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AN INVESTIGATION INTO THE PRESENCE OF A CULTIVATION HOE PAN UNDER SMALLHOLDER FARMING CONDITIONS

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by

M.G. Douglas, S.K. Mughogho, A.R. Saka,
T.F. Shaxson and G. Evers

MALAWI GOVERNMENT
MINISTRY OF AGRICULTURE AND IRRIGATION

FOOD AND AGRICULTURE ORGANIZATION
OF THE UNITED NATIONS ROME

INVESTMENT CENTRE DIVISION

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ABBREVIATIONS

ADD	Agricultural Development Division
DARTS	Department of Agricultural Research and Technical Services
FAO	Food and Agriculture Organisation of the United Nations
LHO	Land Husbandry Officer
LRCD	Land Resources Conservation Department
MAFEP	Malawi Agroforestry Extension Project
MoAI	Ministry of Agriculture and Irrigation
MoFFEA	Ministry of Forestry, Fisheries and Environmental Affairs
PROSCARP	Promotion of Soil Conservation and Rural Development Project
SFI	Soil Fertility Initiative
WB	World Bank

FOREWORD

1. Under the auspices of the Malawi Soil Fertility Initiative (SFI), a nationwide pilot investigation was initiated to answer the question: *is there a hoe pan problem in Malawi i.e. a compacted soil layer immediately below the crop ridge that is restricting rainfall infiltration and root development.* The investigation was conducted in March and early April 1999 and involved the identification and sampling of areas within each Agricultural Development Division (ADD) where it was expected that there might be a hoe pan problem[1].

2. The preliminary identification of sites (minimum of 12 sites per ADD) was undertaken by the Land Husbandry section in each ADD. Each identified site was subsequently sampled by a mobile team from Chitedze (Department of Agricultural Research and Technical Services (DARTS)), and characterised as to its past land use history and soil type. Pits were dug and the profile studied and described in the field. Prior to digging the pit the farmer was interviewed as to the site's past land use history.

3. The Chitedze team members were responsible for taking samples from the key horizons of each profile described, for subsequent laboratory chemical and physical analysis. Undisturbed soil cores (minimum of 3 per site) were taken from different depths to determine bulk density, assess soil moisture characteristics (hydrological conductivity) and check the field assessed texture.

4. Field visits were made by an FAO SFI follow-up mission to see the sites sampled within Lilongwe ADD. During these visits, a number of tobacco plants and weeds with tap roots (black jack and wild hibiscus) were uprooted to observe the shape and distribution of the roots within the soil profile. Most of the tap roots bent sideways, rather than continuing vertically downwards, thereby confirming the presence of a layer immediately below the crop ridge that limited root growth.

5. A one-day technical meeting on the hoe pan investigation was held to review the findings of the field observations and laboratory analysis work. The meeting reached consensus that the field observations and laboratory analysis provided evidence (from all 8 ADDs) which verified the hypothesis that there is a compacted hoe pan and that this could be one of the factors contributing to current low maize yields under smallholder conditions.

6. The implications of the investigation's findings are that one of the requirements for raising crop yields throughout much of Malawi is to improve rooting conditions within the subsoil (by breaking the hoe pan) so as to increase the effective volume of soil which each plant's roots could explore for both moisture and nutrients. Combatting subsoil compaction would also improve rainfall infiltration, thereby reducing surface runoff and the risk of soil erosion and making more water available to the crop. The study added to the evidence that there are a number

[1] The field investigation and laboratory analysis were supervised by Alex Saka (DARTS) and Spider Mughogho (national consultant). A preliminary report on the investigation was prepared by the national consultant and this has been used as the basis for this summary report of the findings, lessons learnt and recommendations. The summary report has been prepared by Malcolm Douglas (FAO consultant) with contributions from Spider Mughogho, Francis Shaxson and Guy Evers (FAO Investment Centre). The study was funded by the FAO-WB Cooperative Programme.

of different factors that currently contribute to low soil productivity within the small-scale farming sector in Malawi, and these cannot all be solved simply through increasing the use of hybrid maize seed and chemical fertiliser.

7. Through this investigation, it has been possible to confirm the occurrence of a simple but surprisingly unrecognized problem. To look at what goes on under the soil surface, especially to look at plant root systems and soil porosity, seems to be a new (or rather a forgotten) concept to the study team and most workshop participants. It is as if biological, physical and moisture processes occurring under the soil surface (i.e. which are not seen), are not worth considering in a strategy for improving soil productivity. Discussions also revealed that most participants had little knowledge about what ought to be a normal root system for the most common crops or weeds, and they were not conversant with the various factors affecting crop root growth. Simple observations on root development and soil compaction can also be done by the farmers themselves, and therefore contribute to a better understanding of soil productivity constraints and possible solutions on their farms.

8. While this investigation confirms the occurrence of soil compaction problems in Malawi, further research will be required to better define the extent of the problem and its economic implications. More work is also urgently required for developing, together with farmers, appropriate solutions for breaking the pan and/or preventing its development: remedial measures are likely to involve few costs but may generate substantial returns.

A. BACKGROUND

1. There is growing concern over the decline in the productive capacity of Malawi's soil resources as a result of soil erosion and adverse changes in the hydrological, biological, chemical and physical properties of these soils. The most recent State of the Environment Report (MoFFEA 1998) ranks soil degradation (erosion and declining productivity) as the most serious environmental problem facing modern Malawi.

2. Evidence for declining soil productivity is provided by a pronounced fall in unfertilised maize yields, and a parallel decline in the response of crops to fertilizer. During the 1960s, unfertilized local maize typically yielded 1,700 kg/ha, but now yields have fallen to a national average of less than 1,000 kg/ha, with performance lowest in the more densely populated Southern Region (yields had fallen as low as 600-800 kg/ha in Chiradzulu and Phalombe by the early 1980s). Across the country, the maize response to fertilizer has declined, for example in Lilongwe it has fallen from an average of 23 kg (local) maize per kg of nitrogen in 1957-62 to 13 kg per kg of nitrogen by 1983-85.

3. There are a number of different factors that have contributed to the present low maize yields under smallholder farming conditions in Malawi. These include:

- **Low soil nutrient levels**: As a result of past cultivation practices most of the soils currently used for crop production in Malawi are severely depleted in nutrients, particularly nitrogen, and depending on location, phosphorus, magnesium, zinc and sulphur. Lack of financial resources at the household level and the high price of chemical fertilizer means that there has been little, or no, replenishment of the nutrients removed in the harvested products.

- **Low soil organic matter levels**: Land pressure has led to the cessation of former soil-restorative fallowing practices so that most of the agricultural land in Malawi is now cropped on a continuous basis. Crop residues are commonly burnt and there has been no significant incorporation of organic matter into the soil to improve topsoil structure and nutrient status. The end result is a lowering of organic matter levels in the topsoil which in turn leads to reduced levels of plant nutrients, lower nutrient holding capacity, poorer topsoil structure (resulting in reduced erosion resistance) and poorer rainfall infiltration and moisture retention qualities.

- **Increased moisture stress**: In years of low and erratic rainfall, the effect of moisture stress on reducing maize yields will be exacerbated when a compacted subsoil horizon (below the level of cultivation), combined with poor rainfall infiltration and moisture retention qualities, limits the available water capacity of the soil, and the depth from which roots can draw on whatever moisture reserves are available.

- **Increased incidence of *Striga***: There is a growing incidence of, and damage from, the parasitic weed *Striga* in maize fields. In addition to its debilitating effects as a parasite on the plants roots, it is in itself an indicator of declining soil fertility.

- **Poor quality seed**: There has been a degeneration in the quality of seed of the so called local maize planted by many smallholder farmers. Recent droughts resulted in the loss of many of their traditional varieties as either the crops failed totally, or what little seed was produced was consumed, rather than being retained for the next season. Subsequently, farmers lacked the financial resources to purchase replacement seed from certified improved varieties and planted whatever they could obtain locally. Maize grains sold in the local market are usually a mixture of local, composite and recycled hybrid varieties. Once such a mixture is planted it produces a highly variable stand of maize, only part of which can be explained away by micro-scale variations in soil fertility.

4. One of the primary strategies advocated for combatting declining soil productivity has been to promote the use of hybrid maize and chemical fertilizer. However this apparent "silver bullet" solution fails to recognise that there are a variety of reasons for low maize yields. Poor cultivars and lack of nutrients (nitrogen especially) are only some of the limiting factors.

5. An area that has received little attention is the potential detrimental effect on crop yields when rooting depth is restricted by the presence of a compacted subsoil horizon (hoe pan) formed as a result of the tillage practices used. There has been divided opinion within Malawi as to whether, or not, there is a hoe pan problem within the fields of the country's small-scale farmers. There was therefore a need to determine whether the problem existed, and if so was it a widespread problem. It was to answer this question that a rapid field investigation was undertaken during the 1998/99 growing season to validate, or reject, the hypothesis that crop root development, particularly of maize, is restricted by a compacted layer immediately below the crop ridge at the level of the furrow.

B. THE NATURE OF THE HOE PAN PROBLEM INVESTIGATED

6. Since the 1930s, smallholder farmers in Malawi have been encouraged to plant crops on ridges, rather than as previously on the flat or on mounds. This recommended practice has been widely taken up so that planting on crop ridges has become the traditional practice in most of Malawi. As a consequence, the primary strategy for erosion control on cultivated land in Malawi is to get farmers to align their crop ridges along the contour. The crop ridges are constructed by hand using a broad bladed hoe. In the following season the ridge is usually split and reformed in the previous furrow.

7. There is a growing body of opinion that cultivation using the hoe to the same depth, for the purpose of splitting and reforming planting ridges, has resulted in the formation of a compacted horizon immediately below the crop ridge (Figure 1). The repeated impact and scraping of the hoe blade across the soil surface is believed to collapse and close the macro-pores that would otherwise allow the free movement of air and water between the topsoil and upper subsoil horizons. The sealing process is thought to be more complete when cultivation is done when the soils are moist. The problem is exacerbated by the pressure of people's feet walking along the furrows while performing such operations as weeding when wet. The fear of such a hoe pan was raised as far back as the 1958/59 annual report of the Department of Agricultural Research. However, the phenomenon has not been subsequently systematically investigated, although several trials with deep ploughing have been conducted over the years. For instance,

minor investigations were conducted at Mbawa and Chitedze in the 1970s and 1980s but were discontinued due to funding constraints.

8. If the traditional cultivation methods used in Malawi are resulting in the formation of a hoe pan then this is cause for concern, and a problem that will need to be addressed as a part of any strategy directed at improving smallholder maize production, for the following reasons:

- A compacted hoe pan will severely restrict the infiltration of rainfall into the subsoil profile, thereby: (i) diminishing the proportion of the rainfall received at the surface that is effective for crop production; (ii) limiting soil moisture build up; (iii) and hindering groundwater replenishment.

- Reduced infiltration of rainwater means increased surface runoff down the furrow with potentially heavy soil loss where ridge breakage takes place (Photographs 1, 2 and 3).

- A dense compacted soil layer will severely restrict the downward movement of the roots of maize, and most other annual crops in Malawi, thereby limiting the effective volume of soil that each plant's roots could explore for both moisture and nutrients (Photograph 4).

- By restricting root development to the top 15 cm of the soil profile (the crop ridge), a hoe pan would, for a given offtake of crop, lead to a more rapid depletion of the soil nutrients available to the plant than would be the case for the same soil when unconstricted.

- Crops that, because of a hoe pan, are only able to develop a shallow network of roots suffer plant inhibiting moisture stress, leading to progressive losses of the final yield potential, more rapidly (after 3-4 days without rain) than the same crops whose roots are able to penetrate to the moisture reserves in deeper soil layers, thereby enabling them to withstand longer dry periods (10-15 days) before physiological moisture stress in the plants becomes damaging.

9. Some soils within Malawi have subsoil horizons with chemical and physical properties that naturally inhibit root penetration. Roots may have difficulty penetrating through a layer of laterite, a strongly argillic B horizon, or a very acidic subsoil with excess (toxic) levels of aluminium. When such soils are cultivated yield potential will always be limited by such adverse natural properties.

10. What have been termed as "hardsetting" soils have been recorded in Zambia and may also occur in a few locations within Malawi (e.g. the Mopanosols of the Bwanje Valley and Middle Shire; Maps1 and 2). Such soils are characteristically dense, often with few visible pores, with a hard to very hard consistence in the dry state, and may severely restrict root development. Some sandy soils, particularly those with a high fine sand content, are particularly prone to hardsetting, especially when organic matter levels are low, but finer textured soils, including sandy clays, can also be hardsetting. A recently cultivated hardsetting soil, that is in a loose state, can rapidly slump after heavy rainfall and become very dense. As it dries it progressively hardens and may severely impede root growth. The physical properties of hardsetting soil layers may

resemble those of a tillage induced pan, but the hardsetting properties can extend throughout the whole of the top 30 cm, unlike a hoe pan which is usually restricted to a thin layer at 15-20 cm depth.

11. Although some of Malawi's soils may have properties that limit root development, what is of concern is where a compacted hoe pan has been induced close to the surface in a soil that would not naturally have a limiting horizon. Such a situation it is believed can occur when repeated cultivation, to the same depth, leads to a progressive deterioration in the structure, and porosity (soil architecture), of the upper subsoil horizon, with a consequent reduction in the effective depth of soil that can be utilised by the roots of annual crops.

C. INVESTIGATION METHODOLOGY

12. A nationwide pilot, rapid field investigation was conducted in March and early April 1999 involving the identification and sampling of areas within each ADD where, based on the local knowledge of the ADD Land Husbandry Officers, it was expected that there might be a hoe pan problem. The investigation was initiated at the beginning of March, with a one-day inception workshop, held in Lilongwe, for all of those who were to be involved in the field and laboratory investigation work. The purpose of the workshop was to agree on a common methodology as to what was to be done, and how it would be done.

13. Preliminary site identification (minimum of 12 sites per ADD) was undertaken by the Land Husbandry section in each Agricultural development Division (ADD) of the Ministry of Agriculture and Irrigation (MoAI). Within each ADD, one Land Husbandry Officer (LHO) was assigned to the task. Each identified site was subsequently sampled by the LHO, with the support of a mobile team from the Chitedze Agricultural Research Station of DARTS. There were two such teams, one visited Salima, Kasungu, Mzuzu and Karonga ADDs, the other visited Lilongwe, Machinga, Blantyre and Ngabu ADDs (Map 3).

14. Whereas the primary emphasis was on identifying sites where a hoe pan was expected, a smaller number of sites, where the prevailing soil type would suggest one was not expected, were selected for comparative purposes. Each site was characterised as to its past land use history and soil type. Pits were dug towards the end of the growing season adjacent to one or two maize plants. The pit was usually excavated in the furrow between two crop ridges to a depth of one metre. For each pit the profile was studied and described in the field using the standard Land Husbandry Field Recording Sheet (Attachment 1). Those doing the recording were asked to pay particular attention to describing observable variations down the profile with regard to the distribution and size of roots, and the type, size and abundance of pores. Prior to digging the pit, the farmer was interviewed as to the site's past land use history, notably how many years the field had been cultivated, what crops had been grown and what crop and land husbandry practices had been used (e.g. rotations, fallowing, fertilisation, tillage, etc.). Information on this, gathered from the farmer interview and direct observations, was recorded on a specially designed data sheet (Attachment 2). In addition, a photographic record of each profile sampled was obtained.

15. During the visits of the Chitedze mobile team, samples were taken from the key horizons of each profile described, for subsequent laboratory chemical and physical analysis. Undisturbed soil cores (minimum of 3 per site) were taken from different depths to determine bulk density, porosity, assess soil moisture characteristics (hydrological conductivity) and check

the field assessed texture. All work on the field descriptions and collection of soil samples was completed by late March with the laboratory analysis work completed by the end of April.

16. At the beginning of May two follow up field visits were made to the sites sampled within Lilongwe ADD. During these visits a number of tobacco plants and weeds with tap roots (black jack *Bidens pilosa* and wild hibiscus *Hibiscus* sp.) were also uprooted and observations made on the shape and distribution of the roots within the soil profile, with particular emphasis on the distribution of the roots in relationship to their position within their crop ridge.

17. During the first week in May, a one-day technical meeting on the hoe pan investigation was held to review the findings of the field observations and laboratory analysis work. The participants at this meeting included the members of the Chitedze field teams, Land Husbandry Officers from the ADDs, representatives from LRCD, DARTS, PROSCARP and MAFEP, as well as FAO personnel (namely a national consultant, international consultant, and FAO staff member) involved with the FAO/World Bank Soil Fertility Initiative in Malawi.

D. RESULTS

18. During the May technical review meeting, there was consensus agreement amongst the participants that the preliminary field observations and laboratory analysis provided evidence to confirm the presence of a compacted subsoil layer (hoe pan) within the maize fields of smallholder farmers. It is believed that the investigation has verified the hypothesis that present cultivation practices have led to the formation of a hoe pan. The consensus of the meeting was that this is one of the factors that has contributed to the present low maize yields obtained under smallholder farming conditions in Malawi. The investigation revealed that the hoe pan problem can be found in all 8 ADDs and on a variety of soil types (notably Lixisols, Cambisols and Luvisols). However, the reconnaissance nature of the investigation means that it is not yet possible to determine the exact location and aerial extent of the hoe pan problem within Malawi.

19. Evidence for the presence of a hoe pan was derived from three sources of information, namely: (i) field observation of the shape and distribution of roots; (ii) laboratory determination of bulk density and porosity; and (iii) laboratory determination of hydraulic conductivity. Detailed discussion of the individual results on an ADD by ADD basis can be found in the report prepared by the national consultant. The following discussion on the results represents a summary of the key findings.

Root Observations

20. Field observations were made in Lilongwe ADD on the shape and distribution of the tap roots of tobacco plants and weeds (black jack and wild hibiscus) uprooted from fields at several different locations. Most of the plants uprooted had tap roots that were bent sideways, rather than continuing vertically downwards (See Photographs 5 and 6). In the case of the tobacco plants (both smallholder Burley and Western tobacco), very few of the tap roots seen (less than 20%) penetrated to any depth below the level of the crop ridge. With regard to the weeds uprooted from both within maize and tobacco fields, the portion of the tap root that grew vertically depended on whether they were growing near the top or bottom of the crop ridge, the bend in the tap root coinciding with the bottom of the crop ridge (Photographs 7 and 8). The consistent depth at which the tap root was observed to bend sideways, confirms the presence of a layer

immediately below the crop ridge that limits root growth. It has been suggested that poor transplanting practices could explain the shape of the tobacco tap root (the so-called J root syndrome). However, the sheer number of bent tap roots and limited penetration of secondary roots observed at different locations, and with different standards of crop management, suggests that the problem cannot be explained purely as poor tobacco transplanting practices. Such an explanation can likewise not be attributed to the observed distortion of the weed roots.

21. Field observations were made on the distribution of the roots of maize plants, within the soil profile, at the time that samples were collected for laboratory analysis. Maize plants have no central tap root, but produce a mass of small roots, rootlets and root hairs. Under ideal growing conditions, the roots of maize plants can be expected to extend to at least one metre in depth. In the profiles sampled, it was rare to find any maize roots that extended below 60 cm. In those soils where a hoe pan was expected, there was a very rapid drop-off in the number of roots present at a depth of no more than 30 cm from the top of the crop ridge (see Photograph 4). In sandier dambo, margin soils in the Lilongwe Plain maize roots were usually more abundant and would extend to some 60 cm below the crop ridge (see Photograph 9). Thus, field observations of reduced root distribution below the crop ridge provided visual confirmation of a subsoil horizon that was limiting to root development. In Blantyre ADD, it was observed that the tap roots of pigeon pea had the ability to penetrate a hoe pan and that this could improve the root penetration of the intercropped maize plant where intercropped.

Bulk Density

22. Bulk density and porosity can be used as indicators of the ease with which plant roots can penetrate the soil. Increases in bulk density and corresponding decline in porosity will impose the following stresses on a plant's root system:

- ➢ the mechanical resistance to root penetration increases, reducing the plant's ability to exploit its environment;
- ➢ the air supply to plant roots is increasingly restricted as the proportion of the soil occupied by pore spaces decreases, facilitating the build up of toxic products such as carbon dioxide and ethylene. As well as decreasing total porosity, soil compaction decreases the volume of the soil occupied by coarse pores relative to that occupied by fine ones, thereby increasing the volume of water relative to air within the soil's pore spaces;
- ➢ in general, the permeability of the soil decreases with increasing density, as it becomes harder for water to drain down through the soil profile, which increases the risk of waterlogging adversely affecting field crops.

23. Soil horizons with bulk densities (g cm^{-3}) greater than 1.6-1.8 for sands and 1.4-1.6 for silts and clays can be expected to cause hindrance to root penetration. With regard to porosity, sands with a total pore space of less than 40% are liable to restrict root growth due to excessive strength, whilst in clay soils, limiting soil porosities are higher, and less than 50% can be taken as the corresponding approximate value (Landon 1991).

24. The results of the laboratory analysis revealed that the average bulk density of the topsoil[1] (0-15 cm depth) was much lower than in the subsoil horizons (see Table 1). Typically, there was a marked increase in bulk density in the upper subsoil (1.50 g cm^{-3} at 15-30 cm depth) compared to that of the topsoil (1.41 g cm^{-3}). Whereas, the lower subsoil horizons (30-45 and 45-60 cm depth) typically would show a less marked increase in bulk density (1.52 g cm^{-3} and 1.56 g cm^{-3} respectively). There was similarly a marked decrease in porosity between the topsoil and upper subsoil and a more gradual decrease with increasing depth (see Table 1).

25. Although some of the changes in bulk density and porosity could be attributed to the presence of an argillic B horizon, careful scrutiny of the laboratory analysis results for each of the profiles sampled (combined with the field observations) would suggest that the marked changes recorded between the topsoil and upper subsoil can in most cases be attributed to cultivation induced compaction (hoe pan) immediately below the crop ridge, rather than natural clay accumulation in the 15-30 cm layer.

Hydraulic Conductivity

26. Hydraulic conductivity, expressed in centimetres per hour, defines the volume of water which will pass through a unit cross sectional area of soil in a unit time, given a unit difference in water potential. It is thus an accurate way to measure soil permeability within the laboratory. Comparison of the hydraulic conductivity rates of different soil horizons will show the ease with which water can move down the profile.

27. The results of the laboratory analysis revealed a marked difference in hydraulic conductivity between the topsoil and subsoil horizons (see Table 1). Typically, the top layer (0-15 cm depth) had a very rapid hydraulic conductivity, with an average figure of 19.2 cm/hour. Thereafter, the hydraulic conductivity declined significantly, to a moderately rapid rate, with figures of 7.1 cm/hour for the upper subsoil (15-30 cm depth), and around 6.9 cm/hour and 6.4 cm/hour in the lower subsoil horizons (30-45 and 45-60 cm depths respectively). Under normal circumstances, hydraulic conductivity will usually decease gradually with increasing depth. Whereas the very rapid conductivity rate recorded for the topsoil can be explained as a result of loosening due to cultivation, the very significant change in rate immediately below the cultivated area is suggestive of induced soil compaction (hoe pan), as the relative hydraulic conductivity is reduced more abruptly than would normally be expected.

E. IMPLICATIONS

28. The findings of this (preliminary) investigation show that there is sufficient field and laboratory evidence to confirm that in many parts of Malawi, cultivation using a broad bladed hoe has produced a compacted subsoil horizon (hoe pan) immediately below the crop ridge. The implications of this are that agricultural development programmes seeking to improve soil productivity will need to include a component targeted at improving rooting conditions within the subsoil. Specifically there will be a need to break any hoe pan, so as to increase the effective volume of soil which each plant's roots could explore for both moisture and nutrients. Combatting

[1] Note, soil depth was recorded from the top of the crop ridge rather than the furrow, thus the top 0-15 cm depth corresponds to the ridge itself, with the upper subsoil (15-30 cm) starting at the base of the ridge' level with the furrow.

such subsoil compaction would also improve rainfall infiltration, thereby reducing surface runoff and the severity of associated soil erosion.

29. As indicated earlier, there are a number of different factors that currently contribute to low soil productivity within the small-scale farming sector in Malawi. It is recognised that the use of hybrid maize seed and chemical fertiliser would address some of these problems, specifically those associated with low soil nutrient levels and low yielding varieties. However, they would not *per se* tackle some of the other limiting factors, namely low soil organic matter levels, and the rapid onset of moisture stress, during drought periods, due to a cultivation hoe pan limiting rooting depth. Which, singly or in various combinations, would limit plant responses to the use of improved seed and fertiliser alone.

F. TACKLING THE HOE PAN PROBLEM

30. It is clear from the results of the investigation that many smallholder farmers in Malawi are faced with a compacted subsoil horizon (hoe pan) problem within their fields. There is thus a need to identify potential practical management options for tackling the problem. The starting point has to be to break the hoe pan and to reform soil macro pores which link, by physical channels, the topsoil and subsoil horizons. This can be achieved by mechanical and/or biological means. Subsequently the need is to avoid cultivation practices that would result in its reformation.

31. Technically, the most effective way to break a hoe pan is by deep ripping/subsoiling using a chisel tine. This is most effective when carried out in dry soils. The effect can last at least 3 cropping seasons depending on soil type and subsequent type of tillage. Within the commercial farming sector, combatting a plough pan, formed through the use of a tractor-drawn disc plough, would require a tractor-mounted sub-soiler drawn at high speed through the soil so as to fracture the pan and develop secondary cracking within the subsoil. Given the small field size and high operating costs, this would not be a realistic option within the small-scale farming sector without a hefty subsidy from government and/or donor sources.

32. The type of hoe pan that would be formed under small-scale farming conditions, where cultivation is done by hand, is likely to be thinner (may be no more than 5 cm) than the plough pan formed following tillage using a tractor-drawn plough (disc or mouldboard). Given that less physical effort would be required to break it, this could be done with the aid of ox-drawn implements. In this regard, the Magoye Research Station in Zambia has designed a strong ripper that can be attached to a standard ox plough beam. This implement has been used successfully in Zambia and Tanzania to break plough pans where they have formed due to continuous cultivation with ox-drawn mouldboard ploughs. Those farmers that have draft oxen could be assisted in obtaining the Magoye ripper and then trained in its use.

33. Regrettably, the number of farmers with draft oxen is decreasing, very few farmers now own them anywhere in Malawi, and in the short term there is little scope for reversing this trend. Thus, for most small-scale farmers the only mechanical option for breaking a hoe pan is to crack it (deep digging) using hand implements. Undertaking such deep digging when the soils are hard during the dry season would be difficult with the traditional broad bladed hoe, and alternative implements would be needed, such as a pickaxe, mattock or the three tined forked "jembe" hoe used in Kenya.

34. The practice of composted double dug beds, which combines improved plant nutrition with improved subsoil rooting conditions, has successfully been used by some farmers in Malawi on a small-scale basis (usually for vegetable production). In this practice, the soil is dug out to twice the normal cultivation depth and then back-filled with a mixture of soil and compost. Given the high labour requirement for this practice, very few farmers would have the resources to adopt it as a means of breaking a hoe pan for the whole of their field during one cropping season. However, for the growing numbers of farm families with very small land holdings (0.5 ha or less) it would be possible for them to cover their whole farm within 4-5 years by double digging a portion of the holding each year. The residual effects on improved rooting depth can be expected to last for a similar period. Adding compost would also improve soil nutrient levels and moisture retention, thereby improving soil productivity in more ways than just improved rooting depth.

35. The traditional way of restoring soil productivity to fields that had become exhausted, compacted and weed infested after a period of cropping, was to leave them for a prolonged period to bush fallow. Rural population pressure and land scarcity means that this is no longer an option for most small-scale farmers. For those farmers with larger land holdings (e.g. in Kasungu and parts of the Northern Region) there is some scope for incorporating into the crop rotation a 2-3 year enriched fallow planted to deep-rooted herbaceous and/or woody legumes. For farmers with very small land holdings the only options for breaking a hoe pan, and preventing its reformation, are to inter-crop/plant, at a high planting density, with deep rooted shrubs and/or perennial crops. The most promising inter-planting options in Malawi are currently pigeon pea (*Cajanus cajan*), and a small number of tried and tested nitrogen fixing shrubs (notably *Tephrosia vogelli, Sesbania sesban* and *Gliricidia sepium*) (see Photographs 10 & 11).

36. Given that planting on ridges is an almost universal smallholder cultivation practice, and if properly aligned can be an effective soil conservation practice, it would be inadvisable to recommend to farmers that they should adopt so called conservation tillage practices that involve planting on the flat. To avoid the reformation of a hoe pan once broken, one option would be to advise farmers not to split the crop ridge and remake it in the previous furrow, but instead to reform it in the same position. This would ensure the maintenance of the macro pore spaces, and old root channels, that allow for the exchange of water and air between the topsoil and the subsoil horizons below the crop ridge. However, ridge splitting was originally recommended as a means of weed control and, as with other reduced tillage techniques, there could be a risk that weed problems would increase.

G. LESSONS LEARNT AND RECOMMENDATIONS FOR FUTURE INVESTIGATIONS

37. The investigation was undertaken in the nature of a preliminary reconnaissance exercise to determine the likely presence of a cultivation induced compacted subsoil horizon (hoe pan). It was not intended to be a definitive study of the nature and extent of the problem. However, a number of lessons can be drawn from the way the work was conducted that would improve the implementation of future studies. These can be considered under the following headings:

- **Improved field recording**: In some instances, field observations of the soil profile were poorly recorded on the standard land husbandry field sheets. It had been wrongly assumed that all of the LHOs would be familiar with the use of these field sheets for recording soil profile data. Whereas they were familiar to the long serving LHOs, few of the more recent recruits had experience with their use. In future those involved in the field observation work should receive "hands-on" training on what to observe in the field and how to record this systematically on the field sheets. Particular attention should be given to achieving a common understanding between the different recorders on how they should describe observable variations down the profile, especially with regard to the distribution and size of roots, and the type, size and abundance of pores.

- **Farmer interviews**: The quality of the information obtained from the farmer interviews was highly variable. Some of the answers recorded during the field work, particularly with regard to how long water remained in the furrow following rainfall, and the number of days without rain before maize wilts, were unbelievable. In future more training should be given to the recorders in how to conduct farmer interviews, and how to "probe" for further information when there is doubt about the accuracy of the answers. In some cases more accurate information might have been obtained by talking to the female members of the farm household, as they are likely to spend more time in the maize fields during the rains (weeding and harvesting relish) than the men, hence will have a better recall of observable seasonal features (standing water, onset of moisture stress, etc.).

- **Indicator species**: The field observations on the shape and distribution of the tap roots of tobacco plants and weeds (black jack and wild hibiscus) provided a clearer indication of the presence of a hoe pan than was the case with the more diffuse root network of maize. There is thus scope for identifying indicator species that, by simply uprooting them, can be used to quickly reveal the presence and real extent of a hoe pan within a field. This would avoid the time and effort required to dig exploratory soil pits. Agronomists and weed specialists should be consulted for advice on the most promising species (i.e. those with a susceptible taproot) and, for comparison purposes, what the shape and distribution of these roots should be under ideal growing conditions.

- **Excavation/mapping of root distribution**: Although root distribution observations were made on the side of the pits, time did not allow for the systematic excavation and mapping of the roots to quantify their abundance and distribution within individual soil horizons. Obtaining such information would involve undertaking a limited number of detailed studies in which the roots of individual maize plants would be carefully excavated in order to map their distribution down the soil profile. It is recommended that such an exercise be done and that several different sites should be selected to allow comparisons, of root development, to be made between different soil types, and between the same soil types with, and without, a hoe pan. Such an exercise would lend itself to being undertaken as the subject of an MSc research project.

- **Orientation of the soil pits**: Most of the pits dug were located in the furrow running parallel to the crop ridge. Although the side of the ridge was cut back to the maize plant this may not have given a true indication of root distribution within the crop ridge itself. Future studies should consider excavating the pit across the ridge to produce a cross section of the ridge and subsoil horizons. This would also avoid any confusion over the depth at which particular features were recorded by starting measurements from the top of the ridge rather than the side of the pit in the furrow.

- **Incremental depth sampling**: The compacted layer (hoe pan) may be no more than 2-3 cm thick. By taking a limited number of samples from fixed depths there is a distinct possibility that the layer with the hoe pan may be missed in the sampling exercise. This may explain some of the variation in bulk density found between individual sites and horizons sampled. To be sure of picking up a thin compacted layer it would be necessary to take a series of undisturbed soil cores from small increments of soil depth.

- **Penetrometer readings**: A penetrometer was not available at the time of the investigation. However should one become available then this could also be used to detect the presence of a compacted soil layer by taking readings from different soils, at small incremental depths, under both wet and dry conditions.

H. NEED FOR FURTHER STUDIES

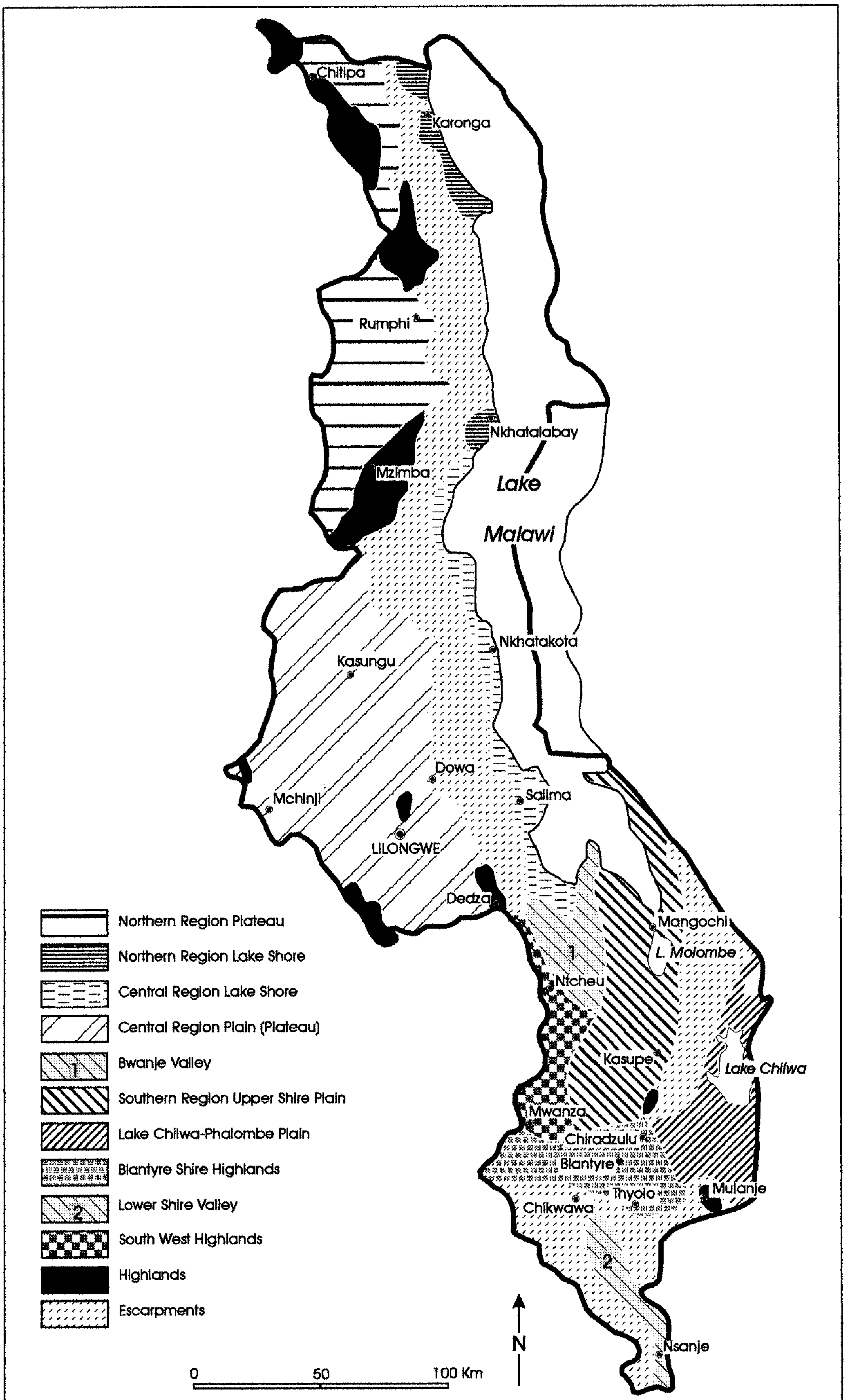
38. Whereas the investigation has confirmed the presence of a cultivation-induced compacted subsoil horizon (hoe pan), more detailed field and laboratory work is needed to determine the full nature, severity and extent of the problem, i.e. which soil types are the most susceptible, where these occur and the type of cultivation and land use practices that lead to the formation of a hoe pan. Studies are also needed to determine the type, nature and interaction effects of different levels of moisture stress that occur when rooting depth is limited by a hoe pan (including soil moisture studies and plant-water-stress studies). The yield potential of a plant in a specific location is determined by a variety of factors, of which the presence or absence of a hoe pan is only one. Thus, plant response studies should also consider the relative contribution made to the final yield by such factors as improved seed, applied nutrients (organic and inorganic fertilisers), weeding, pest and disease control and tillage practices.

39. Given that current tillage practices can result in the formation of a hoe pan, there is a need to identify improved land husbandry practices that would: (i) prevent the formation of a hoe pan; and/or (ii) break existing hoe pans. This calls for a series of practical investigations into alternative non-hoe pan forming tillage techniques, using hand-help cultivation implements. Likewise, there is a need to identify and test a range of cost-effective mechanical and biological means that could be used by resource-poor smallholder farmers for breaking existing hoe pans.

40. It is recommended that such work be carried out as one of the initial activities of the research component of the proposed Malawi Better Land Husbandry Programme. The more scientific field and laboratory investigations would of necessity have to be undertaken by the DARTS and university research workers. However, there is considerable scope for involving farmers in the uprooting and excavation of roots as part of a more participatory farmer centred approach to both training and research. This would be an ideal exercise for farmers to undertake as part of a "farmer field school" devoted to integrated soil management/better land husbandry, as it would make them aware of the problem and enable them to learn more about subsoil rooting

conditions within their farm holdings. They could then become involved in testing alternative biological and mechanical means of improving subsoil rooting conditions, by comparing the relative abundance, distribution and length of roots under different treatments.

Map 1. Major Relief Units of Malawi



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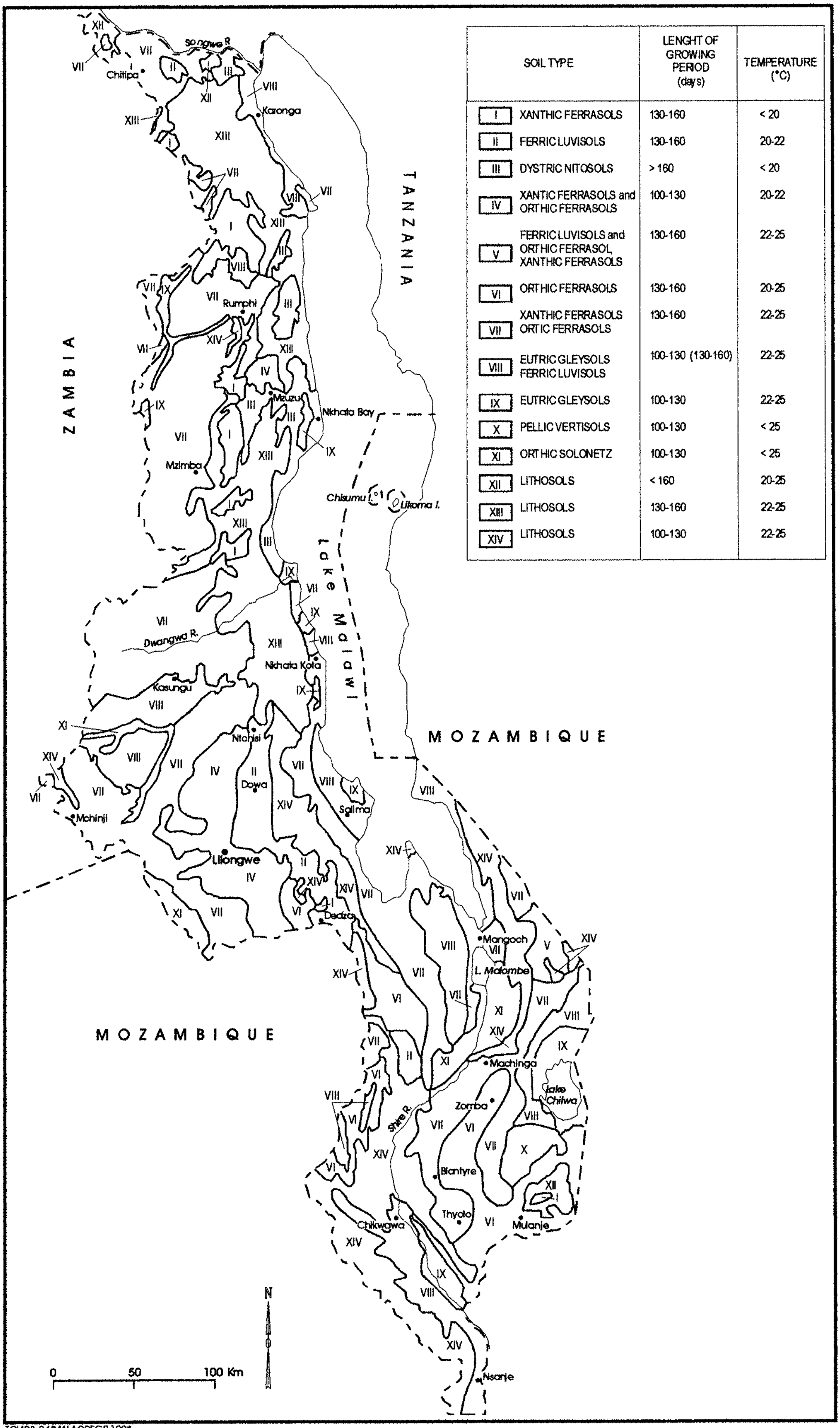
Map 2. Agro-ecological Zones of Malawi



SOIL TYPE		LENGHT OF GROWING PERIOD (days)	TEMPERATURE (°C)
I	XANTHIC FERRASOLS	130-160	< 20
II	FERRIC LUVISOLS	130-160	20-22
III	DYSTRIC NITOSOLS	> 160	< 20
IV	XANTIC FERRASOLS and ORTHIC FERRASOLS	100-130	20-22
V	FERRIC LUVISOLS and ORTHIC FERRASOL, XANTHIC FERRASOLS	130-160	22-25
VI	ORTHIC FERRASOLS	130-160	20-25
VII	XANTHIC FERRASOLS ORTIC FERRASOLS	130-160	22-25
VIII	EUTRIC GLEYSOLS FERRIC LUVISOLS	100-130 (130-160)	22-25
IX	EUTRIC GLEYSOLS	100-130	22-25
X	PELLIC VERTISOLS	100-130	< 25
XI	ORTHIC SOLONETZ	100-130	< 25
XII	LITHOSOLS	< 160	20-25
XIII	LITHOSOLS	130-160	22-25
XIV	LITHOSOLS	100-130	22-25

TCI498-94/MALAGREC/1199*

Map 3. Agricultural Development Divisions and Extension Planning Areas 1997

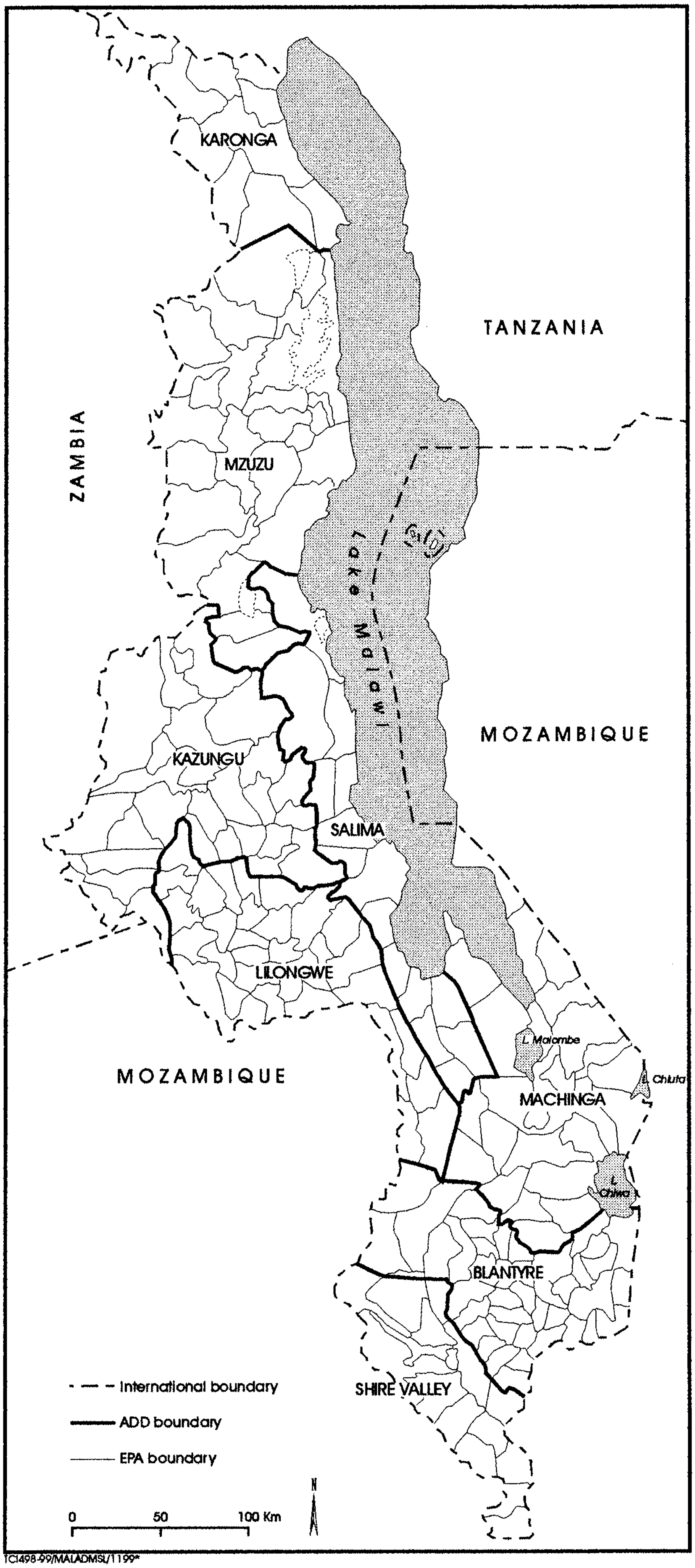
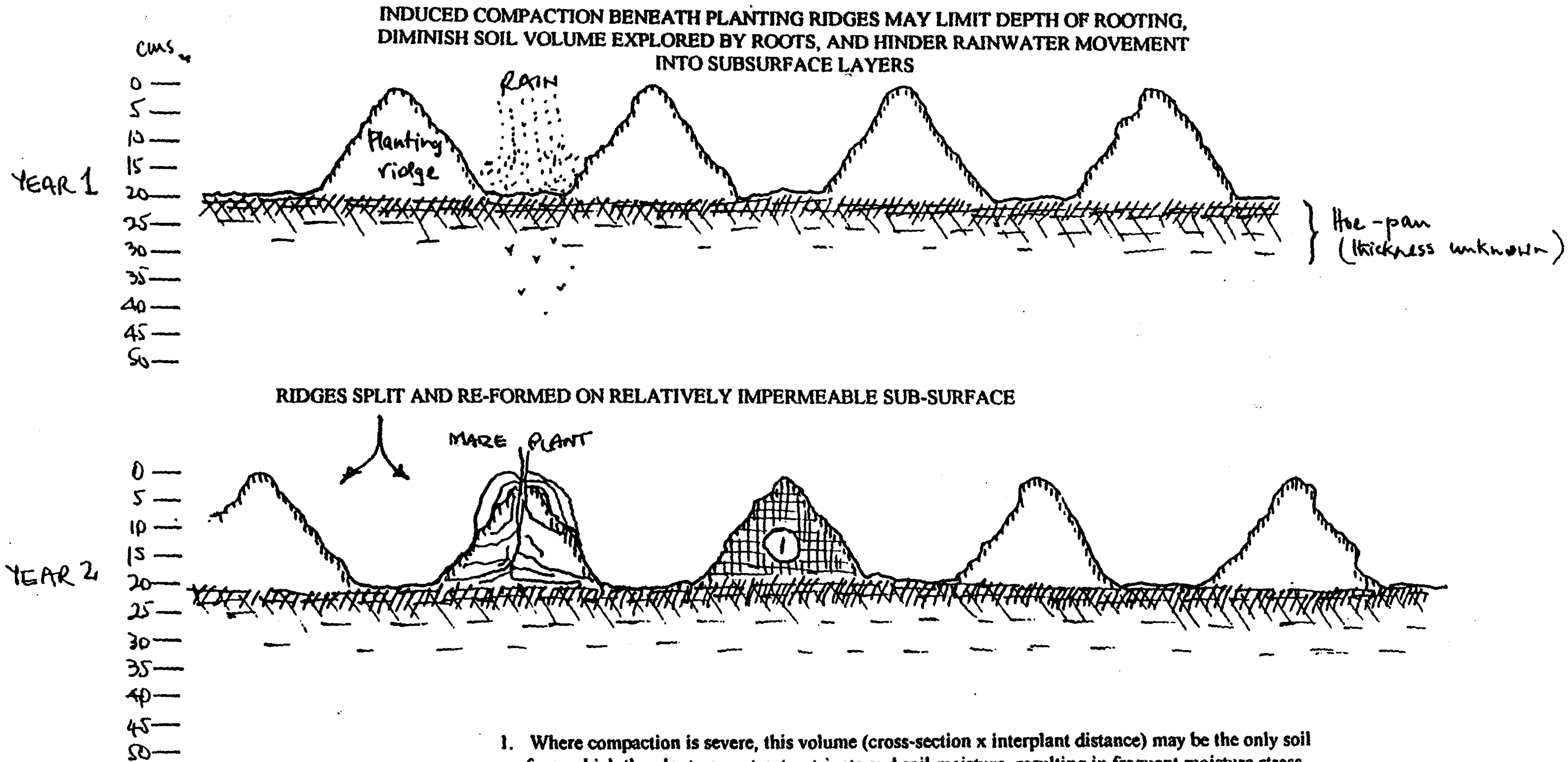


Figure 1. Effects of Possible Hoe Pan



1. Where compaction is severe, this volume (cross-section x interplant distance) may be the only soil from which the plant can extract nutrients and soil moisture, resulting in frequent moisture stress and possible insufficiency of nutrients during plant development.

Table 1. Average Figures From the Physical Analysis Undertaken on All of the Soils Sampled Within the Eight ADDs

Depth	Bulk Density	Porosity	Hydraulic Conductivity	% Silt	% Clay	Texture Class
0-15 cm	1.41g cm^{-3}	46.5%	19.2 cm/hr	8.44%	16.9%	Sandy loam
15-30 cm	1.50g cm^{-3}	43.4%	7.1 cm/hr	8.87%	22.4%	Sandy clay loam
30-45 cm	1.52g cm^{-3}	43.1%	6.9 cm/hr	9.56%	23.4%	Sandy clay loam
45-60 cm	1.57g cm^{-3}	40.9%	6.4 cm/hr	9.36%	24.3%	Sandy clay loam

Table 2. Classification of Hydraulic Conductivity Classes

cm/hr	Conductivity Class
<0.8	Very slow
0.8 - 2.0	Slow
2.0 - 6.0	Moderate
6.0 - 8.0	Moderately rapid
8.0 - 12.5	Rapid
>12.5	Very rapid

Source FAO 1963 (cited in Landon 1991).

Front

Recorder:	Area:	GRID POINT
Date :	Airphoto No:	

Present Land-use			
Vegetation	trees	shrubs	grasses
Topography		Microtopography	
Slope position		Altitude	

SURFACE	SUBSURFACE	DESCRIPTION			CODE SYMBOL
Slope	—	Compass direction	Abney degrees	%	
Past erosion	—				
Wetness .					
—	Effective depth				
Surface Hindrances	—				
Top 8" texture					
—	Permeability upper SS				
—	Permeability lower SS				
—	Limiting material				
Surface 't' factor	—				
—	Colour upper SS				
—	Texture upper SS				
—	Parent material				

DEPTH ins	DEPTH mm	COLOUR (moist)	TEXTURE	PERME-ABILITY	MOTTLING	GRAVEL/ STONES	OTHER	SAMPLE Reference
6	150							
12	300							
18	450							
24	600							
30	750							
36	900							
42	1050							
48	1200							

Remarks:	CODE FRACTION	LAND CLASS

Back

DEPTH ins	DEPTH mm	CONSISTENCE dry wet wet plastic	STRUCTURE grade shape size	PORES type size abundance cracks	WATER ABSORBING RATE	ROOTS distribution size	ROCK FRAGMENTS types	SECONDARY MINERALS types	HARD PANS cementing	CLAY SKINS	HORIZON BOUNDARY width topography	OTHER
6	150											
12	300											
18	450											
24	600											
30	750											
36	900											
42	1050											
48	1200											
60	1350											

Date:		Map sheet		Grid reference	
Name of recorder					
Name of farmer					
Village					
EPA		RDP		ADD	
Year field first opened for cultivation					
Last time field left under fallow					
Number of years of fallow					
Present land use (ie. what crops are grown, rotations/fallowing practiced, manure/fertiliser used)					
Past land use history (ie how has land use - crops & management practices - changed)					
Present method of cultivation (hand hoe, ox plough, tractor etc)					
Former method of cultivation if different					
Presence and alignment of crop ridges					
Number of hours water remains in furrow after heavy rainfall					
Observed changes over last few years in number of hours water remains in furrow after heavy rainfall					
Number of days without rain before maize wilts					
Observed changes over the last few years in number of days without rain before maize wilts					

Photograph 1. Upper subsoil exposed by erosion of the crop ridge Zomba, December 1970

Photograph 2. Heavy soil loss following the breaking of the crop ridge where induced subsoil compaction has restricted rainfall infiltration, Zomba, December 1970

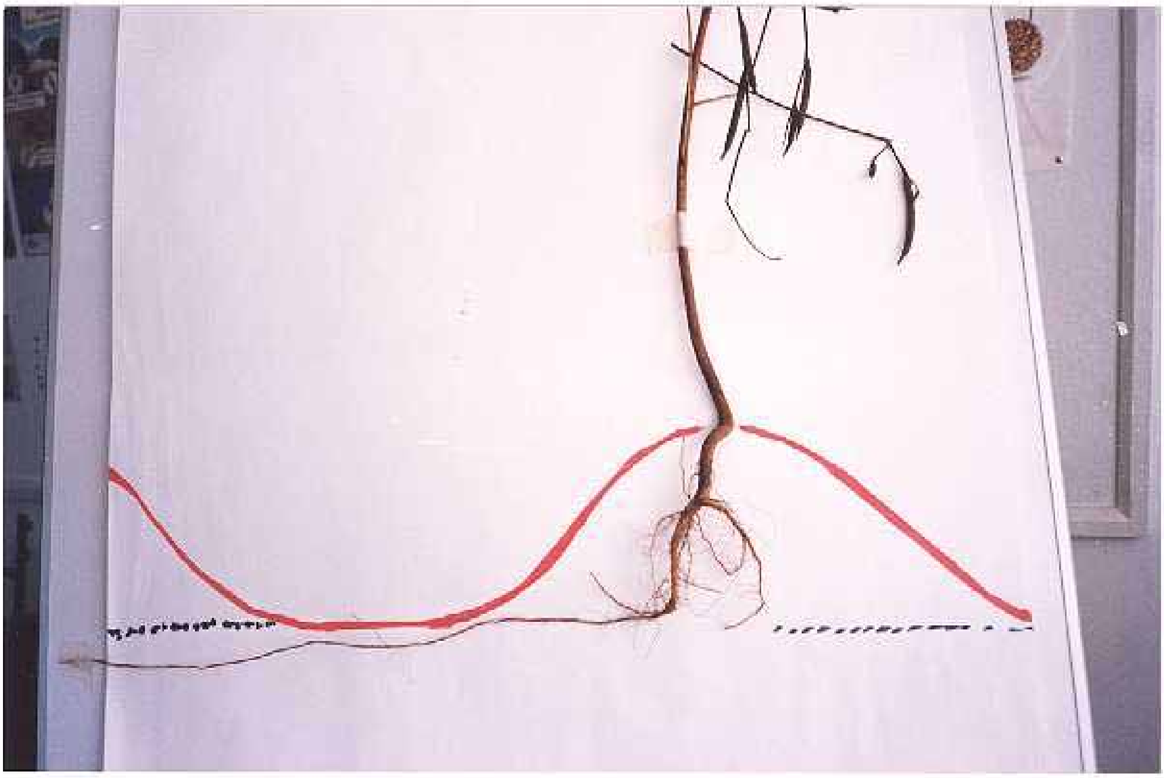
Photograph 3. Crop ridge breakage as rainfall unable to infiltrate due to the presence of a hoe pan, Nathenje, March 1999

Photograph 4. Compacted subsoil layer (hoe pan) restricts the depth to which maize roots can penetrate for moisture and nutrients

Photograph 5. Tobacco tap root distortion due to the presence of compacted upper subsoil horizon (hoe pan)

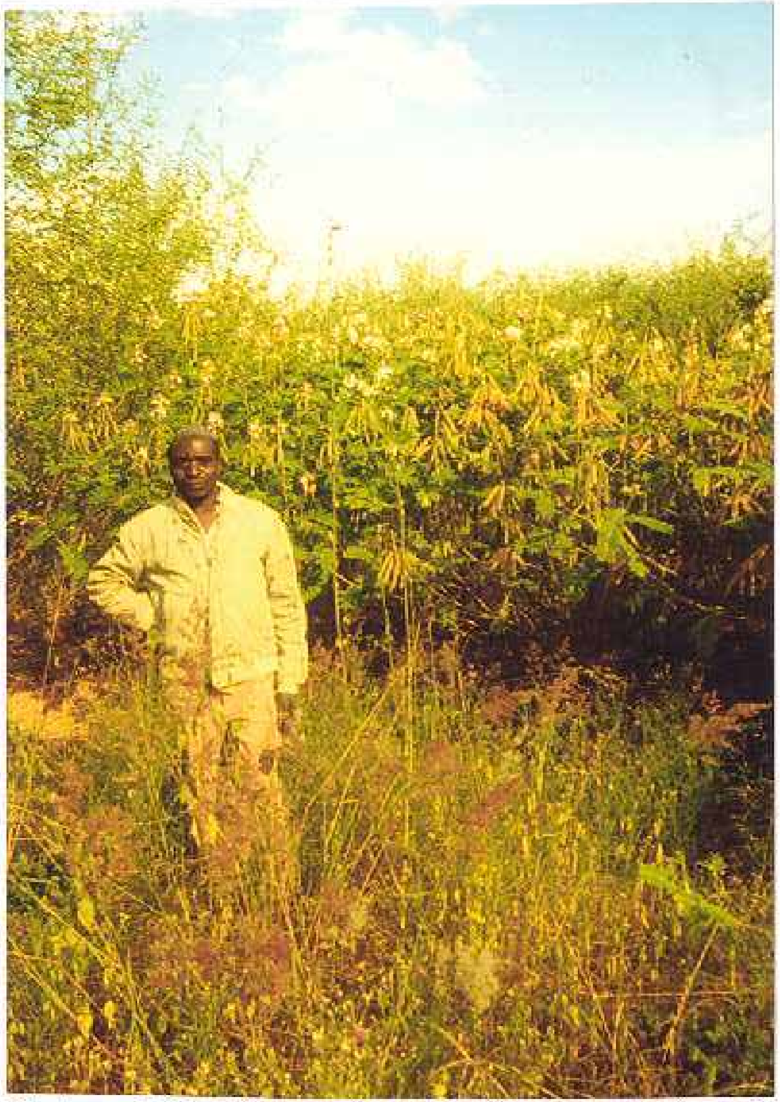
Photograph 6. Tobacco tap root distortion due to the presence of compacted upper subsoil horizon (hoe pan)

Photograph 7. Subsoil compaction induced distortion of the tap root of two weeds (black jack) growing in a maize field



Photograph 8. Sideways development of the tap root of a wild okra weed (growing in a maize field) on meeting a compacted layer (hoe pan) at the base of the crop ridge

Photograph 9. Maize root development in a sandy soil without a compacted subsoil (hoe pan) layer



Photograph 10. **The growing of *Tephrosia vogelli* (centre) and *Sesbania sesban* (left) as a 1-2 year fallow break is one way for farmers to both restore soil fertility and break a compacted subsoil layer (Kasungu, May 1999)**

Photograph 11. **Intercropping maize with alleys of the deep rooted shrub, *Gliricidia sepium*, was reported by the farmer to improve rainfall infiltration compared with an adjacent pure stand maize plot (Zomba, February 1999)**

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