weed | 8 | 1 | 3 | 7 | 1 | 1 | 1 | | | | 60 | | | 1 | | | | 1 | | | 1 | 1 | | 1 | |
| 25 | Ox-weed | 9 | 1 | 1 | 8 | 2 | 2 | 1 | | | | 25 | | | | | | | | | | | | | | |
| 26 | Ox-A-share-weed | 9 | 1 | 1 | 8 | 2 | 2 | 1 | 17 | | | 12 | | | | 1 | | | | | | | | | | |
| 27 | Man-weed | 9 | 1 | 3 | 8 | 1 | 1 | 1 | | | | 290 | | | | 1 | | | | | | | | | | |
| 28 | Man-Int -weed | 9 | 1 | 3 | 8 | 1 | 1 | 1 | | | | 70 | | | | 1 | | | | 1 | | | 1 | 1 | | 1 |
| 29 | Man-Int -weed | 10 | 1 | 3 | 9 | 1 | 1 | 1 | | | | 70 | | | | | | | | | | | | 1 | 1 | |

## Appendix C: Worked out examples for matrices input

Data for LP input matrices were calculated as shown in the following paragraphs.

### *A.C.1 Crop yield response to Time of Planting and Time of weeding.*

Table 4.1.1 was generated from secondary data by Keating et al (1992) and Makatiani (1971) using the following equations:

$$\beta_{nm} = n\beta_p + m\beta_w - m\beta_w \times n\beta_p \qquad 3.7$$

$$Y_{nm} = Y_{oo}(1 - \beta_{nm}) \qquad 3.8$$

Where $\beta_p$ = (2.5/100) per day x 7days = 0.175 per week.

$\beta_w = \frac{2485 - 1210}{2485\text{x}2\text{weeks}}$ =0.256 per week

For example for n=2 weeks late planting and m=2 weeks late weeding

$\beta_{nm}$ =2× 0.1785×2 × 0.256 -2× 0.256 × 2×0.175

= 0.35 = 0.512 – 0.512 x0.315= 0.683

Substituting in equation 6.28

$Y_{nm}$ = 2060(1-0.683)=653Kg/hac.

or 6.53quintals /ha.

### *A.C.2 Net Yields*

Net yields shown in Table AC2 were applied as the coefficients of the objective function in the LP model defined by equation 3.3. Calculations made are based on Keating et.al. (1992). For purposes of this study the following assumptions were made:

(i) That innovative farmers will apply FYM and supplement it with 20Kg N

(ii) That less innovative farmers use only FYM

Those less innovative farmers use traditional ADP and pay in kind or cash.

That innovative farmers will hire tractors or innovative ADP equipment for early land preparation at market prices reported by Ministry of agriculture (1989 as follows:

1st stubble ploughing Ksh 357 per ha

| | |
|---|---|
| 2nd Stubble ploughing (instead of harrowing) | Ksh 357 per ha |
| Total | Ksh 714 |
| Add 105 to get 1990 prices at | Ksh 785 per ha |

When the innovative farmer is late the machinery is used to plough plant only at reduced time from 123 hours to 55hr/ha. The corresponding reduced cost equals
(55/123) x 785= Kshs 351

**Table AC.1 Summary of costs**

| Item | Innovative Farmer | | Less innovative farmer | |
|---|---|---|---|---|
| | Early planting (Shs) | Late planting (Shs) | Item | Late planting (Shs) |
| Ploughing | 785 | 351 | Ploughing once | 393 |
| Fertiliser 20kg N @ Shs 16.3 | 326 | 326 | Fertiliser 20kg N @ Shs 16.3 | 326 |
| Seed 24kg@ Shs 4 | 96 | 96 | Seed 24kg@ Shs 4 | 96 |
| ***Total*** | 1207 | 773 | ***Total*** | 815 |
| Grain equivalent @ Shs 3 per kg | 402 Kg. | 258Kg | Grain equivalent @ Shs 3 per kg | 272 kg |

The corresponding gross margins are shown in Table AC2 in quintals (100 kg) per hectare.

### *A.C.3 Man hours and Equipment hours per hectare*

Data for man hours and equipment hours utilisation for conventional practices were drawn from Mutebwa (1979) as detailed in Section AB1. In other words equipment hours and man hours per ha defined by $H_{(i,j,k,t)}$ and $M_{(i,j,k,t)}$ in equation 5.8 and 5.9 respectively. Inputs into these equations are drawn from Table AB3. Tractor and man hours were estimated by

$$H_{(i,j,k,t)} = \frac{10(np \times r)_{(i,j,k,t)}}{(v \times e \times w)_{(i,j,k,t)}} = \frac{(np \times r)_{(i,j,k,t)}}{C_{a\,(i,j,k,t)}} \qquad 3.26$$

$$M_{(i,j,k,t)} = \frac{10(np \times nm \times r)_{(i,j,k,t)}}{(v \times e \times w)_{(i,j,k,t)}} = \frac{(np \times nm \times r)_{(i,j,k,t)}}{C_{a(i,j,k,t)}} \qquad 3.27$$

Substituting from Table AB3 for i=1 , j=2, k=2 t=1; from Table AB1 Ca =1/8 ha/hr or 8 hrs/ha

Therefore,

$$H_{(1,2,2,1)} = \frac{(1 \times 1)}{1/8} = 8hr/ha$$

as shown in the appropriate matrix Table AC3.

For planting by hand after the tractor has ploughed

$$M_{(i,j,k,t)} = \frac{(np \times nm \times r)_{(i,j,k,t)}}{(v \times e \times w/10)_{(i,j,k,t)}} = \frac{(np \times nm \times r)_{(i,j,k,t)}}{Ca_{(i,j,k,t)}}$$

Substituting from Table AB3 and Tables AB1 i=1, j=3, k=3 and t=2

For THH Ca = 1/88 ha/hr or 88 man-hours /ha

$$M_{(1,3,3,2)} = \frac{(1 \times 1 \times 1)}{(1/88)} = 88$$

For ADP equipment innovations the data was drawn from Table AB2 as shown below.

For ox-chiselling

$$M_{(i,j,k,t)} = \frac{(np \times r)_{(i,j,k,t)}}{(v \times e \times w/10)_{(i,j,k,t)}} = \frac{(np \times r)_{(i,j,k,t)}}{Ca_{(i,j,k,t)}}$$

Substituting from Table AB2 and AB3

Ca =0.12ha/hr or 8.3hr per ha.

i =1, j =1, k =1, t =1

Therefore

$$H_{(1,1,1,1)} = \frac{(2 \times 2)_{(1,1,1,1)}}{(1/8.3)} = 33.2 \quad \text{or say 34 ox-hours}$$

The corresponding human power input is given by

$$M_{(i,j,k,t)} = \frac{(np \times nm \times r)_{(i,j,k,t)}}{Ca_{(i,j,k,t)}} = \frac{(1 \times 2 \times 2)_{(i,j,k,t)}}{(1/8.3)} = 33.2$$

This value appears in Table AC4 column 1-4

Looking at the linear programming matrix in Table AC4 there is a need to estimate the input values from available data. Consider weekly operations namely:

3 Ox - Desi- plant in week 3

4 Man- Desi- plant in week 3

Starting from Table AB3, the characteristics of these operations are examined as follows:

***Ox-Desi-plant***

This is operation k=7, crop i=1(maize), the power source j=1 (ADP); the period t=2, power units np=2 oxen, number of men nm=4, replications r=1

This operation is carried out for early planted crop before rains.

The Ox- hours can be calculated using equation 5.8 as follows

$$H_{(i,j,k,t)} = \frac{(np \times r)_{(i,j,k,t)}}{(v \times e \times w/10)_{(i,j,k,t)}}$$

Substitute values from Tables AB3 and 3.4 as follows;

$$H_{(1,1,7,3)} = \frac{(2 \times 1)_{(1,1,7,3)}}{0.15} = 13.3 \text{ Or say } 14$$

$$M_{(i,j,k,t)} = \frac{(np \times nm \times r)_{(i,j,k,t)}}{Ca_{(i,j,k,t)}} = \frac{(1 \times 6 \times 1)_{(i,j,k,t)}}{(0.15)} = 40$$

## Table AC.2 Calculations of maize net yields, surplus biomass and energy input

| | 00 | 01 | 02 | 03 | 10 | 11 | 12 | 13 | 20 | 21 | 22 | 23 | 30 | 31 | 32 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
| ADP NEW QUIPMENT | | | | | | | | | | | | | | | |
| **YIELD (Table 2A.6)** | 20 6 | 15.3 | 10.1 | 4.78 | 17.0 | 12 6 | 8 29 | 3 94 | 13.4 | 10.0 | 6 53 | 3.11 | 9 80 | 7 28 | 4 78 |
| **BREAK EVEN YIELD** | 4 0 | 4.0 | 4.0 | 4.0 | 2.5 | 2.5 | 2.5 | 2.5 | 2.5 | 2 5 | 2.5 | 2.5 | 2.5 | 2.5 | 2.5 |
| **NET YIELD** | 16.6 | 11.3 | 6.1 | 0 78 | 14 5 | 10.1 | 5 79 | 1.44 | 10.9 | 7 5 | 4.03 | 0 61 | 7 3 | 4 78 | 2.28 |

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | | 10 | 11 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ADP NEW QUIPMENT | | | | | | | | | | | | |
| **NET YIELD** | 16 6 | 11.3 | 6.1 | 14 5 | 10.1 | 5 8 | 10.9 | 7.5 | 4.0 | | 7 3 | 4 8 |
| **TOTAL BIOMASS** | 36 5 | 27.1 | 17 9 | 30 1 | 22.3 | 14.7 | 23.7 | 17.7 | 1.7 | | 17 3 | 12 9 |
| **BIOMASS RECYCLED** | 25 | 25 | 25 | 25 | 25 | 25 | 25 | 25 | 25 | | 25 | 25 |
| BIOMASS BALANCE. | -11.5 | -2.1 | 7.1 | -5.1 | 2 7 | 10 3 | 1.3 | 7.3 | 13 4 | | 7.7 | 12.1 |
| **ENERGY (Mj).** | | | | | | | | | | | | |
| **TRADITIONALL ADP EQUIPMENT.** | | | | | | | | | | | | |
| **YIELD** | 20 6 | 15 3 | 10.1 | 17 0 | 12 6 | 8 29 | 13 4 | 10 0 | 6 53 | | 9 8 | 7 3 |
| **BREAK EVEN YIELD** | 2 8 | 2 8 | 2 8 | 2 8 | 2 8 | 2 8 | 2 8 | 2 8 | 2 8 | | 2 8 | 2 8 |
| **NET YIELD** | 17 8 | 12 5 | 7 3 | 14.2 | 9 8 | 5 5 | 10 6 | 7 2 | 3 7 | | 7 0 | 4 5 |
| **ENERGY (Mj).** | 854 | 874 | 894 | 446 | 466 | 486 | 446 | 466 | 486 | | 446 | 466 |
| **TRACTOR HIRE.** | | | | | | | | | | | | |
| **YIELD** | 20 6 | 15 3 | 10.1 | 4 8 | | | | | | | | |
| **BREAK EVEN YIELD** | 4 0 | 4.0 | 4 0 | 4 0 | | | | | | | | |
| **NET YIELD** | 16 6 | 11.3 | 6 1 | 14 5 | | | | | | | | |
| **ENERGY (Mj).** | 5079 | 5079 | 5079 | 5079 | | | | | | | | |

**Table AC.3 Linear programming input matrixes for a farmer who owns ADP and access to TP decision variables (OHOTHO)**

| | $X_{PW}$ | 00 | 01 | 02 | 03 | 00 | 01 | 02 | 03 | 10 | 11 | 12 | 13 | 20 | 21 | 22 | 31 | 32 | OX/MAN | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| WEEKLY OPERATIONS | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | HRS/WK | | |
| N.Y.(QU./Ha) | | 16.6 | 11.7 | 6.8 | 2 | 17.8 | 12.9 | 8 | 3.2 | 14.2 | 10.2 | 6.1 | 2.1 | 10.6 | 7.4 | 4.2 | 7 | 4.7 | 2 | 3 | 4 |
| 1 TRACTOR PLOUGH | (1-3) | 8 | 8 | 8 | 8 | | | | | | | | | | | | | | 8 | 8 | 8 |
| 2 MAN-OPEN-PLANT | (1-3) | 88 | 88 | 88 | 88 | | | | | | | | | | | | | | 150 | 150 | 150 |
| 3 OX-OPEN-PLANT | (1-3) | | | | | 51 | 51 | 51 | 51 | | | | | | | | | | 150 | 130 | 150 |
| 4 MAN-OPEN-PLANT | (1-3) | | | | | 101 | 101 | 101 | 101 | | | | | | | | | | 150 | 130 | 150 |
| 5 OX-OPEN-PLANT | 4 | | | | | | | | | 51 | 51 | 51 | 51 | | | | | | 34 | 34 | 34 |
| 6 MAN-OPEN-PLANT | 4 | | | | | | | | | 101 | 101 | 101 | 101 | | | | | | 34 | 54 | 74 |
| 7 OX-OPEN-PLANT | 5 | | | | | | | | | | | | | 51 | 51 | 51 | | | 43 | 43 | 43 |
| 8 MAN-OPEN-PLANT | 5 | | | | | | | | | | | | | 101 | 101 | 101 | | | 60 | 85 | 110 |
| 9 OX-WD-OPEN-PLA | 6 | | | | | 25 | 25 | 25 | 25 | | | | | | | | 51 | 51 | 50 | 50 | 50 |
| 10 MAN-WD-OPEN-PLA | 6 | 200 | | | | 65 | | | | | | | | | | | 101 | 101 | 70 | 100 | 130 |
| 11 OX-WEED | 7 | | | | | | | | | 25 | 25 | 25 | 25 | | | | | | 50 | 50 | 50 |
| 12 MAN-WEED | 7 | | 230 | | | | 75 | | | 65 | | | | | | | | | 70 | 100 | 130 |
| 13 OX-WEED | 8 | | | | | | | | | | | | | 25 | 25 | 25 | | | 50 | 50 | 50 |
| 14 MAN-WEED | 8 | | | 260 | | | | 85 | | | 75 | | | 65 | | | | | 62 | 88 | 114 |
| 15 OX-WEED | 9 | | | | | | | | | | | | | | | | 25 | 25 | 50 | 50 | 150 |
| 16 MAN-WEED | 9 | | | | | 290 | | | 95 | | | 85 | | | 75 | | 65 | | 50 | 80 | 110 |
| 17 | 10 | | | | | | | | | | | | 95 | | | 85 | | 75 | 50 | 80 | 110 |
| 18 LAND | | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 3 | 4 |
| 19 BIOMASS | | -12 | -2.8 | 5.9 | 14.5 | -12 | -2 8 | 5.9 | 14.5 | -5.1 | 2 | 9 2 | 16 3 | 1.3 | 7 | 12 5 | 7.7 | 11 8 | <=0 | | |

**Table AC.4 Linear programming matrix for innovative ADP equipment (NOHO)**

| DECISION VARIABLES: MAIZE ACTIVITIES IN HECTARES | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Weekly Operations | Wks | Xp w: | X00 | X01 | X02 | X03 | X10 | X11 | X12 | X13 | X20 | X21 | X22 | X30 | X31 | X32 | OX/MAN | | |
| | | | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | | HRS/WK | | |
| | N.Y. (qu/ha) | | | 17 | 12 | 6.8 | 2 | 15 | 12 | 6.4 | 2.4 | 11 | 7.7 | 4.5 | 7.3 | 5 | | | | |
| 1 | Ox-chisel | (1-2) | | 34 | 34 | 34 | 34 | | | | | | | | | | | <=100 | 100 | 100 |
| 2 | Man-chisel | (1-2) | | 34 | 34 | 34 | 34 | | | | | | | | | | | <=100 | 160 | 220 |
| 3 | Ox-open | 3 | | 14 | 14 | 14 | 14 | | | | | | | | | | | <=50 | 50 | 50 |
| 4 | Man-open-seed | 3 | | 41 | 41 | 41 | 41 | | | | | | | | | | | <=50 | 80 | 110 |
| 5 | Ox-open | 4 | | | | | | 14 | 14 | 14 | 14 | | | | | | | <=34 | 34 | 34 |
| 6 | Man-open-seed | 4 | | | | | | 41 | 41 | 41 | 41 | | | | | | | <=34 | 54 | 74 |
| 7 | Ox-open | 5 | | | | | | | | | | 14 | 14 | 14 | | | | <=43 | 43 | 43 |
| 8 | Man-open-seed | 5 | | | | | | | | | | 41 | 41 | 41 | | | | <=60 | 85 | 110 |
| 9 | Ox-open-weed | 6 | | 12 | 12 | 12 | 12 | | | | | | | | 14 | 14 | | <=50 | 50 | 50 |
| 10 | Man-open-seed-weed | 6 | | 52 | 12 | 12 | 12 | | | | | | | | 41 | 41 | | <=70 | 100 | 130 |
| 11 | Ox-weed | 7 | | | | | | 12 | 12 | 12 | 12 | | | | | | | <=50 | 50 | 50 |
| 12 | Man-weed | 7 | | | 50 | | | 52 | 12 | 12 | 12 | | | | | | | <=70 | 100 | 130 |
| 13 | Ox-weed | 8 | | | | | | | | | | 12 | 12 | 12 | | | | <=50 | 50 | 50 |
| 14 | Man-weed | 8 | | | | 60 | | | 50 | | | 52 | 12 | 12 | | | | <=62 | 88 | 114 |
| 15 | Ox-weed | 9 | | | | | | | | | | | | | 12 | 12 | | <=44 | 44 | 44 |
| 16 | Man-weed | 9 | | | | | 70 | | | 60 | | | 50 | | 52 | 12 | | <=50 | 70 | 96 |
| 17 | Man-weed | 10 | | | | | | | | | 70 | | | 60 | | | | <=50 | 80 | 110 |
| 18 | Land Hectares | | | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | | <=2 | 3 | 4 |
| 19 | Biomass qu. | | | -12 | -3 | 5.9 | 15 | -5 | 2 | 9.2 | 16 | 1.3 | 7 | 13 | 7.7 | 12 | | 0 <= 0 | | |

**Table AC.5 Linear programming input matrix for a farmer who hires tractor power and innovative equipment for land preparation and planting (late) and weeding early (NCOCOTHO)**

| | | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Wks | 16.6 | 11.7 | 6.8 | 2 | 16.6 | 11.7 | 6.8 | 2 | 14.5 | 11.5 | 6.4 | 2.4 | 10.9 | 7.7 | 4.5 | 7.3 | 5 | | | |
| 1 | Tractor plough | (1-3) | 8 | 8 | 8 | 8 | | | | | | | | | | | | | | 8 | 8 | 8 |
| 2 | Man plant | (1-3) | 88 | 88 | 88 | 88 | | | | | | | | | | | | | | 150 | 240 | 330 |
| 3 | Ox-chisel | (1-2) | | | | | | | | | 34 | 34 | 34 | 34 | | | | | | 100 | 100 | 100 |
| 4 | Man –chisel | (1-2) | | | | | | | | | 34 | 34 | 34 | 34 | | | | | | 100 | 160 | 220 |
| 5 | Ox-plough plant | 4 | | | | | | | | | 14 | 14 | 14 | 14 | | | | | | 34 | 34 | 34 |
| 6 | Man-plough-plant | 4 | | | | | | | | | 41 | 41 | 41 | 41 | | | | | | 34 | 54 | 74 |
| 7 | Ox-plough plant | 5 | | | | | | | | | | | | | 14 | 14 | 14 | | | 43 | 43 | 43 |
| 8 | Man-plough-plant | 5 | | | | | | | | | | | | | 41 | 41 | 41 | | | 60 | 85 | 110 |
| 9 | Ox-plough plant-weed | 6 | 12 | 12 | 12 | 12 | | | | | | | | | | | | 14 | 14 | 50 | 50 | 50 |
| 10 | Man-plough-plant-weed | 6 | 52 | 12 | 12 | 12 | | | | | | | | | | | | 41 | 41 | 70 | 100 | 130 |
| 11 | Ox-weed | 7 | | | | | | | | | 12 | 12 | 12 | 12 | | | | | | 50 | 50 | 50 |
| 12 | Man-weed | 7 | | 50 | | | | | | | 52 | 12 | 12 | 12 | | | | | | 70 | 100 | 130 |
| 13 | Ox-weed | 8 | | | | | | | | | | | | | 12 | 12 | 12 | | | 50 | 50 | 50 |
| 14 | Man-weed | 8 | | | 60 | | | | | | | 50 | | | 52 | 12 | 12 | | | 62 | 88 | 114 |
| 15 | Ox-weed | 9 | | | | | | | | | | | | | | | | 12 | 12 | 44 | 44 | 44 |
| 16 | Man-weed | 9 | | | | 70 | | | | | | | 60 | | | 50 | | 52 | 12 | 50 | 70 | 96 |
| 17 | Man weed | 10 | | | | | | | | | | | | 70 | | | 60 | | 50 | 50 | 80 | 110 |
| 18 | Land | | 1 | 1 | 1 | 1 | | | | | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 3 | 4 |
| 19 | Crop residue | | -12 | -2.8 | 5.9 | 14.5 | | | | | -5.1 | 2 | 9.2 | 16.3 | 1.3 | 7 | 12.5 | 7.7 | 11.8 | 0 | 0 | 0 |
| | | | | | | | | | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | | | | | | | | |

**Table AC.6 LP input matrix for a farmer who does not own farm power and equipment but has access to hired TP and ADP (COHHTHH)**

| | | | DECISION VARIABLES | | | | | | | | | | | | | AME/wk | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | | | | | 2 | 3 | 4 |
| | | Xpw | 0 | 1 | 2 | 3 | 10 | 11 | 12 | 13 | 20 | 21 | 22 | 30 | 31 | | | |
| | WEEKLY OPERATIONS | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | OX AND MAN HRS/WK | | |
| | | NY | 16.6 | 11.7 | 6.8 | 2 | 14.2 | 10.2 | 6.1 | 2.1 | 10.6 | 7.4 | 4.2 | 7 | 4.7 | | | |
| 1 | PLOUGH-TRACTOR | (1-3) | 8 | 8 | 8 | 8 | | | | | | | | | | | 8 | |
| 2 | PLANT-HAND | (1-3) | 88 | 88 | 88 | 88 | | | | | | | | | | <= 150 | 150 | |
| 3 | OPEN-PLANT-OX | 4 | | | | | 51 | 51 | 51 | 51 | | | | | | <= 34 | 34 | |
| 4 | OPEN-PLANT-HAND | 4 | | | | | 101 | 101 | 101 | 101 | | | | | | <= 34 | 54 | |
| 5 | OPEN-PLANT-OX | 5 | | | | | | | | | 51 | 51 | 51 | | | <= 43 | 43 | |
| 6 | OPEN-PLANT-HAND | 5 | | | | | | | | | 101 | 101 | 101 | | | <= 60 | 85 | |
| 7 | OX-OPEN-PLANT | 6 | | | | | | | | | | | | 51 | 51 | <= 50 | 50 | |
| 8 | OX-OPEN-PLANT-WD | 6 | 200 | | | | | | | | | | | 101 | 101 | <= 70 | 100 | |
| 9 | WEED-HAND | 8 | | 230 | | | 200 | | | | | | | | | <= 50 | 50 | |
| 10 | WEED-HAND | 8 | | | 260 | | | 230 | | | 200 | | | | | <= 62 | 88 | |
| 11 | WEED-HAND | 9 | | | | 290 | | | 260 | | | 230 | | 200 | | <= 50 | 80 | |
| 12 | WEED-HAND | 10 | | | | | | | | 290 | | | 260 | | 230 | <= 50 | 80 | |
| 13 | LAND | 11 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | <= 2 | | |
| 14 | BIOMASS | 12 | -11.5 | -2.8 | 5.9 | 14.5 | -5.1 | 2 | 9.2 | 16.3 | 1.3 | 7 | 12.5 | 7.7 | 11.8 | <= 0 | | |

**Table AC.7 LP input matrix for a farmer who does not own farm equipment but has access to hired TP and ADP (COHOTHO)**

| | | | | | | | | DECISION VARIABLES | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $X_{PW}$ | $X_{00}$ | $X_{01}$ | $X_{02}$ | $X_{03}$ | $X_{10}$ | $X_{11}$ | $X_{12}$ | $X_{13}$ | $X_{20}$ | $X_{21}$ | $X_{22}$ | $X_{30}$ | $X_{31}$ | AME/week | | |
| | | | | | | | | | | | | | | | 2 | 3 | 4 |
| | $Y_{PW}$ | $Y_{01}$ | $Y_{02}$ | $Y_{03}$ | $Y_{04}$ | $Y_{05}$ | $Y_{06}$ | $Y_{07}$ | $Y_{08}$ | $Y_{09}$ | $Y_{10}$ | $Y_{11}$ | $Y_{12}$ | $Y_{13}$ | | | |
| WEEKLY OPERATIONS | WKS GM | 16.6 | 11.7 | 6.8 | 2 | 14.2 | 10.2 | 6.1 | 2.1 | 10.6 | 7.4 | 4.2 | 7 | 4.7 | OX AND MAN HRS/WK | | |
| | | | | | | | | | | | | | | | | | |
| 1 TRACTOR PLOUGH | (1-3) | 8 | 8 | 8 | 8 | | | | | | | | | | <= 8 | 8 | 8 |
| 2 MAN-PLANT | (1-3) | 88 | 88 | 88 | 88 | | | | | | | | | | <= 150 | 150 | 150 |
| 3 OX-PLOUGH PLANT | 4 | | | | | 51 | 51 | 51 | 51 | | | | | | <= 34 | 34 | 34 |
| 4 MAN-PLOUGH PLANT | 4 | | | | | 101 | 101 | 101 | 101 | | | | | | <= 34 | 54 | 74 |
| 5 OX-PLO-PLA | 5 | | | | | | | | | 51 | 51 | 51 | | | <= 43 | 43 | 43 |
| 6 MAN-PLO-PLA | 5 | | | | | | | | | 101 | 101 | 101 | | | <= 60 | 85 | 110 |
| 7 OX-PLOUGH-WD | 6 | 25 | 25 | 25 | 25 | | | | | | | | 51 | 51 | <= 50 | 50 | 50 |
| 8 MAN-PO-PLA-WD | 6 | 65 | 25 | 25 | 25 | | | | | | | | 101 | 101 | <= 70 | 100 | 130 |
| 9 OX-WEED | 7 | | | | | 25 | 25 | 25 | 25 | | | | | | <= 50 | 50 | 50 |
| 10 MAN-WEED | 7 | | 75 | | | 65 | 25 | 25 | 25 | | | | | | <= 70 | 100 | 130 |
| 11 OX-WEED | 8 | | | | | | | | | 25 | 25 | 25 | | | <= 50 | 50 | 50 |
| 12 MAN-WEED | 8 | | | 85 | | | 75 | | | 65 | 25 | 25 | | | <= 62 | 88 | 114 |
| 13 OX-WEED | 9 | | | | | | | | | | | | 25 | 25 | <= 50 | 50 | 50 |
| 14 MAN-WEED | 9 | | | | 95 | | | 85 | | | 75 | | 65 | 25 | <= 50 | 80 | 110 |
| 15 MAN-WEED | 10 | | | | | | | | 95 | | | 85 | | 75 | <= 50 | 80 | 110 |
| 16 LAND(HA) | 11 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | <= 2 | 3 | 4 |
| 17 BIOMASS | 12 | -11.5 | -2.8 | 5.9 | 14.5 | -5.1 | 2 | 9.2 | 16.3 | 1.3 | 7 | 12.5 | 7.7 | 11.8 | <= 0 | | |
| | | | | | | | | | | | | | | | | | |

## Table AC.8 Goal programming with energy use as the objective function for OHOTHO

| | | Xpw | X00 | X01 | X02 | X03 | X10 | X11 | X12 | X13 | X20 | X21 | X22 | X30 | X31 | X32 | X21 | X22 | X31 | X32 | AME/week | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Energy | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | | 14 | 15 | 16 | 17 | 2 | 3 | 4 |
| | Weekly Operations | Wks Consu-mption | 5.54 | 5.71 | 5.73 | 5.75 | 1.6 | 1.67 | 1.69 | 1.71 | 1.09 | 1.16 | 1.08 | 1.2 | 1.09 | | 1.16 | 1.18 | 1.09 | 1.16 | TP/OX/MAN Hrs/week | | |
| 1 | Tractor Plough | (1-2) | 8 | 8 | 8 | 8 | | | | | | | | | | | | | | | 8 | 8 | 8 |
| 2 | Man-open-plant | (1-3) | 88 | 88 | 88 | 88 | | | | | | | | | | | | | | | <=150 | 220 | 330 |
| 3 | Ox-plough | (1-2) | | | | | 102 | 102 | 102 | 102 | | | | | | | | | | | <=100 | 100 | 100 |
| 4 | Man-open-plant | 3 | | | | | 101 | 101 | 101 | 101 | | | | | | | | | | | <=50 | 80 | 110 |
| 5 | Ox-open-plant | 4 | | | | | | | | | 51 | 51 | 51 | 51 | | | | | | | <=34 | 34 | 34 |
| 6 | Man-open-plant | 4 | | | | | | | | | 101 | 101 | 101 | 101 | | | | | | | <=34 | 54 | 74 |
| 7 | Ox-open-plant | 5 | | | | | | | | | | | | | 51 | | 51 | 51 | | | <=43 | 43 | 43 |
| 8 | Man-open-plant | 5 | | | | | | | | | | | | | 101 | | 101 | 101 | | | <=60 | 85 | 110 |
| 9 | Ox-open-plant-weed | 6 | 25 | 25 | 25 | 25 | 25 | 25 | 25 | 25 | | | | | | | | | 51 | 51 | <=50 | 50 | 50 |
| 10 | Man-open-plant-weed | 6 | 65 | 25 | 25 | 25 | 65 | 25 | 25 | 25 | | | | | | | | | 101 | 101 | <=70 | 100 | 130 |
| 11 | Ox-weed | 7 | | | | | | | | | 25 | 25 | 25 | 25 | | | | | | | <=50 | 50 | 50 |
| 12 | Man-weed | 7 | | 75 | | | | 75 | | | 65 | 25 | 25 | 25 | | | | | | | <=70 | 100 | 130 |
| 13 | Ox-weed | 8 | | | | | | | | | | | | | 25 | | 25 | 25 | | | <=50 | 50 | 50 |
| 14 | Man-weed | 8 | | | 85 | | | | 85 | | | 75 | | | 65 | | 25 | 25 | | | <=60 | 88 | 114 |
| 15 | Ox-weed | 9 | | | | | | | | 95 | | | | | | | | | 25 | 25 | <=50 | 50 | 50 |
| 16 | Man-weed | 9 | | | | 95 | | | | | | | 85 | | | | 75 | | 65 | 25 | <=50 | 80 | 110 |
| 17 | Man-weed | 10 | | | | | | | | | | | | 95 | | | | 85 | | 75 | <=50 | 80 | 110 |
| 18 | Land | | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | | 1 | 1 | 1 | 1 | <=2 | 3 | 4 |
| 19 | Biomass | | -11.5 | -2.8 | 5.9 | 14.5 | -11.5 | -2.8 | 5.9 | 14.5 | -5.1 | 2 | 9.2 | 16.3 | 1.3 | | 7 | 12.5 | 7.7 | 11.8 | <=0 | 0 | 0 |
| 20 | Productivity | | 16.6 | 11.7 | 6.8 | 2 | 17.8 | 12.9 | 8 | 3.2 | 14.2 | 10.2 | 6.1 | 2.1 | 10.6 | | 7.4 | 4.2 | 7 | 4.7 | <= obJ Func | | |

# Appendix D: Linear programming outputs

**Table AD.1 L.P model output showing the variables in the solution and the limiting constraints (✓)**

| File Labour x land | Obj value | *Variables* | | | | | | | | | | Labour constraints | | | | | | | | | | | | Land* used, ha | Biomass** surplus |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 4 | 5 | 7 | 8 | 9 | 10 | 11 | 13 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 |
| COHH22 | 9 4 | | | 4.9 | | 3.3 | 1.3 | | | | 2.6 | | | | ✓ | | | | | ✓ | ✓ | ✓ | | 1.17 | 0.0 |
| COHH23 | 9.4 | | | 4.9 | | 3 3 | 1.3 | | | | | | | | ✓ | | | | | ✓ | ✓ | ✓ | | 2.17 | 0.0 |
| COHH24 | 9.4 | | | 4.9 | | 3.3 | 1.3 | | | | | | | | ✓ | | | | | ✓ | ✓ | ✓ | | 3 17 | 0.0 |
| COHHTHH22 | 15.8 | 5.8 | 0 13 | 4 8 | | 3 3 | 1.6 | 0.25 | | | | | | | ✓ | | ✓ | | ✓ | ✓ | ✓ | ✓ | | 0 7 | 2.9 |
| COHHTHH23 | 15.8 | 5 8 | 0 13 | 4 8 | | 3 3 | 1.6 | 0.25 | | | | | | | ✓ | | ✓ | | ✓ | ✓ | ✓ | ✓ | | 1 7 | 2.9 |
| COHHTHH24 | 15 8 | 5 8 | 0 13 | 4 8 | | 3 3 | 1 6 | | 0 25 | | | | | | ✓ | | ✓ | | ✓ | ✓ | ✓ | ✓ | | 2 7 | 2 9 |
| COHH32 | 13.7 | | | 7.1 | | 4 7 | 2.0 | | | | | | | ✓ | ✓ | ✓ | | | ✓ | ✓ | ✓ | | | 0 8 | 0 0 |
| COHH33 | 13.7 | | | 7.1 | | 4 7 | 2 0 | | | | 0 30 | | | ✓ | ✓ | ✓ | | | ✓ | ✓ | ✓ | | | 1.7 | 0 0 |
| COHH34 | 13 7 | | | 7.1 | | 4 7 | 2.0 | | | | 0 31 | | | ✓ | ✓ | ✓ | | | ✓ | ✓ | ✓ | | | 2 8 | 0 0 |
| COHHTHH32 | 22 8 | 8 3 | | 7.1 | 0 34 | 4.2 | 2 5 | 0 35 | | | | | | ✓ | ✓ | ✓ | ✓ | | ✓ | ✓ | ✓ | ✓ | | 0 12 | 3 9 |
| COHHTHH33 | 22.8 | 8 3 | | 7.1 | 0 34 | 4 2 | 2 5 | 0 35 | | | | | | ✓ | ✓ | ✓ | ✓ | | ✓ | ✓ | ✓ | ✓ | | 1 12 | 3 9 |
| COHHTHH34 | 22 8 | 8 3 | | 7.1 | 0 34 | 4 2 | 2 5 | 0 35 | | | | | | ✓ | ✓ | ✓ | ✓ | | ✓ | ✓ | ✓ | ✓ | | 2 12 | 3 9 |
| COHH42 | 17 8 | | | 9 2 | | 6 0 | 2.0 | | 0.53 | | | | | ✓ | ✓ | ✓ | ✓ | | ✓ | ✓ | ✓ | ✓ | ✓ | 0 43 | 0 0 |
| COHH43 | 17 8 | | | 9 2 | | 6 0 | 2.0 | | 0.53 | | 0 14 | | | ✓ | ✓ | ✓ | ✓ | | ✓ | ✓ | ✓ | ✓ | ✓ | 1 43 | 0 0 |
| COHH44 | 17 8 | | | 9.2 | | 6 0 | 2.0 | | 0 53 | | 1 8 | | | ✓ | ✓ | ✓ | ✓ | | ✓ | ✓ | ✓ | ✓ | ✓ | 2 43 | 0 0 |
| COHHTHH42 | 27 0 | 10 8 | | 9 23 | | 6 0 | 0 94 | | | | | | | ✓ | ✓ | | ✓ | | ✓ | ✓ | ✓ | ✓ | ✓ | 0 0 | 9 1 |
| COHHTHH43 | 28 4 | 10 8 | 1 6 | 6 9 | 1 7 | 3 9 | 3 4 | | | | | | | ✓ | ✓ | ✓ | ✓ | | ✓ | ✓ | ✓ | ✓ | ✓ | 0 70 | 5 8 |
| COHHTHH44 | 28 4 | 10 8 | 1.6 | 6 9 | 1.7 | 3 9 | 3 4 | | | | | | | ✓ | ✓ | ✓ | ✓ | | ✓ | ✓ | ✓ | ✓ | ✓ | 1 70 | 5 8 |

COHH (THH) = Land preparation by hired oxen, the rest by hand (land preparation by hired tractor, the rest by hand).

* Idle land

** Surplus Biomass

**Table AD.2 LP model output showing the variables in the solution and the limiting constraints (✓) OHO(THO)**

| File | Obj value | Variables | | | | | | | | | | *Labour constraints* | | | | | | | | | | | | Land * | Biomass** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 4 | 5 | 7 | 8 | 10 | 11 | 12 | 13 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 18 | 19 |
| OHO22 | 30.2 | | | 19.2 | | 4.9 | | 6.2 | | | 2.6 | | | ✓ | ✓ | | ✓ | | ✓ | | ✓ | | | 0.0 | 13.3 |
| OHO23 | 33.9 | | | 14.9 | | 4.9 | | 6.3 | | | | | | ✓ | ✓ | | ✓ | | ✓ | | ✓ | | ✓ | 0.6 | 11.8 |
| OHO24 | 33.9 | | | 14.9 | | 4.9 | | 6.3 | | | | | | ✓ | ✓ | | ✓ | | ✓ | | ✓ | | ✓ | 1.6 | 11.8 |
| OHOTHO22 | 30.2 | | | 19.2 | | 4.9 | | 6.2 | | | | | | ✓ | ✓ | | ✓ | | ✓ | | ✓ | | | 0.0 | 13.3 |
| OHOTHO23 | 33.9 | 02 | | 14.8 | 8.0 | 4.9 | | 6.3 | | | | | | ✓ | ✓ | | ✓ | | ✓ | | ✓ | | ✓ | 0.6 | 11.8 |
| OHOTHO24 | 33.9 | .02 | | 14.8 | 8.0 | 4.9 | | 6.3 | | | | | | ✓ | ✓ | | ✓ | | ✓ | | ✓ | | ✓ | 1.6 | 11.8 |
| OHO32 | 33.7 | | | 26.2 | | 7.5 | | | | | | | | ✓ | ✓ | | ✓ | | | | ✓ | | | 0.0 | 19.6 |
| OHO33 | 43.0 | | | 26.2 | | 7.6 | | 8.92 | | | 0.30 | | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓ | | | 0.1 | 18.2 |
| OHO34 | 43.0 | | | 26.2 | | 7.6 | | 8.9 | | | 0.3 | | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓ | | | 1.1 | 18.2 |
| OHOTHO32 | 33.9 | 1.1<br>3 | | 26.2 | | 6.6 | | | | | | | | ✓ | ✓ | | ✓ | | | | ✓ | | | 0.0 | 20.0 |
| OHOTHO33 | 44.5 | 2.5 | | 23.7 | 1.7 | 7.6 | | | | | | | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | | 0.0 | 19.0 |
| OHOTHO34 | 47.5 | 8.7 | | 12.8 | 9.4 | 7.6 | | | | | | | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓ | 0.6 | 17.6 |
| OHO42 | 33.7 | | | 26.2 | | 7.5 | | | | | | | | ✓ | ✓ | ✓ | | | ✓ | | | | | 0.0 | 19.6 |
| OHO43 | 44.7 | | | 26.2 | | 9.5 | | 8.9 | | | 0.14 | | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | | | | 0.0 | 19.1 |
| OHO44 | 46.4 | | | 26.2 | | 9.5 | | 8.9 | | | 1.8 | | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | | 0.76 | 17.2 |
| OHOTHO42 | 35 | 8.8 | | 26.2 | | | | | | | | | | ✓ | ✓ | | | | ✓ | ✓ | ✓ | | | 0.0 | 23 |
| OHOTHO43 | 48 | 8.8 | | 26.2 | | 9.5 | | 3.5 | | | | | | ✓ | ✓ | ✓ | ✓ | | ✓ | ✓ | ✓ | | | 0.0 | 26 |
| OHOTHO44 | 53.4 | 8.8 | | 26.2 | | 9.5 | | 8.9 | | | | | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | | 0.49 | 25.3 |

* Idle land

**Surplus Biomass

**Table AD.3 L.P model output showing the variables in the solution and the limiting constraints (✓)**

| File | Obj value | Variables | | | | | | | | | Labour constraints | | | | | | | | | | | | Land * | Biomass** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 4 | 5 | 7 | 8 | 10 | 11 | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 16 | 17 |
| COHO22 | 11.9 | | | 4.9 | | 6.3 | | 0.86 | | | | | | ✓ | | ✓ | | | | | | | 0.95 | 0 0 |
| COHO23 | 11 9 | | | 4.9 | | 6.3 | | 0.86 | | | | | | ✓ | | ✓ | | | | | | | 1.95 | 0.0 |
| COHO24 | 11.9 | | | 4.9 | | 6.3 | | 0.86 | | | | | | ✓ | | ✓ | | | | | | | 2.95 | 0.0 |
| COHOTHO22 | 28 0 | 16 6 | | 4.8 | | 6.3 | | 0.35 | | | ✓ | | | ✓ | | ✓ | | ✓ | | | | | 0.02 | 12.1 |
| COHOTHO23 | 28.0 | 16 6 | | 4 8 | | 6.3 | | 0.35 | | | ✓ | | | ✓ | | ✓ | | ✓ | | | | | 1.02 | 12.1 |
| COHOTHO24 | 28.0 | 16 6 | | 4.8 | | 6 3 | | 0.35 | | | ✓ | | | ✓ | | ✓ | | ✓ | | | | | 2.02 | 12 1 |
| COHO32 | 18 0 | | | 7.6 | | 8 9 | | 1.5 | | | | | ✓ | ✓ | ✓ | ✓ | | | | | | | 0.41 | 0 0 |
| COHO33 | 18.0 | | | 7.6 | | 8.9 | | 1.5 | | | | | ✓ | ✓ | ✓ | ✓ | | | | | | | 1.41 | 0 0 |
| COHO34 | 18 0 | | | 7.6 | | 8 9 | | 1.5 | | | | | ✓ | ✓ | ✓ | ✓ | | | | | | | 2 41 | 0.0 |
| COHOTHO32 | 29 1 | 16 6 | | 7 6 | | 4 9 | | | | | ✓ | | ✓ | ✓ | | | | | | | | | 0 01 | 13 6 |
| COHOTHO33 | 35 5 | 16 6 | | 7.6 | | 8.9 | | 2.4 | | | ✓ | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | | | | 0 28 | 10 5 |
| COHOTHO34 | 35 5 | 16 6 | | 7 6 | | 8 9 | | 2.4 | | | ✓ | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | | | | 1.3 | 10 5 |
| COHO42 | 20 5 | | | 9 5 | | 8 9 | | 2 1 | | | | | ✓ | ✓ | ✓ | ✓ | | | | | | | 0 2 | 0 0 |
| COHO43 | 20 5 | | | 9 5 | | 8 9 | | 2 1 | | | | | ✓ | ✓ | ✓ | ✓ | | | | | | | 1 2 | 0 0 |
| COHO44 | 20 5 | | | 9 5 | | 8 9 | | 2 1 | | | | | ✓ | ✓ | ✓ | ✓ | | | | | | | 2 2 | 0 0 |

* Idle land **Surplus Biomass

COHO (THO) = land preparation and weeding by hired oxen, planting by hand (land preparation by tractor and weeding hired oxen and planting by hand).

Table AD.4 L.P model output showing the solution and the limiting constraints (✓)

| File | Obj value | Variables | | | | | | | | | Labour constraints | | | | | | | | | | | | | | | | | | Land * | Biomass** | comments |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 4 | 5 | 7 | 8 | 10 | 11 | 13 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | | 18 | 19 | |
| NOHO2*4 | 48.8 | 14.7 | 3.8 | 12.0 | | 12.1 | 2.6 | 3.6 | | | | | | ✓ | | ✓ | | ✓ | | ✓ | | | | ✓ | | ✓ | | | 0.0 | 7.3 | |
| NOHO2*3 | 42.6 | 20.2 | | 12.0 | | 10.4 | | | | | | | | ✓ | | ✓ | | | | ✓ | | | | | | | | | 0.0 | 17.0 | |
| NOHO2*2 | 31.6 | 20.2 | | 11.3 | | | | | | | | | | ✓ | | ✓ | | | | ✓ | | | | | | | | | 0.0 | 18.0 | |
| NOHO3*4 | 59.3 | 31.9 | | 19.1 | | 8.3 | | | | | | | | ✓ | | ✓ | | | | ✓ | | | | | | | | | 0.0 | 27.8 | |
| NOHO3*3 | 47.5 | 31.9 | | 15.6 | | | | | | | | | | ✓ | | ✓ | | | | ✓ | | | | | | | | | 0.0 | 27.6 | |
| NOHO3*2 | 33.0 | 31.9 | | 1.1 | | | | | | | | | | ✓ | | | | | | ✓ | | | | | | | | | 0.0 | 22.5 | |
| NOHO4*4 | 63.25 | 41.5 | | 21.75 | | | | | | | | | | ✓ | | | | | | ✓ | | | | | | | | | 0.0 | 36.4 | |
| NOHO4*3 | 48.75 | 41.5 | | 7.5 | | | | | | | | | | ✓ | | | | | | ✓ | | | | | | | | | 0.0 | 31.3 | |
| NOHO4*2 | 33.2 | 33.2 | | | | | | | | | | | | | | | | | | | | | | | | | | | 0.0 | 23.0 | |

Obj= Maximum productivity in quintals *Idle land in ha **Surplus Biomass in quintals

NOHO = Owned new ADP equipment for land preparation and weeding

**(OHOTHOE- energy use)**

| File | Obj values. | Variables | | | | | | | | | Labour constraints. | | | | | | | | | | | | * ha | ** qu | *** qu |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | GJ | 1 | 2 | 4 | 5 | 7 | 8 | 10 | 11 | 13 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | | | |
| OHOTE4*2 | 2.58 | | | 1.85 | | 0.73 | | | | | | | ✓ | ✓ | ✓ | ✓ | | ✓ | | | | | 0.18 | 16.7 | 30 |
| OHOTE4*2 | 3.50 | 0.71 | | 2.35 | | 0.44 | | | | | | | ✓ | ✓ | | | | ✓ | | | | | 0.0 | 20.4 | 34 |
| OHOTE4*3 | 4.18 | 0.20 | | 2.35 | | 0.73 | | 0.90 | | | | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | | | | 0.0 | 19.6 | 45 |
| OHOTE4*3 | 6.0 | 2.50 | | 2.35 | | 0.73 | | 0.45 | | | | | ✓ | ✓ | ✓ | ✓ | | ✓ | ✓ | ✓ | | | 0.0 | 25.0 | 47.5 |
| OHOTE4*4 | 6.79 | 2.80 | | 2.35 | | 0.73 | | 0.92 | | 0.015 | | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | | 0.50 | 24.9 | 53 |
| OHOTE3*2 | 2.87 | | | 2.28 | | 0.58 | | | | | | | ✓ | ✓ | ✓ | ✓ | | | | ✓ | | | 0.4 | 19.1 | 33 |
| OHOTE3*2 | 3.12 | 0.24 4 | | 2.35 | | 0.53 | | | | | | | ✓ | ✓ | ✓ | ✓ | | | | ✓ | | | 0.0 | 19.9 | 33.8 |
| OHOTE3*3 | 4.36 | 0.50 | | 2.29 | 0.06 | 0.58 | | 0.92 | | | | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓ | | | 0.6 | 19.2 | 44.0 |
| OHOTE3*3 | 4.64 | 0.78 | | 2.16 | 0.2 | 0.58 | | 0.92 | | | | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | | 0.01 | 6.87 | 44.4 |
| OHOTE3*4 | 6.48 | 2.5 | | 1.31 | 1.08 | 0.58 | | 0.92 | | | | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | | 0.69 | 17.8 | 47.4 |

Obj = energy in MJ

* Idle land

** Surplus biomass

*** Production in quintals

Table AD.6 L.P model objective function value, activities in the solution and the limiting constraints (✓)

| File | Obj value | Variables | | | | | | | | | Labour constraints | | | | | | | | | | | | | | | | | | * | ** | *** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | | | | | | | | | | | | | | | | | | ha | Qu | qu |
| | GJ | 1 | 2 | 4 | 5 | 7 | 8 | 10 | 11 | 13 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | | | | |
| NCOHOTE2*2 | 5.91 | 5.43 | | 0.37 | | 0.11 | | | | 0.68 | | | | | | ✓ | | | | | | | | | | | | +0.68 | 0.0 | 14.4 | 30.0 |
| NCOHOTE2*3 | 6.56 | 5.63 | | 0.37 | | 0.53 | | 0.01 | | 0.398 | | | | | | ✓ | | | | | | | | ✓ | | | | +0.40 | 0.0 | 13.4 | 41.0 |
| NCOHOTE2*4 | 7.06 | 5.69 | | 0.37 | | 0.54 | | 0.42 | 0.04 | 0.324 | | | | | | ✓ | | | | | | | | ✓ | | ✓ | | | 0.0 | 5.54 | 48.2 |
| | | | | | | | | | | | | | | | | | | | | | | | | | | | | +0.324 | | | |
| NCOHOTE3*2 | 5.07 | 4.52 | | 0.56 | | | | | | | | | | | | ✓ | | | | | | | | | | | | +0.190 | 0.0 | 15.1 | 30.6 |
| NCOHOTE3*3 | 6..31 | 5.37 | | 0.59 | | 0.35 | | | | 0.76 | | | | | | ✓ | | | | | | | | | | | | +0.76 | 0.0 | 16.1 | 42.6 |
| NCOHOTE3*4 | 6.94 | 5.56 | | 0.59 | | 0.76 | | 0.02 | | 0.49 | | | | | | | | | | | | | | ✓ | | | | +0.49 | 0.0 | 14.9 | |
| | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| NCOHOTE4*2 | 5.07 | 4.52 | | 0.56 | | | | | | 1.90 | | | | | | | | | | | | | | | | | | | 0.0 | 15.1 | 30.6 |
| NCOHOTE4*3 | 6.35 | 5.41 | | 0.81 | | 0.13 | | | | 0.698 | | | | | ✓ | ✓ | | | | | | | | | | | | +0.698 | 0.0 | 19.3 | 44.4 |
| NCOHOTE4*4 | 6.80 | 5.41 | | 0.81 | | 0.58 | | | | 0.698 | | | | | ✓ | ✓ | | | | | | | | | | | | +0.698 | 0.0 | 18.0 | 53.3 |

Obj = energy in MJ

* Idle land

** surplus biomass

*** Productivity in quintals

NCOHOTHOE= New ADP equipment hired for land preparation and weeding plus tractor hire for land preparation only.

**Table AD.7 L.P model objective function value, activities in the solution and the limiting constraints (✓)**

| FPE | Obj | Variables | | | | | | | | | Labour constraints | | | | | | | | | | | | | | | | | * ha | ** qu |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | | |
| NCOHO2*4 | 27.6 | YK D | | 12.0 | | 13.0 | | 2.5 | | | | | | | | ✓ | | | | | | | | ✓ | | | | 1.6 | 0.0 |
| NCOHO2*3 | 27.6 | - | | 12.0 | | 13.0 | | 2.5 | | | | | | | | ✓ | | | | | | | | ✓ | | | | 0.6 | 0.0 |
| NCOHO2*2 | 24.8 | YK D | | 12.0 | | 12.8 | | | | | | | | | | ✓ | | | | | | | | ✓ | | | | 0.0 | 2.71 |
| NCOHO3*4 | 41.8 | - | | 19.1 | | 18.4 | | 4.2 | | | | | | | | ✓ | | | | | | | | ✓ | | | | 0.4 | 0.0 |
| NCOHO3*3 | 37.4 | YK D | | 19.1 | | 18.3 | | | | | | | | | | ✓ | | | | | | | | ✓ | | | | 0.0 | 4.5 |
| NCOHO3*2 | 26.5 | - | | 19.1 | | 7.4 | | | | | | | | | | ✓ | | | | | | | | | | | | 0.0 | 5.8 |
| NCOHOTHO3*4 | 54.0 | 16.6 | | 19.1 | | 18.3 | | | | | ✓ | | | | | ✓ | | | | | | | | ✓ | | | | 0.0 | 18.0 |
| NCOHOTHO3*3 | 43.1 | 16.6 | | 19.1 | | 7.4 | | | | | ✓ | | | | | ✓ | | | | | | | | | | | | 0.0 | 17.3 |
| NCOHOTHO3*2 | 31.1 | 16.6 | | 14.5 | | | | | | | ✓ | | | | | ✓ | | | | | | | | | | | | 0.0 | 16.6 |
| NCOHOT4*4 | 50.1 | | | 26.2 | | 23.9 | | 0.02 | | | | | | | ✓ | ✓ | | | | | | | | ✓ | | | | 0.0 | 6.3 |
| NCOHOT4*3 | 39.2 | | | 26.2 | | 13.0 | | | | | | | | | ✓ | ✓ | | | | | | | | | | | | 0.0 | 7.65 |
| NCOHOT4*2 | 28.3 | | | 26.2 | | 2.10 | | | | | | | | | ✓ | ✓ | | | | | | | | | | | | 0.0 | 8.95 |
| NCOHOT3*4 | 55.8 | 16.6 | | 26.2 | | 13.02 | | | | | ✓ | | | | ✓ | ✓ | | | | | | | | | | | | 0.0 | 19.15 |
| NCOHOT3*3 | 44.9 | 16.6 | | 26.2 | | 2.1 | | | | | ✓ | | | | ✓ | ✓ | | | | | | | | | | | | 0.0 | 20.45 |
| NCOHOT3*2 | 31.1 | 16.6 | | 14.5 | | | | | | | ✓ | | | | | | | | | | | | | | | | | 0.0 | 16.6 |
| NCOHOT2*4 | 48.7 | 16.6 | | 12.0 | | 13.0 | | 7.0 | 0.1 | | ✓ | | | | | ✓ | | | | | | | | ✓ | ✓ | | | 0.0 | 6.54 |
| NCOHOT2*3 | 41.4 | 16.6 | | 12.0 | | 12.8 | | | | | ✓ | | | | | ✓ | | | | | | | | ✓ | | | | 0.0 | 14.2 |
| NCOHOT2*2 | 30.5 | 16.6 | | 12.0 | | 1.86 | | | | | ✓ | | | | | ✓ | | | | | | | | | | | | 0.0 | 15.5 |

Obj = Maximum productivity in quintals; * idle land; ** surplus biomass.

## Appendix E Tillage equipment specifications

### *A.E.1 Specifications for Tillage Equipment*

In order to meet the requirements for land preparation, timely planting and weeding as discussed in chapter four above, the following three attachments are necessary:

- Chisel share and standard
- A-shares and standard
- Desi plough body and standard

The three attachments are alternatively mounted on a modified Sine Hoe type tool bar with appropriate clamps. However, the soil strength and operating conditions such as density, shear strength and depth are different from place to place. It is therefore necessary to stipulate the design criteria for each set of soil conditions such as those prevailing at Katumani. The basic information for soil conditions at the test site are given below.

For chisel share and standard the design criteria were developed by Bernacki *et al.* (1972, p. 359). Figure AE1 show the main force (F) acting on chisel share.

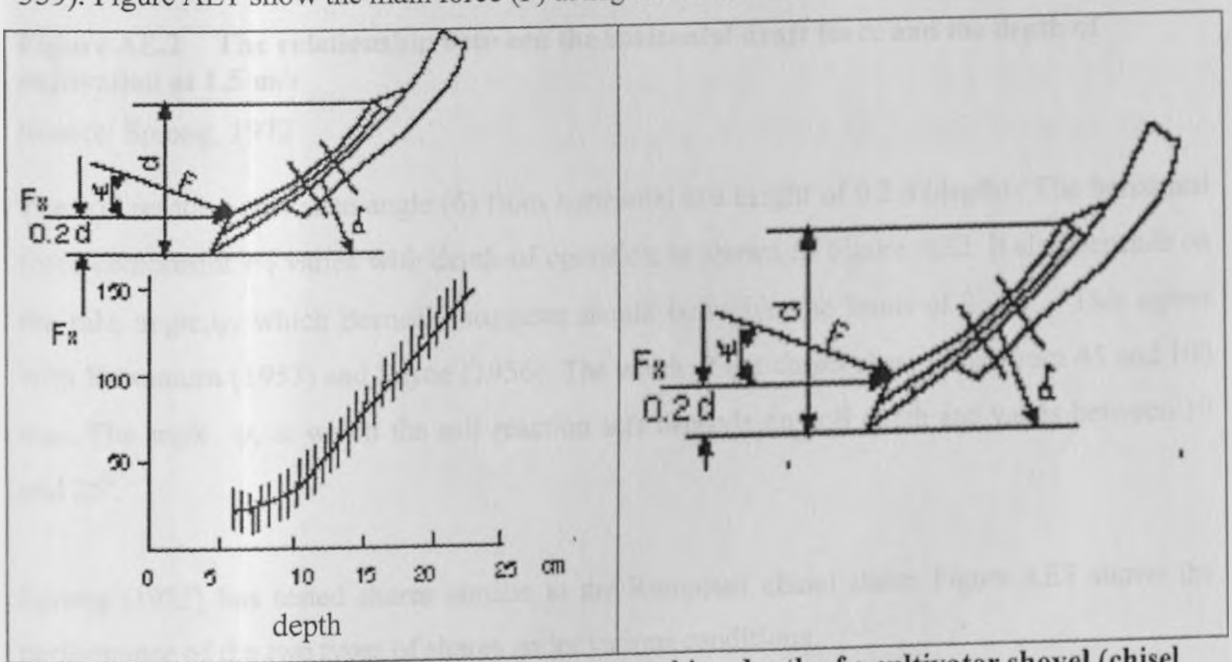



**Figure AE.1 Dependence of soil resistance on working depth of a cultivator shovel (chisel share)**

Source: Bernacki *et al*, 1972

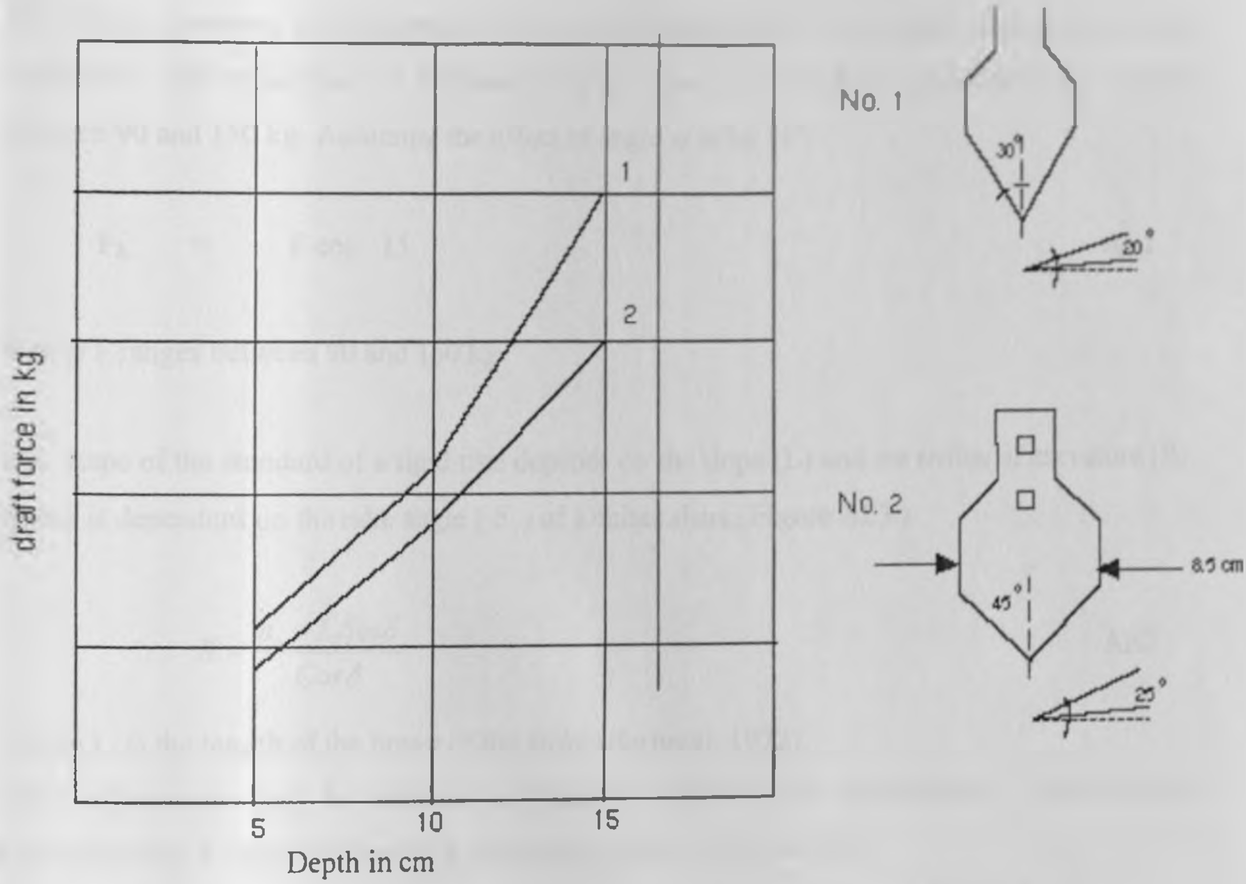



**Figure AE.2 The relationship between the horizontal draft force and the depth of cultivation at 1.5 m/s**

Source: Sprong, 1972

The soil reaction acts at an angle (δ) from horizontal at a height of 0.2 d (depth). The horizontal force component $F_X$ varies with depth of operation as shown in Figure AE2. It also depends on the rake angle,ψ, which Bernacki suggests should be within the limits of $20\text{-}45^0$. This agrees with Kawamura (1953) and Payne (1956). The width of the chisel share varies from 45 and 100 mm. The angle, ψ, at which the soil reaction acts depends on soil depth and varies between 10 and 25°.

Sprong (1972) has tested shares similar to the Rumpstad chisel share. Figure AE2 shows the performance of the two types of shares under various conditions.

The relation between the horizontal draft and operating depth is very much dependent on soil conditions. The experience at Katumani shows that the total draft requirement (F) ranges between 90 and 150 kg. Assuming the effect of angle $\psi$ to be $15^0$,

$$F_X = F \cos.\ 15 \qquad \text{AE1}$$

Where F ranges between 90 and 150 kg

The shape of the standard of a rigid tine depends on the slope (L) and the radius of curvature (R) which is dependant on the rake angle ( $\delta$ ) of a chisel share (Figure AE3.).

$$R = \frac{h_o - L_1 Sin\delta}{Cos\delta} \qquad \text{AE2}$$

Where $L_l$ is the length of the breast of the share (Bernacki, 1972).
Other dimensions may be selected according to the tool bar requirements. The relevant dimensions for Rumpstad chisel and standard are given in Figure AE3.

The standard of the tine is exposed first of all to a bending moment arising from soil resistance. For calculation purposes it may be assumed that the soil resistance is entirely horizontal. The calculation resistance is also assumed to be 3-5 times higher than the average horizontal resistance $F_X$. Shock loads that may occur when the share comes against a rock or root may make this safety factor justified. For our purpose safety factor of 5 was used to calculate the maximum resistance given by:

$$F_{max} = 5 * \frac{(90+150)}{2} = 600kg \qquad \text{AE3}$$

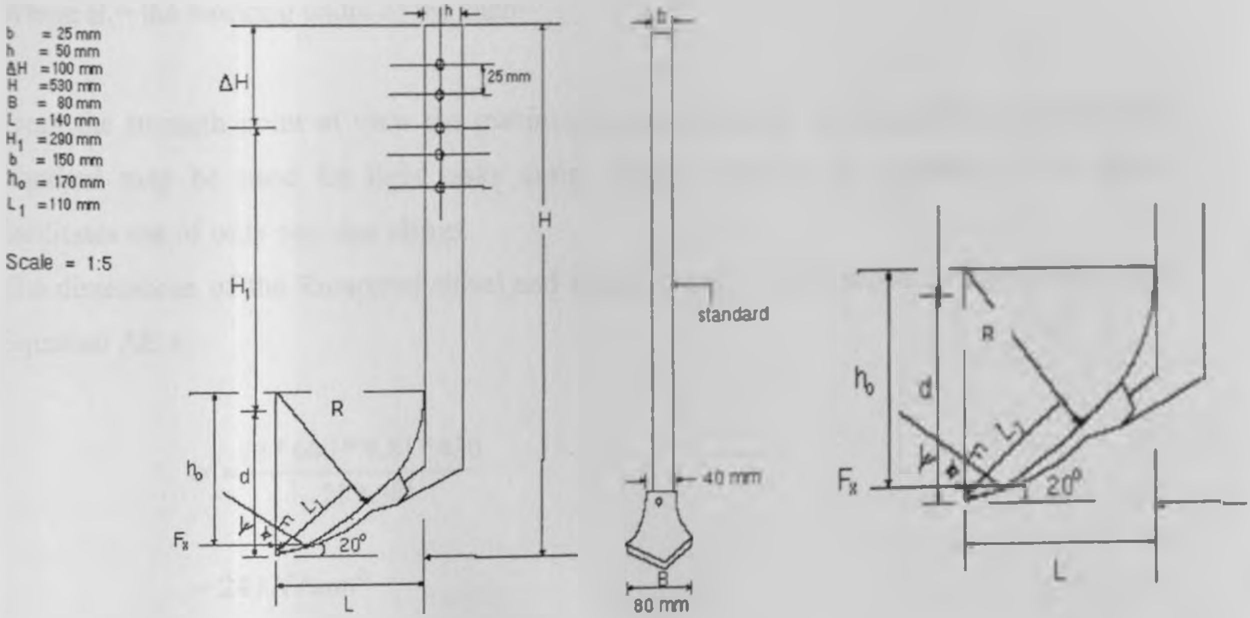



**Figure AE.3 Rumpstad chisel share and standard**

The stress experienced at the point of maximum bending moment is given by:

$$\sigma = \frac{M}{Z} = 6\frac{F_{max}(H_1 + d)}{bh^2} \qquad \text{AE4}$$

Where:

| | | |
|---|---|---|
| σ | = | allowed stress |
| M | = | maximum bending moment |
| Z | = | section modulus |
| $H_l$ | = | effective length of the standard above ground |
| d | = | operating depth |

The torsion stress is calculated according to the formula:

$$T = \frac{T}{Z_0} = \frac{9F_{max}\frac{B}{4}}{2b^2h} \qquad \text{AE5}$$

Where B = the working width of the share

From the strength point of view the maximum stress will arise during chiselling and the same standard may be used for light tasks during furrow opening and weeding. This practice facilitates use of only one size clamp.

The dimensions of the Rumpstad chisel and standard assembly are shown in figure AE3. Using Equation AE.4;

$$\sigma = \frac{6 * 600 * 9.81 * 430}{25 * 50^2}$$

$$= 243 N / mm^2$$

For

H1 = 280mm; h = 50mm; b = 25mm;

D = 150mm; B = 80mm;

And using equation AE.5,

$$\sigma = \frac{9 * 600 * 9.81 * 80}{2 * 50 * 25^2 * 4}$$

$$= 17.0 N / mm^2$$

The stresses are well within $332 N/mm^2$ allowed for mild steel. Section size can be reduced if better quality steel is used although the extra weight of the standard is desirable for penetration. The optimum choice is a compromise between the cost and extra weight. Different specifications may also be made for light, medium and heavy soil conditions.

# Appendix F: Tillage Implements

Several pieces of tillage equipment were tested under field conditions to evaluate their effective field capacity, depth of tillage, draught requirement and surface roughness to control runoff. They include: mouldboard plough (Figure AF1), chisel shares (Figure AF2 & AF3, A – shares (Figure AF4), Desi plough (Figures AF5 and AF6). Desi plough is a modification of the traditional Indian Ard. All the above tools were mounted on Sine Hoe tool bar as shown in Figure AF8.

### *A.F.1. Mouldboard Plough*

The mouldboard plough, although a complex tool, is universally so well known that only brief description is given here. It is a warped surface to which cutting edge known as the share is attached (Figure AF1)

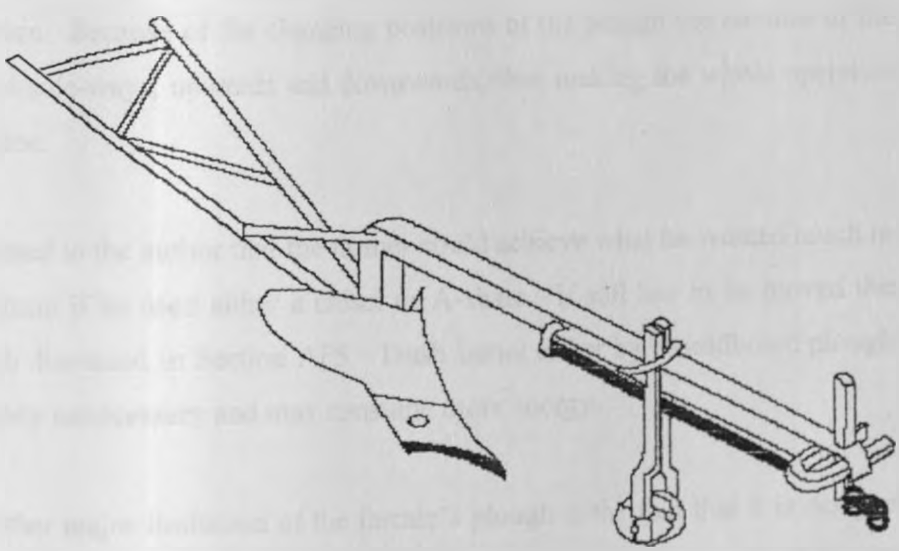


**Figure AF.1 Traditional mouldboard (Victory) plough used by farmers**

The frog connects the share, mouldboard and the landside. It is usually connected to the tool frame, which is a combined vertical and horizontal beam. The tool is used basically for burying the trash so that the weeds seeds emergence is handicapped while the trash rots well to form humus. Because of the soil movement involved in turning over the furrow slice the mouldboard plough is essentially a soil pulveriser. Under stable operating conditions, the share point and the heel of the landside touch the furrow bottom. The third point of support is the land wheel. The landside slides along the furrow wall and thus absorbs the side forces generated by the side movement of the furrow slice. Ideally a well adjusted mouldboard plough should not require more than a light touch to guide the implement. The pull force through the chain is directed in such a way as to be equal to the resultant of soil reaction and gravitational forces.

The farmer's plough is not used according to the design requirements, because it is rarely well adjusted and the share is often worn out. To make matters worse the soil conditions are rarely ideal for ploughing due to surface crusting. More often than not, the plough is used with the share and landside lifted up so that the share point approaches the soil in the same way as the chisel or A-share. When the penetration is achieved the landside is lowered to produce a soil lifting action. In the meantime the whole tool has moved forward and it is too late for the mouldboard to turn the trash under. Often the furrow slice breaks up too early due to low soil moisture. Because of the changing positions of the plough the handles of the plough have to be moved side-ways, upwards and downwards, thus making the whole operation very unstable and tiresome.

It seemed to the author that the farmer could achieve what he wanted much more easily and with less strain if he used either a chisel or A-share. If soil has to be moved then perhaps the Desi plough discussed in Section AF5. Trash burial either by mouldboard plough or ridging body is probably unnecessary and may consume more energy.

The other major limitation of the farmer's plough is the fact that it is designed for one function, primary tillage with trash burial. Yet farmers have to prepare seedbed, plant and weed. For lack of alternative equipment the farmer is obliged to use the same tool, *al bait* inefficiently, for the secondary tillage operations.

### *A.F.2. Chisel share*

The chisel share is usually a narrow double pointed blade. Figures AF2 and AF3 show the two types of chisel shares Rumpstad and Ariana respectfully; each assembled on a standard. One, two or three chisel assemblies may be mounted on a tool bar. It is used for loosening the soil at a depth without undue surface disturbance or trash burial. The depth/width ratio is usually greater than 2 and according to Payne (1956) the chisel used in these experiments may be classified as a narrow tine. The rake angle of about $40^0$ for the Ariana chisel share was highest permissible for low draft. Being a narrow tool it easily penetrates the soil surface crust. In the case of Rumpstad chisel the depth/width ration was just under 2.0 and can be considered a borderline case between narrow and wide tools. The rake angle of $20^0$ is near optimum value for low draft (Kawamura, 1953; Sohne, 1956).

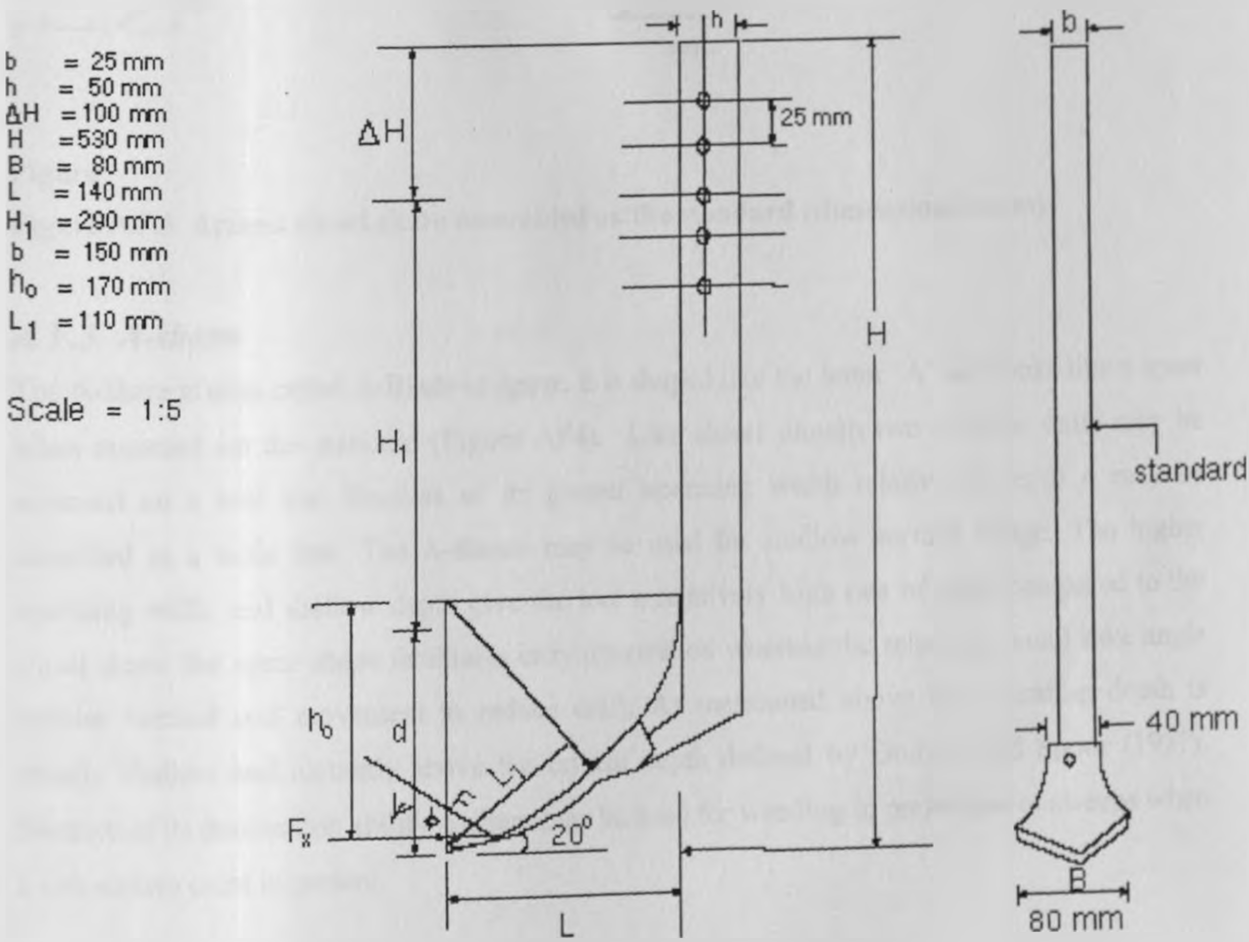
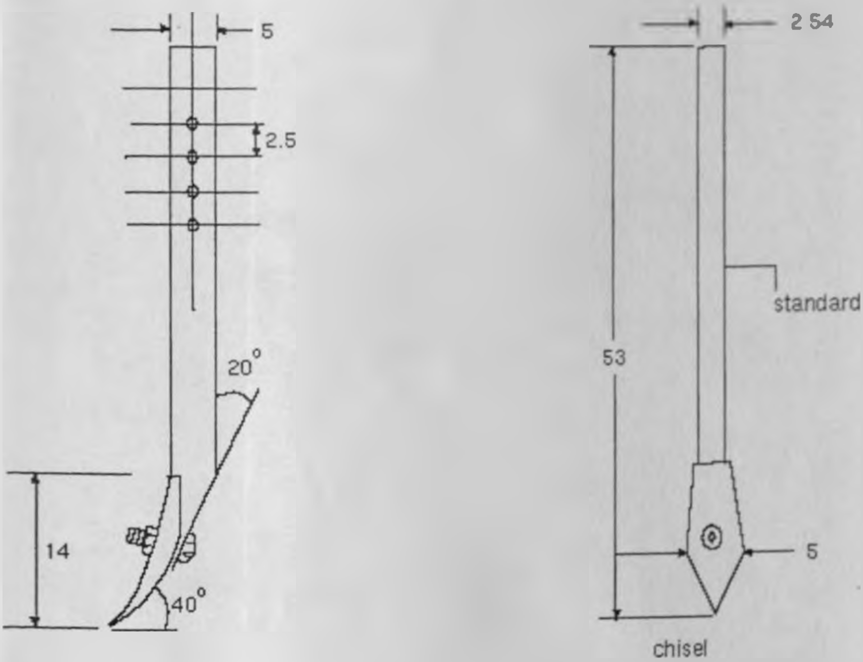



**Figure AF.2 Rumpstad chisel share and standard**




**Figure**

**Figure AF.3 Ariana chisel share assembled on the standard (dimensions in cm)**

## *A.F.3. A-share*

The A-share is also called A-Blade or spear. It is shaped like the letter 'A' and looks like a spear when mounted on the standard (Figure AF4). Like chisel plough two or three units may be mounted on a tool bar. Because of its greater operating width relative to depth it may be classified as a wide tine. The A-shares may be used for shallow surface tillage. The higher operating width and shallow depth give the tool a relatively high rate of work compared to the chisel share; the spear shape facilitates easy penetration whereas the relatively small rake angle enables vertical soil movement to reduce draft. As mentioned above the operating depth is usually shallow and certainly above the critical depth defined by Godwin and Spoor (1977). Because of its penetration ability A-share may be used for weeding in preference to sweeps when a soil surface crust is present.

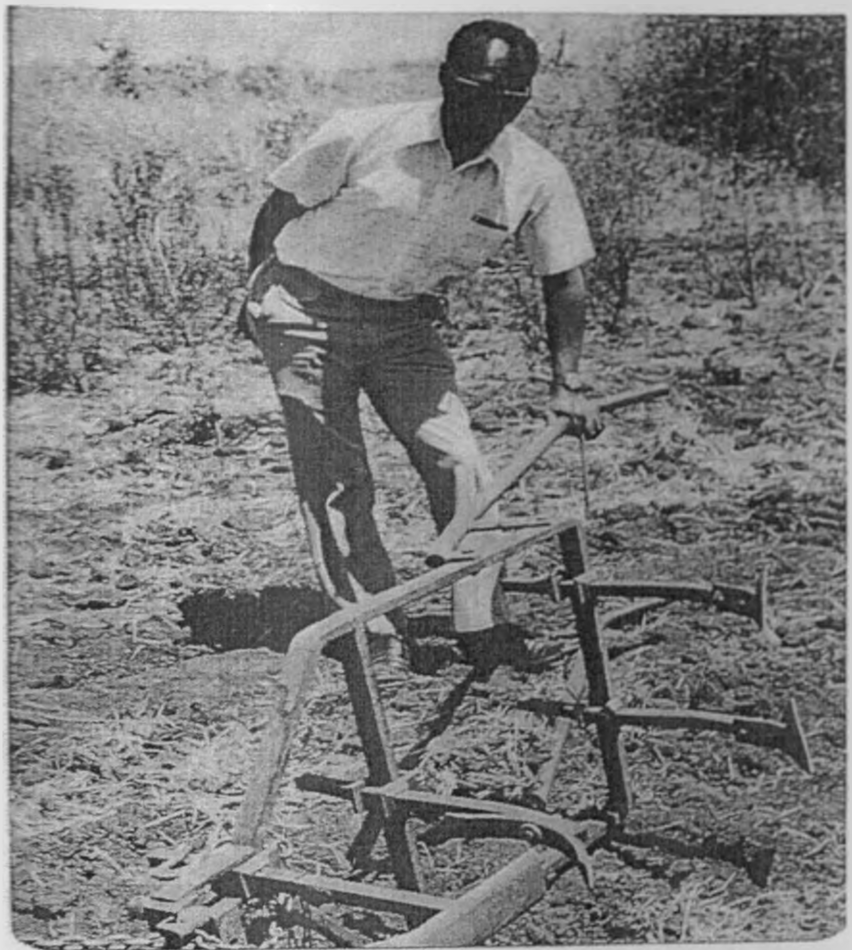


**Figure AF.4 Two A-shares in the rear and one chisel in the front mounted on the Ariana tool bar**

In order to stagger the A-share standard assemblies two units are mounted behind one front unit. For primary tillage experiments the front A-share was replaced by a chisel share to gain penetration under hard dry conditions prevailing before the rains.

### *A.F.4. Sweeps*

The sweep is very similar to an A-share although the shape is more like a duck foot. Mounted on the standard the rake angle is much smaller than that for a chisel or an A-share. Its depth/width ratio is also high and fits well in to the wide tool classification. Its main use is for surface cultivation at a very shallow depth (less than 5cm) primarily for weeding.

### *A.F.5. Desi plough*

The Indian Desi plough was discussed in Section 2.1. Krishseva Company of Gujarati in India manufactures the model used for these experiments. It is a metal construction mounted on a multi-purpose tool bar to which other attachments such as mouldboard plough, bund former, weeding attachment, etc., can be mounted. The tool bar is connected to the harness by means of a long pole.

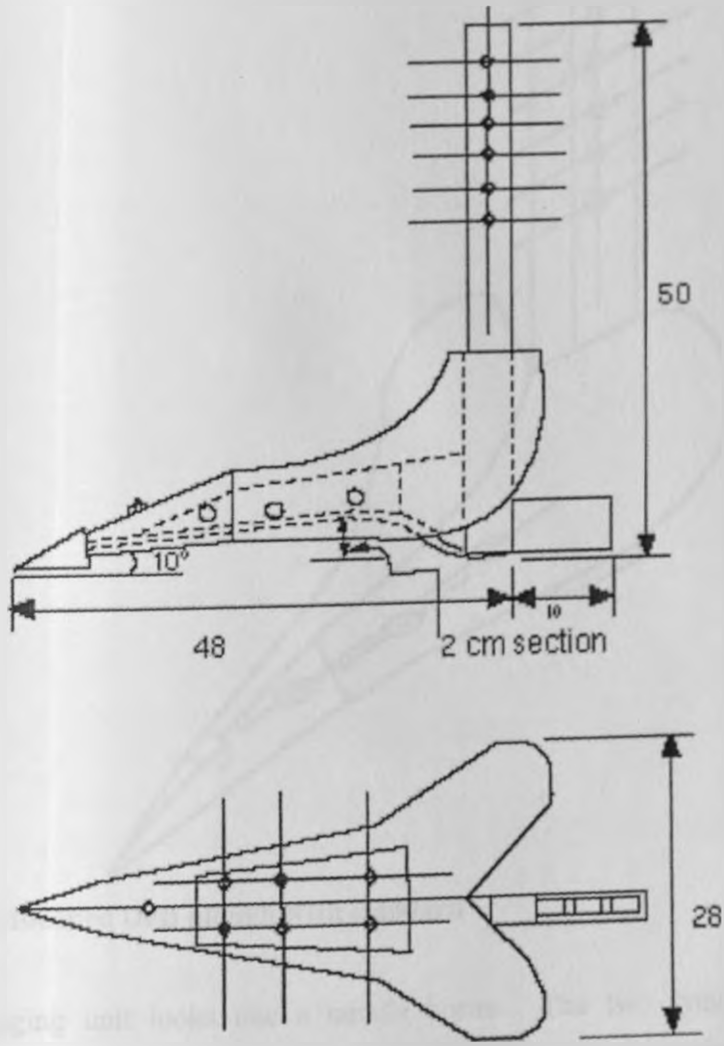



**Figure AF.5 Modified Desi plough (dimensions in cm)**

Because of soil conditions heavier than those for which it was designed, a stronger standard was made. Poor penetration under Katumani conditions necessitated reconstruction to increase the suction (Figures AF5 and Figures AF6). Metal construction facilitates the provision for a detachable long bar point made of mild steel surface welded with cast steel to increase hardness and reduce wear.

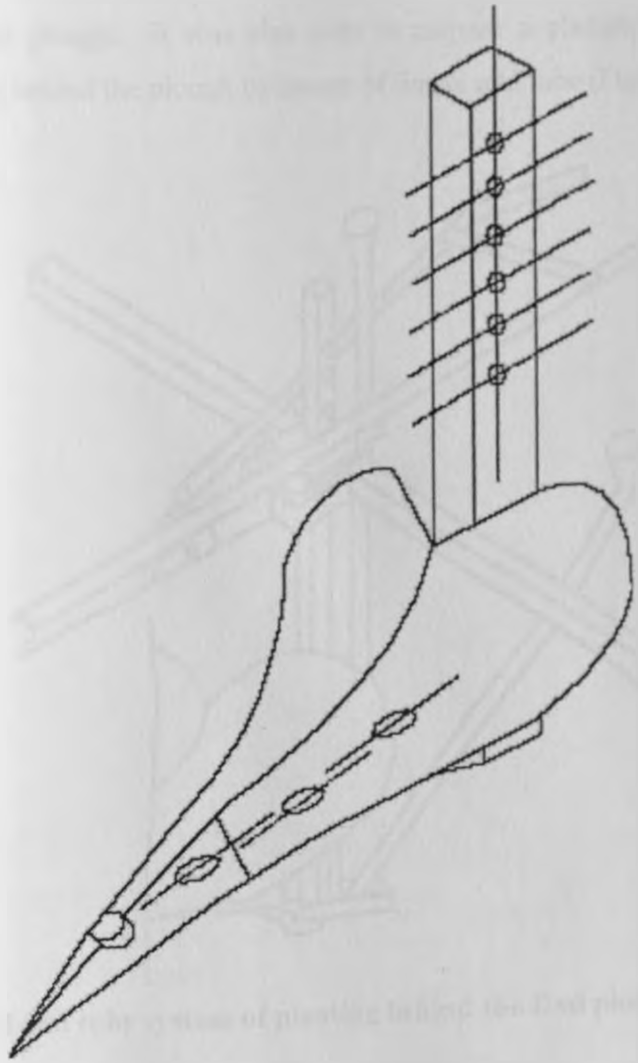


**Figure AF.6 Modified Desi plough with standard**

The soil engaging unit looks like a middle buster. The two symmetrical wings are not sufficiently pronounced to turn over the furrow slice like the mouldboard plough or the ridging body. However a clean furrow is produced and some soil is lifted to the surface inevitably burying a minimum amount of trash. In India and the Middle East, it is used for primary and secondary tillage. Four or five runs are done before planting. In this case soil is loosened at a shallow depth while trash if any, is mixed with the soil on the surface. At the same time weeds are kept down.

In these experiments the Desi plough was also used as a primary and secondary tillage tool but with only one run. The need for more than one run was eliminated by the use of the chisel share operations before Desi plough. It was also used to prepare a planting furrow. Seeds and fertilizer were dropped behind the plough by means of funnel and tube (Figure AF7).

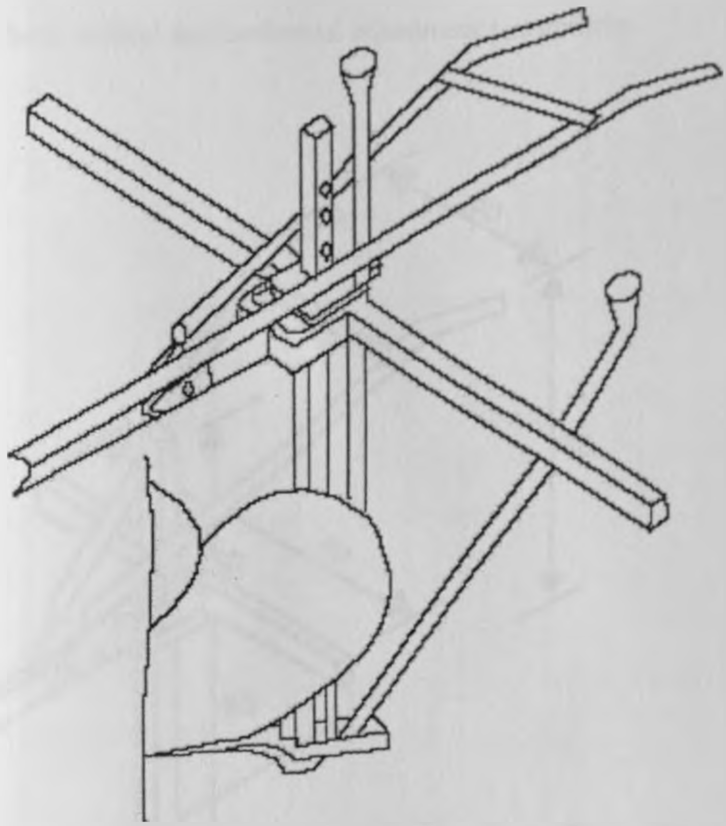


**Figure AF.7 Funnel and tube system of planting behind the Desi plough**

### *A.F.6. Tool Bars*

The Sine Hoe is very similar to the Ariana tool bar and can accept virtually all the attachments designed for the Ariana too bar (Figure AF9). The main difference is in simplicity and cost. The Sine Hoe is simply a T-frame with a skid or wheel support and on which various attachments can be mounted (Figure AF6). Simplicity is substituted for stability since the tool is a light T- frame whereas Ariana is a heavier rectangular frame. Human hands are continuously needed to stabilize the tool bar especially when only two supports (front and rear) are available. For unskilled operator the need to closely guide the implement may be of great advantage under non-uniform soil conditions. The cost of a simpler tool has an over-riding advantage.

The Ariana tool bar is a rectangular frame supported on skids or wheels to which various attachments namely: mouldboard, ridging body, chisel and sweeps, etc. can be mounted (Figure AF9). It is a stable design and on flat land, a well-adjusted tool can move without the human hand guiding it. It has both vertical and horizontal adjustment possibilities.

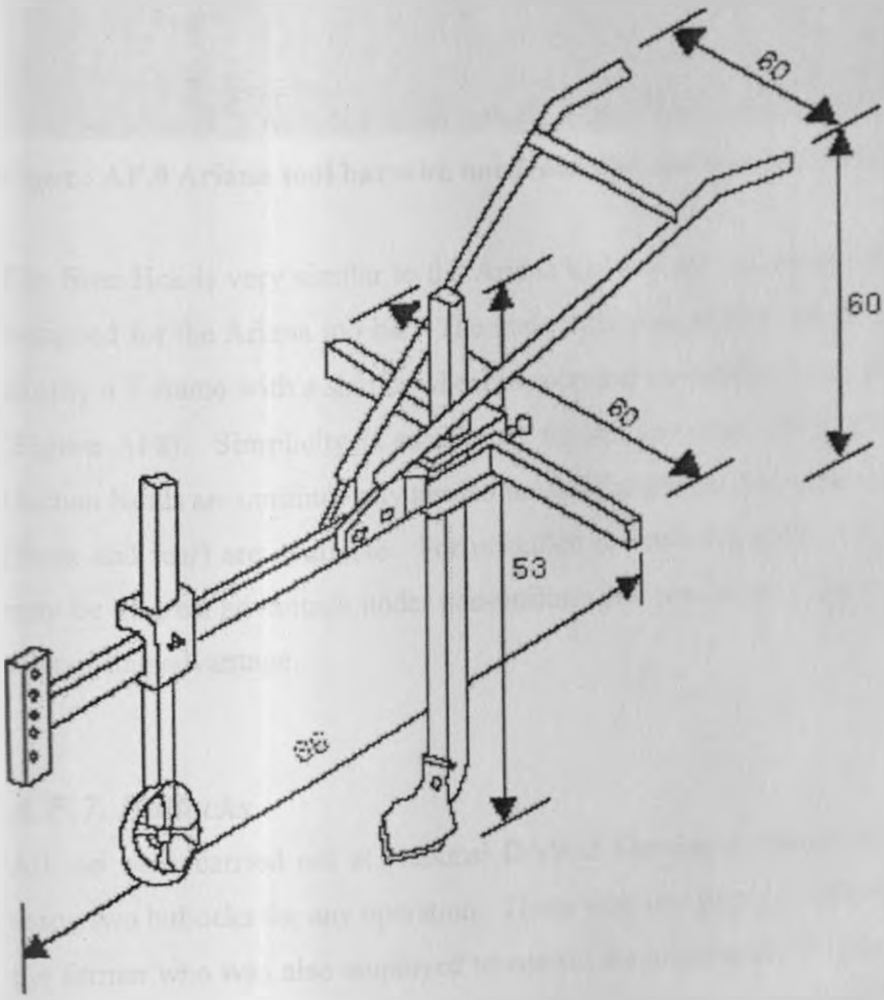



**Figure AF.8 Sine hoe assembly, share and standard (dimensions in cm)**

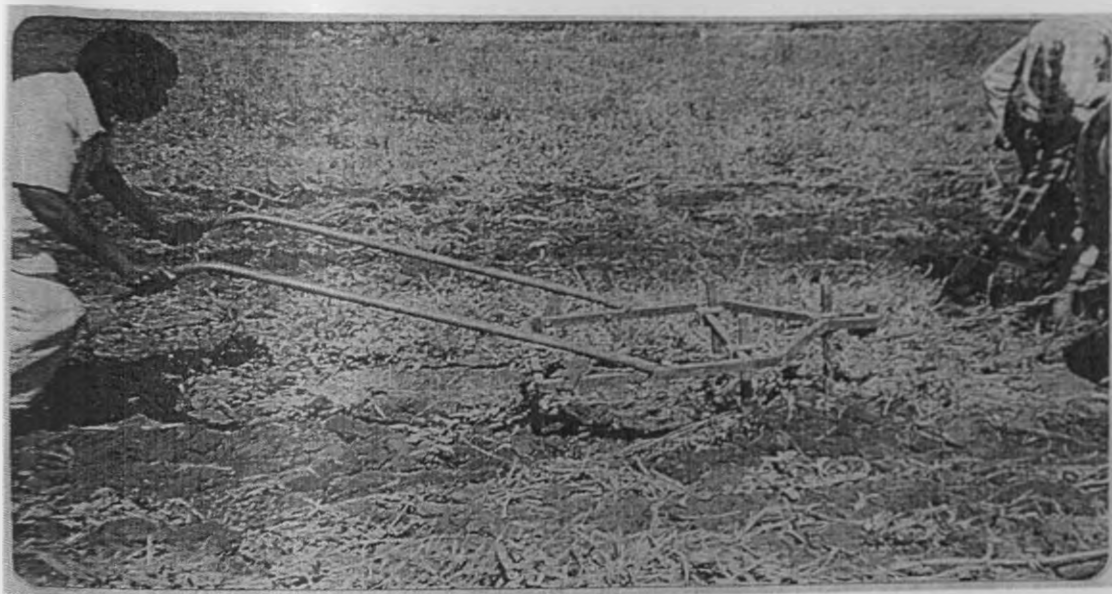


**Figure AF.9 Ariana tool bar with one front skid and 3 standards and shares mounted on it**

The Sine Hoe is very similar to the Ariana tool bar and can accept virtually all the attachments designed for the Ariana too bar. The main difference is in simplicity and cost. The Sine hoe is simply a T-frame with a skid or wheel support and on which various attachments can be mounted (Figure AF8). Simplicity is substituted for stability since the tool has only one rear support. Human hands are continuously needed to stabilize the tool bar especially when only two supports (front and rear) are available. For unskilled operator the need to closely guide the implement may be of great advantage under non-uniform soil conditions. The cost of a simpler tool has an over-riding advantage.

### *A.F.7. Bullocks*

All the work carried out at National Dryland Farming Research Station, Katumani, was done using two bullocks for any operation. There were two pairs of bullocks: the first pair belonged to the farmer who was also employed to control the implements (Figure AF10). The two bullocks together weighed 387 kgf. Each of the oxen about 7-8 years old was considered satisfactory by farmer's standards. They were later purchased from the farmer for the research project.

The second pair belonged to the Faculty of Agriculture, University of Nairobi, Kabete Campus and was transferred to Katumani Station when necessary (Figure AF11). Each ox weighed 390

Kgi. Because of better training, feeding and health care they were able to sustain a greater load than the farmer's oxen.

An important difference between the two pairs of oxen was in their training and control. In the traditional training given by the farmers the bullocks are made to respond to simple words like 'go', 'stop', 'turn', etc. By experience they learn to accept the yoke and to sustain a certain amount of draft at relatively constant speed. They are easily upset by excessive draft requirement. A whip is used to increase response.

The Kabete pair had also received the traditional training but they were later trained in the Indian Method of bullock control. A hole was broken in the nose (Figure AF.10) and a nylon rope passed through and knotted around the head. When yoked each bullock has a rein tied to the nylon rope and long enough to be held by the operator behind the bullocks.

**Figure AF.10 Farmer's bullocks being controlled by him while opening furrow with disc plough mounted on Sine Hoe**

**Figure AF.11 Faculty of agriculture bullocks showing the nylon rope passing through the nose**

The bullocks are trained to respond to the movement of the reins as follows:

- Go when the reigns are relaxed and 'go' order given
- Stop when the rein are pulled back
- Turn right or left when the reins are pulled accordingly

Although light whipping was used it is usually unnecessary with well-trained bullocks. In both cases the bullocks' mouths were muzzled during weeding to bar them from eating the crops.

## Appendix G: Evaluation of furrow effectiveness in run off control

In this section the furrows being produced by the Desi plough were evaluated in terms of their effectiveness in controlling surface runoff likely to arise out of excess water produced by rainfall intensities with return period of 5 and 10 years. Two methods are applied in predicting the likely runoff. In the first method, the amount received in certain durations less the amount that would infiltrate, estimated by basic infiltration rate, gave the resulting surface runoff. In the second method, the runoff is estimated from observed rainfall simulator data. Table AG1 shows the rainfall amounts for various durations at Machakos dam near Katumani which were used for the first method of runoff estimation.

**Table AG.1 Rainfall in mm for Machakos dam for various durations in 5 to 10 year return periods**

| Return period | 15 min. | 30 min. | 60 min. | 180 min |
|---|---|---|---|---|
| 5 years | 23 | 33 | 46 | 71 |
| 10 years | 26 | 36 | 55 | 84 |

*Source: Taylor and Lawes (1971). Rainfall intensity- duration - frequency data for stations in east Africa, E. A. Met. Dept. Tech. Memoir No. 17*

Table AG2 shows the amount of runoff calculated using an estimated basic infiltration rate of 20 mm per hour (Kijne, 1980). The runoff is obtained by subtracting infiltration from rainfall. For the furrow spacing of 90 cm the expected volume of runoff per metre length of furrow per mm of rainfall given by

$$(1/1000) \text{ m} \times 0.9 \text{ m} \times 1 \text{ m} = 0.0009 \text{ m}^3/\text{m}$$

$$= 0.9 \text{ litres/m of furrow length}$$

This factor is used to translate runoff in mm into runoff in litres per metre of furrow length given in column 5 of Table AG2.

**Table AG.2 Estimated runoff for various rainfall duration in 10 and 5 year return periods**

| | | 10 year return period | | |
|---|---|---|---|---|
| Rainfall duration (min) | Rainfall amount (mm) | Infiltration (mm) | Runoff (mm) | Runoff in litres /metre of furrow length |
| 15 | 26 | 5 | 21 | 18.9 |
| 30 | 39 | 10 | 29 | 26.1 |
| 60 | 55 | 20 | 35 | 31.5 |
| | | 5 year return period | | |
| 15 | 23 | 5 | 18 | 16.2 |
| 30 | 33 | 10 | 23 | 20.7 |
| 60 | 46 | 20 | 26 | 23.4 |

Note: The infiltration rate used is 20 mm/hr which is what would occur when the rain falls and the soil is saturated and would contribute to the highest runoffs (columns 4 and 5)

**Table AG.3 Rainfall intensity, duration and frequency for Machakos dam**

| 10 year return period | |
|---|---|
| Rainfall intensity | Duration |
| 100 mm/hr | 16.5 min. |
| 75 ,, | 32.4 ,, |
| 50 ,, | 70.2 ,, |
| 25 ,, | 216 ,, |
| 5 year return period | |
| 100 mm/hr | 10.5 min. |
| 75 ,, | 22.8 ,, |
| 50 ,, | 51.6 ,, |
| 25 ,, | 165 ,, |

*Source: Ministry of water development. Rainfall intensity –density –frequency relationship for Machakos dam*

In the second method the runoff is based on rainfall simulator data obtained at Katumani in 1977 (Barber et al, 1979). The slope on cultivated land was 23 %. Table AG3 shows the rainfall intensity durations and frequency for Machakos dam. Similar rainfall was simulated and runoff was measured for various durations. Figures AG1 & AG2 indicate the runoff rates versus time for different rainfall intensities. The area under the curve represents the amount of runoff for any particular intensity and duration. Figure AG1 represents the expected runoff from a dry soil, i.e. soil at permanent wilting point before the rain start. Figure AG2 represents the expected runoff from a wet soil at field capacity when the rain starts. 75 mm/hr rainfall intensity is an interpolation between 100 mm/hr and 50 mm/hr intensity curves.

Table AG2 gives the observed runoff in mm and litres per metre on dry and wet soil for various rainfall intensities, durations and return periods. Out of six conditions examined three are above 23 mm or 21 litres per m furrow length, the highest being about 29 mm.

Comparing the two methods it appears that the first method tends to overestimate runoff. For instance, 26 mm falling in 15 minutes produces a runoff of 21 mm according to the first method while the observed runoff on wet soil from 25 mm falling in equal period of time produces 13 mm runoff according to the second method. Also 39 mm falling in 30 minutes produces a runoff of 29 mm according to the first method but 40.5 mm falling in 32.4 minutes produces 23 mm runoff. In longer duration (60 min) the first method estimates that 55 mm rainfall would cause runoff of 35 mm. In the second method 58.5 mm falling in 70.2 minutes produced a runoff of 43 mm. Interpolated to 55 mm falling in 60 minutes the runoff would be 35 mm. The two methods give equal estimates. It would therefore appear that actual infiltration depends on rainfall intensity and duration as well as soil conditions and no easy formula is likely to give consistent results. The second method based on actual observation is therefore more reliable but it is expensive to carry out for a large area.

In order to determine the effectiveness of the furrows in stopping the runoff and holding until it infiltrate into the soil, 15 furrow cross-sections were sampled randomly and the area determined. Typical furrow cross-sections are shown in Figure AG3. Table AG5 shows the frequency distribution of cross-section and the range of furrow storage capacity per metre length. Of the situations estimated in Table AG4, only one case having a runoff of about 39 litres per metre length would require furrow storage capacity greater than what can be provided. All other expected runoffs with 5 and 10 years return periods can be effectively handled by the available storage.

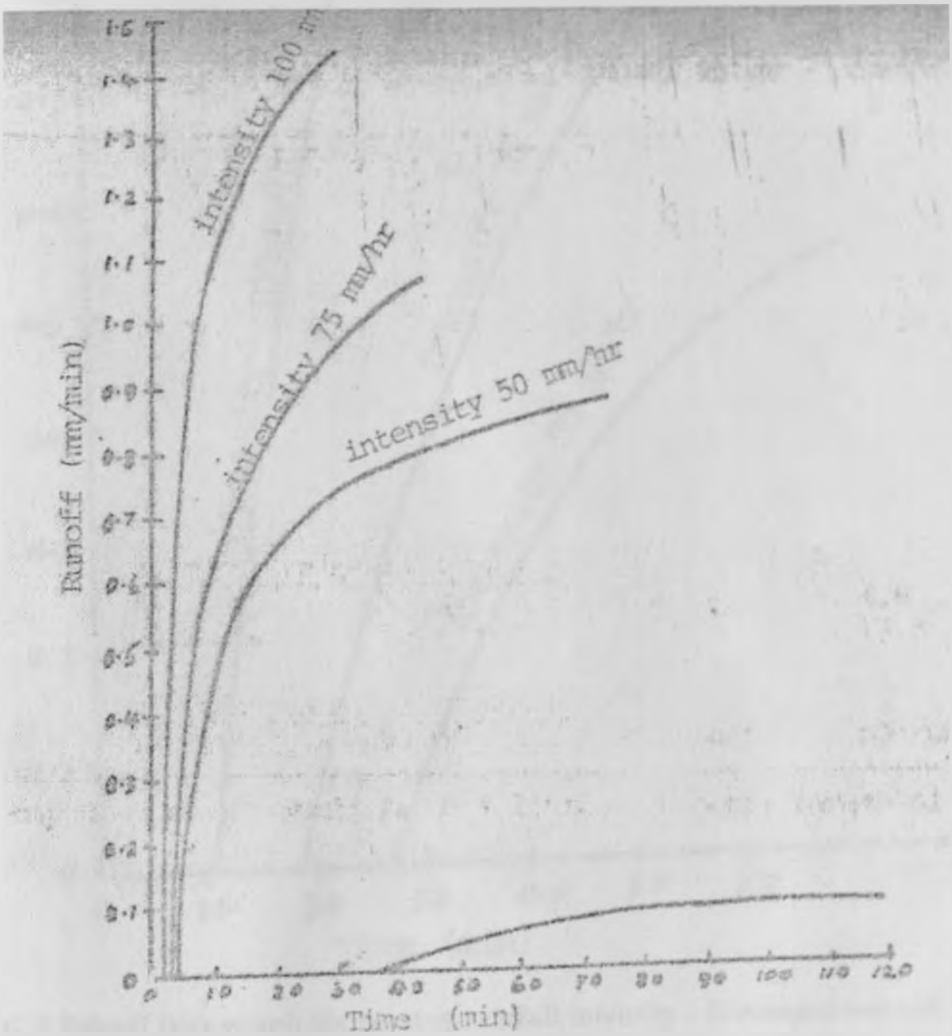



**Figure AG.1 Runoff time graph for varying rainfall intensity – Katumani dry soil**

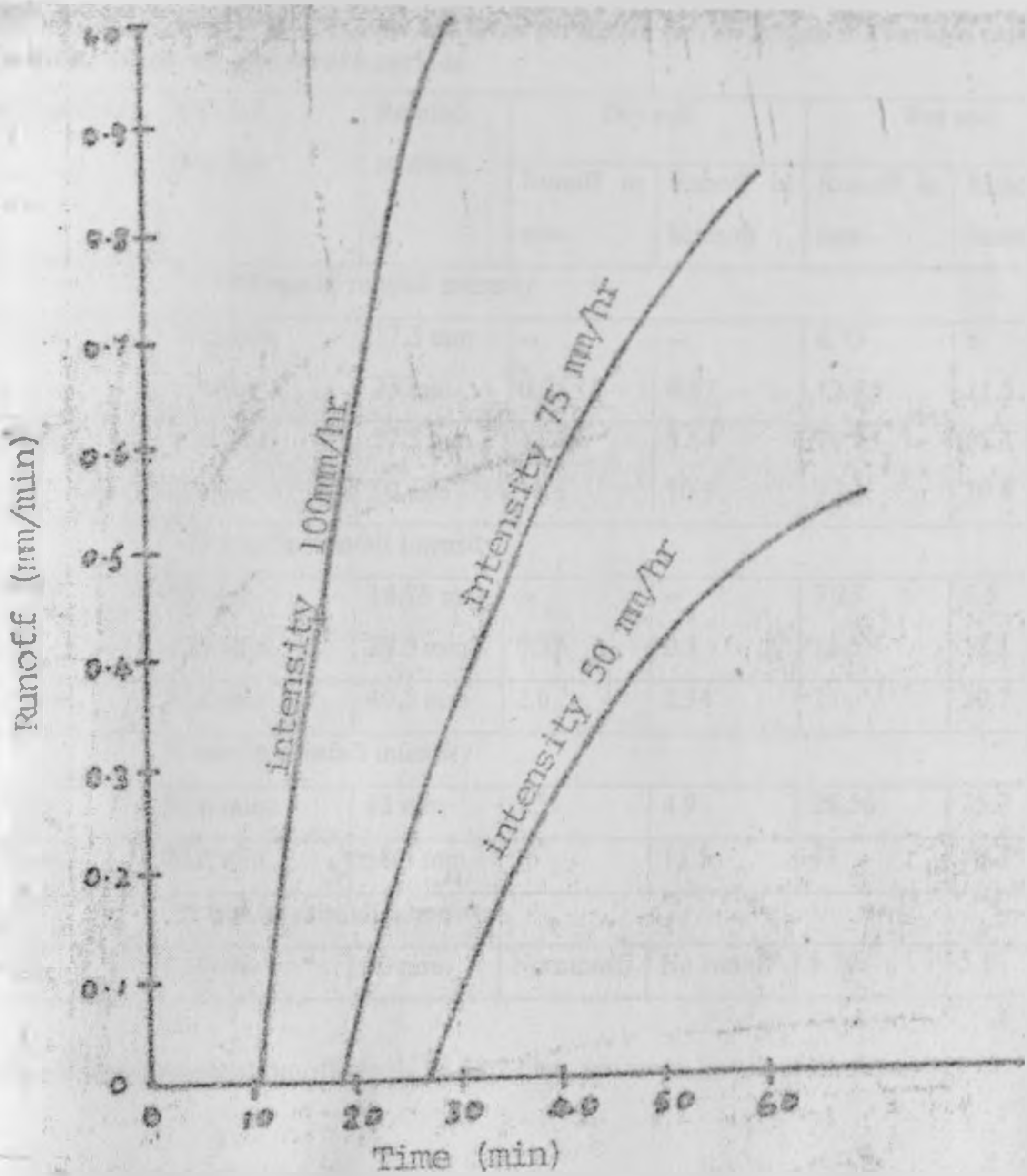



**Figure AG.2 Runoff time graph for varying rainfall intensity - Katumani wet soil**

*Source: Kijne, 1980*

**Table AG.4 Expected runoff in mm and litres per metre furrow length for various rainfall intensities, durations and return periods**

| Return period | Rainfall duration | Rainfall amount | Dry soil | | Wet soil | |
|---|---|---|---|---|---|---|
| | | | Runoff in mm | Runoff in litres/m | Runoff in mm | Runoff in litres/m |
| 100 mm/hr rainfall intensity | | | | | | |
| 1 × 5 yrs | 10.5 min | 17.5 mm | -- | -- | 6.75 | 6 |
| | 15 min | 25 min | 0.75 | 0.67 | 12.75 | 11.5 |
| 1× 10 yrs | 16.5 min | 27.5 mm | 1.275 | 1.14 | 14.75 | 13.3 |
| | 30 min | 50 mm | 11.5 | 10.3 | 33.3 | 29.8 |
| 75 mm/hr rainfall intensity | | | | | | |
| 1 × 5 yrs | 15 min | 18.75 mm | -- | -- | 7.25 | 6.5 |
| | 22.8 min | 28.5 mm | 0.37 | 0.3 | 13.5 | 12.1 |
| 1× 10 yrs | 32.4 min | 40.5 mm | 2.6 | 2.34 | 23 | 20.7 |
| 50 mm/hr rainfall intensity | | | | | | |
| 1 × 5 yrs | 51.6 min | 43 mm | 5.5 | 4.9 | 28.56 | 25.7 |
| 1× 10 yrs | 70.2 min | 58.5 mm | 15 | 13.5 | 43 | 38.7* |
| 25 mm/hr rainfall intensity | | | | | | |
| | 120 min | 50 mm | No runoff | No runoff | 5.75 | 5.1 |

N.B *the highest expected runoff would be 38.7 litres per metre length of the furrow.

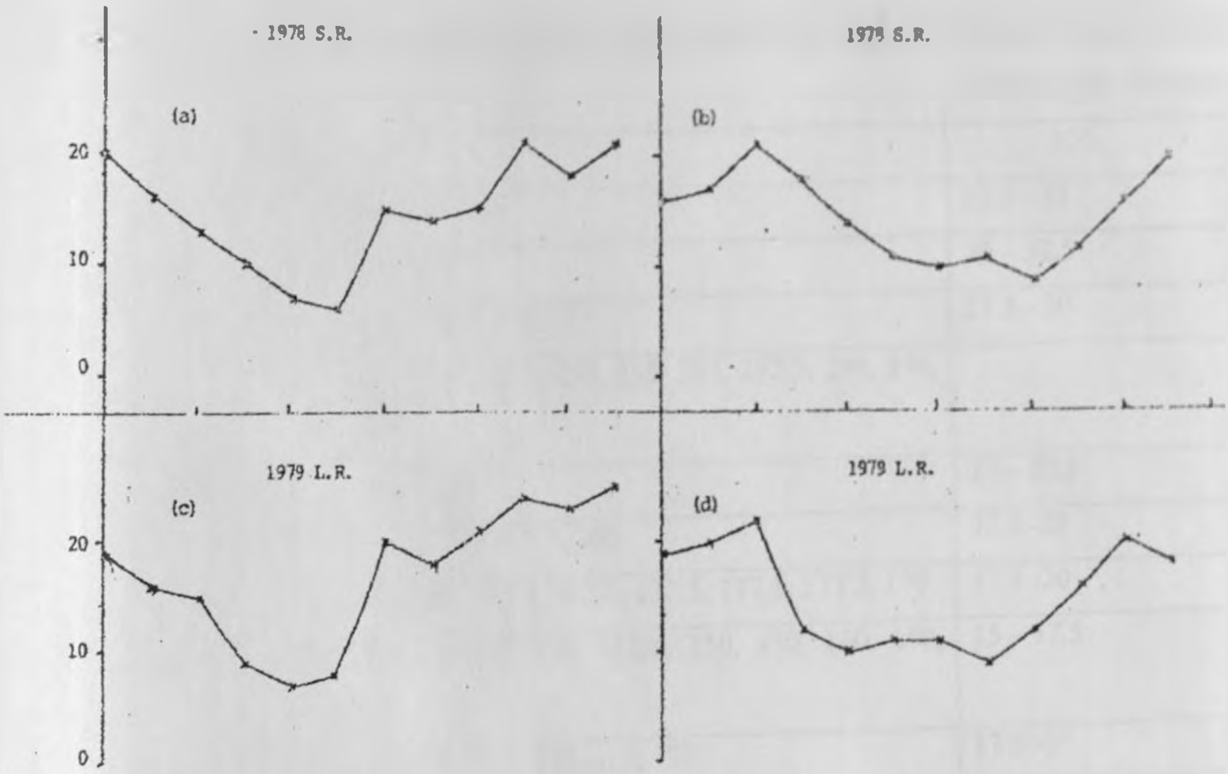



**Figure AG.3 Typical furrow cross-sections made by Desi plough (Dimensions in cm)**

**Table AG.5 The frequency distribution of furrow cross-section area and furrow storage capacity**

| Frequency | % C. F | % | Furrow cross-sectional area values in $cm^2$ | Furrow storage range in l/m length of furrow |
|---|---|---|---|---|
| 1 | | 1.6 | 375 | >35 |
| 3 | 6.6 | 5 | 340, 325, 325 | 32.5 - 35 |
| 2 | 9.9 | 3.3 | 310, 300 | 30 – 32.5 |
| 4 | 10.4 | 6.5 | 282.5, 280, 275, 275 | 27.5 - 30 |
| 10 | 32.8 | 16.4 | 265, 265, 257.5, 255, 255, 255, 252.5, 250, 250, 250 | |
| 2 | 36.1 | 3.3 | 242.5, 240 | 25 – 27.5 |
| 4 | 42.6 | 6.5 | 210, 207.5, 202.5, 200 | 22.5 -25 |
| 7 | 53.6 | 11 | 190, 185, 182.5, 182.5, 177.5, 177.5, 177.5, 175 | 17.5 -20 |
| 9 | 68.3 | 14.7 | 167.5, 176.5, 155, 152.5, 150, 150, 150, 150, 150 | 15 – 17.5 |
| 6 | 78.3 | 10 | 140, 130, 125, 125, 125, 125 | 12.5 -15 |
| 8 | 91.3 | 13 | 120, 105, 105, 102.5, 100, 100, 100,100 | 10 – 12.5 |
| 5 | 99.5 | 8.2 | 92.5, 82.5, 75, 75, 75 | 1.5 -10 |

The mean furrow storage capacity is 19 litres/metre length of furrow.