

Population dynamics and management response of N₂-fixing indigenous legumes for soil fertility restoration in smallholder farming systems of Zimbabwe

By

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Dedication

This work is dedicated to my family and my loved one. Glory be to the Almighty for all the blessings granted unto me.

Abstract

The main problem undermining food security in most smallholder farming systems in Zimbabwe is the limited range of alternative nutrient resources for a wide range of farmers and soils. This study was initiated to investigate field establishment patterns, population dynamics and management dynamics of potential indigenous legume species found in smallholder farming systems of Zimbabwe. Germination patterns were determined under laboratory conditions following various scarification procedures using a germination test technique while field studies were conducted under low (450-650 mm yr⁻¹) to high (>800 mm yr⁻¹) rainfall conditions in Zimbabwe on nutrient depleted soils. Indigenous legume seeds were broadcast on disturbed soil in mixtures at 120 seeds m⁻² species⁻¹ over two growing seasons: 2004/05 and 2005/06 rainfall seasons. Low emergence rates among species were attributed to seed hardness and low seed viability, accounting for > 50 % and 10 - 30 % of germination failure, respectively. Acid scarification significantly (P<0.05) increased germination while hot water treatment had no effect on germination. *Crotalaria pallida* and *C. ochroleuca* were the first to emerge within 14 days from seeding while emergence for other species was spread over two months. *Eriosema ellipticum* had a highest population of 42 plants m⁻² (8 %) while *Crotalaria pallida*, *Crotalaria cylindrostachys*, *Crotalaria ochroleuca* and *Indigofera arrecta* had populations of < 23 plants m⁻² (5 %). Species biomass contribution into the system was spread across time and in space characterized by slow initial growth rate compared to that of non-legume species. Three months after sowing, annual herbs such as *C. cylindrostachys* and *C. glauca* attained peak biomass of 0.5 t ha⁻¹ (dry weight) while other annuals, *C. ochroleuca* and *C. pallida*, attained maximum biomass (> 5 t ha⁻¹) within a growth period of six months. Most biennials only attained maximum biomass in the second season with seasonal yields not exceeding 2 t ha⁻¹. Application of single super phosphate (SSP) or Dorowa phosphate rock (DPR) had no significant (P>0.05) effect on legume species composition and establishment patterns but SSP significantly increased biomass productivity by 20-60 %. Non-legume species responded to SSP application and recovered more phosphorus than legumes. Following addition of SSP, the amount of N fixed by *Crotalaria cylindrostachys*, *C. ochroleuca* and *C. pallida* increased by 2, 27 and 51 kg N ha⁻¹ respectively, resulting in increased total N fixed within the system. Over time in the first season, the abundance of predominant non-legume species such as *Cynodon dactylon* (a grass species) and *Richardia scabra* (a broadleaf species) was suppressed to 17 % and 7 % respectively, while the abundance of the same species in natural fallows increased. There was insignificant change in legume species diversity in the second season characterized by persistent growth of about 50 % of the sown species. However, non-legume species diversity decreased as *C. dactylon* dominated apparently associated with increased N availability. These findings suggest that the indigenous legumes could contribute in restoring productivity of soils continuously cultivated fields with little or no nutrient inputs in most parts of Zimbabwe and similar agro-ecologies in Sub-Saharan Africa. However, low germination of these indigenous legumes still remains a challenge.

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CHAPTER 1

INTRODUCTION

1.0 Background

Natural fallows are a common feature of farming systems in the sub-humid and semi-arid zones of Southern Africa, with over 30% of available land fallowed in any one season (Mafongoya *et al.*, 1998; Mapfumo and Giller, 2001). Low soil fertility and lack of fertilizers have been cited as some of the reasons for fallowing (Nyakanda *et al.*, 2002). Resource-constrained farmers largely depend on natural fallowing for soil fertility restoration (Mtambanengwe and Mapfumo, 2005). However, the current fallowing cycles have been revealed to be too short to build the fertility of soil to levels that can sustain meaningful crop production (Hikwa *et al.*, 1998; Mapfumo and Giller, 2001). Efforts to improve the quality of fallows through agroforestry tree crops such as *Leucaena*, *Sesbania* and *Acacia spp* have often been hindered by high establishment costs and lack of immediate benefits to the farmer (Kwesiga and Coe, 1994; Snapp *et al.*, 1998). There is a need for continued exploration of technologies that can reduce fallow periods, fallow establishment costs and at the same time contribute sufficiently to generation of soil fertility benefits.

In most smallholder farming systems of Sub-Saharan Africa, resource-constrained farmers depend almost entirely on locally available nutrient resources for soil fertility restoration (Mapfumo and Giller, 2001). However, the farmers often do not apply the recommended rates of manure and mineral fertilizers due to a number of reasons (Mugwira, 1985; Chuma *et al.*, 2000), which reduces the potential benefits associated with relatively large

quantities of manure or fertilizers. There is a need to focus on alternative options for increasing crop production, drawing from indigenous knowledge and resources.

Legumes have been known to make realistic nitrogen (N) addition to the cropping systems through biological nitrogen fixation (BNF) (Giller *et al.*, 1997; Mapfumo *et al.*, 1999; Gathumbi *et al.*, 2002). However, most grain legume species such as chickpea (*Cicer arietinum*), soybean (*Glycine max*), faba bean (*Vicia faba*) and groundnut (*Arachis hypogea*), have failed to make significant N contribution to the systems partly due to high harvest indices (> 70%) and poor biomass productivity (< 2 t ha⁻¹) (Sanchez *et al.*, 1997; Gilbert, 1998; Mapfumo and Giller, 2001). Furthermore, some N₂-fixing legumes have failed to significantly improve soil fertility of nutrient-depleted sandy soils with < 0.5% organic carbon and < 5 mg kg⁻¹ available phosphorus partly due to poor stand establishment (Mapfumo *et al.*, 1999; Chikowo *et al.*, 2004). Kamanga and Shamudzarira (2001) also reported that at least 60% of the smallholder farmers selectively use their poorest fields for grain legume production resulting in poor germination and stand establishment. Thus, it is important to develop and evaluate alternative establishment options. For example, establishment of mucuna (*Mucuna pruriens*) on sandy soils in Zimbabwe has been reported to be highly productive when phosphorus is applied (Hikwa *et al.*, 1998).

Apart from poor soil fertility, other causes of poor legume establishment include planting method and depth, quality of seed (seed dormancy and hard seedness), competition from grass and other plant species and low rhizobial population in soils (Clatworthy and Thomas, 1972; Grant, 1979; Mpeperekwi and Makonese, 1998). Successful establishment of legumes is determined by biomass productivity and amount of N fixed in a given

environment (Giller and Wilson, 1991; Gilbert, 1998). In natural ecosystems, N₂-fixing legumes have been revealed to be the most important species in early successional phases (Gorham *et al.*, 1979) but little is known about such successional patterns in natural grass fallows (natural fallows). Most studies on legumes have focused on biomass productivity, N₂-fixing capacity and residual fertility benefits of legumes (Hooper and Vitousek, 1998; Mapfumo, 1999; Chikowo *et al.*, 2004; Mafongoya *et al.*, 2006) with little attention on population dynamics of the legumes.

Phosphorus (P) deficiency is often a major factor limiting biomass production and N₂-fixation of legumes in both cropping and natural systems (Giller and Mapfumo, 2002). There is a paucity of information on the influence of P application on plant species composition and abundance in managed fallows. The main sources of P in cropping systems are from weathering of soil minerals, release from soil sorption sites and mineralization of soil organic matter. However, most soils in sub-Saharan Africa are old and highly weathered resulting in low available P (Giller, 2001) and most locally available nutrient resources have insufficient P to meet the requirement for sustainable crop production.

A strategic option to increasing available P on nutrient depleted soils is through application of soluble inorganic phosphate fertilizers. However, the high cost of soluble inorganic phosphate fertilizers and their inaccessibility has generated considerable interest in the utilization of phosphate rock (PR) (Akande *et al.*, 1998; Nandi and Haque, 1998; Dhliwayo, 1999). Legumes such as lupin (*Lupinus angustifolius*) have been shown to increase the dissolution and utilization of PR compared with non-legumes mainly due to rhizosphere acidification (Kamh *et al.*, 1999; Horst *et al.*, 2001).

After the advocacy for ecological approaches to agriculture (Giller and Cadisch, 1995; Mafongoya *et al.*, 2006), most studies targeted agroforestry tree species for soil fertility management. Despite some of these agroforestry species having great potential, most resource-constrained farmers often failed to adopt them partly due to the high costs involved in the establishment process. Some of the establishment costs include purchase of seed, raising seedlings and meeting labour demands. Most of the agroforestry tree species were also non-coppicing leading to reduced additional organic inputs derived each year from regrowth and an associated decline in maize yields after the second year of cropping (Mafongoya *et al.*, 2006).

Continued establishment failure of single species fallows, mainly attributed to adverse weather conditions (drought, water logging) and low fertility justifies the need for mixed species fallows. The advantages of mixed-stand fallows include increased biodiversity, sustainability of the fallow system, insurance against failure, production of multiple products (fire wood or stakes for climbing crops and light construction wood), improved utilization of available growth resources and reduction of pest pressure (Gathumbi *et al.*, 2004). There is a need for continued exploration of legume-based technologies that are appropriate for all the ranges of farmers and soils.

Over 36 different indigenous legumes species mainly of the genera *Crotalaria*, *Indigofera*, *Rothia* and *Tephrosia* have been identified across different agro-regions in Zimbabwe (Mapfumo *et al.*, 2005). The capacity of these indigenous legumes to establish and grow on nutrient-depleted soils where maize was failing to yield any grain, and where most cultivated annual legumes are usually constrained, is indicative of their potential for

fertility management. This led to the introduction of indigenous fallows (indifallows) concept which involve harnessing self-generating indigenous herbaceous legumes in dense stands in order to improve the N economy of natural fallows (Mapfumo *et al.*, 2005). Building an understanding on the indigenous legume species might be a starting point in the utilisation of a possible nutrient resources existing in our agro-ecosystem for most resource-poor farmers in Southern Africa. However, these indigenous legumes remain unexploited with very little information available regarding their propagation, establishment pattern, population dynamics and management responses. This study investigated the growth performance of indigenous legume species on nutrient depleted soils under smallholder farmer management conditions.

1.1 Hypotheses

The hypotheses that guided this research were:

1. Mixing indigenous legume species of different growth habits ensures successful establishment of indifallow systems that accumulate more biomass to influence soil fertility than natural fallows.
2. Indigenous legume species established in mixtures under one year indifallows are able to persist into the second year without change of species composition or influence on the growth of non-leguminous companion species.
3. Phosphorus application on nutrient depleted soils influences persistence, N₂-fixation and biomass productivity of indigenous legume species in indifallow systems.

1.2 Overall objective

To investigate the establishment patterns, population dynamics and management response of N₂-fixing indigenous legume species for restoration of nutrient depleted soils on smallholder farms.

1.3 Specific objectives

The study had the following specific objectives:

1. To establish germination profiles, emergence and establishment patterns of indigenous legumes under field and laboratory conditions.
2. To determine biomass accumulation patterns of different indigenous legumes and non-leguminous species grown in mixtures under indifallow systems in comparison with natural fallows.
3. To study changes in composition and abundance of indigenous legumes and non-leguminous species grown in indifallow systems over two years in relation to natural fallows under smallholder farm conditions.
4. To evaluate the effect of P application and source on persistence, N₂-fixation and biomass productivity of indigenous legume species under indifallow systems.

CHAPTER 2

LITERATURE REVIEW

2.0 Soil fertility management in Zimbabwe

Over 70% of soils in agro-ecosystems of Zimbabwe have severe fertility constraints, generally yielding less than 1 t ha^{-1} of maize grain (*Zea mays* L.) (Grant, 1981; Mapfumo *et al.*, 2005). Nitrogen and phosphorus are the most limiting nutrients in the predominantly granite derived soils of Zimbabwe (Nyamapfene, 1991). Efforts to increase the N and P availability in these soils using locally available nutrient resources is limited by low quality materials, leading to low supply of N and P to crop production (Giller *et al.*, 1997). For example, miombo litter has been shown to immobilize N instead of supplying N immediately to the crops (Mtambanengwe and Kirchmann, 1995; Mafongoya and Nair, 1997). Mineral fertilizers are accepted as a way to supply N and P to increase productivity (Mapfumo and Giller, 2001). However, fertilizers are being applied at suboptimal rates due to high cost and unavailability in smallholder farming areas. For most smallholders, fertilizer use is as low as $5\text{--}30\text{ kg ha}^{-1}\text{ yr}^{-1}$ (Gerner and Harris, 1993; Chuma *et al.*, 2000).

Many of the farm land in smallholder farming systems are often abandoned by farmers due to lack of appropriate technologies to revitalize them (Mapfumo and Giller, 2001). A wide range of locally derived fertilizers (animal manure, leaf litter, termitaria) and crop residues have been used by farmers but without much impact usually due to inaccessibility and unavailability (Carter and Murwira, 1995; Campbell *et al.*, 1998). Most crop residues are usually fed to livestock in the dry season or burnt during land preparations resulting in limited use of crop residues in soil fertility management. Despite grass fallows being

unproductive, still most resource-constrained farmers desperately resort to natural fallowing as a soil restorative practice.

Studies have revealed strong relationships between farmer resource endowment and adoption of soil fertility management options. For example, cattle manure can be the cheaper source of organic fertilizer but is a privilege (accessible and available) for cattle owners. Manure application improves soil fertility through supply of nutrients (calcium (Ca), magnesium (Mg), nitrogen (N) and phosphorus (P)), improvement of soil structure, increasing water holding capacity and neutralizes soil acidity (Nzuma *et al.*, 1998). However, most farmers can not apply the recommended 10 t ha⁻¹ of manure (Mugwira, 1985) thereby reducing the potential benefits associated with manure for soil fertility improvement. Annual woodland litter fall may be as high as 5 t ha⁻¹ but the total amount of leaf litter incorporated in the field is often < 1.2 t household⁻¹ (Nyathi and Campbell, 1993) due to lack of labour and draft power needed for collection and transportation, respectively. Most communal areas are also in severe state of deforestation which further reduces the availability of leaf litter to households. Although termitarium soil enhances some soil physical properties and benefits can last for 4 - 5 years (Chibudu *et al.*, 1995; Mapfumo *et al.*, 1997), the high labour associated with digging and application of termitarium soil is a major limitation to resource-constrained farmers. The current limitations of most locally available resources suggest that there is need to identify alternative organic nutrient sources for smallholder conditions. Recently, over 36 different indigenous legume species have been identified in Zimbabwe but still remain untapped (Mapfumo *et al.*, 2005). These indigenous legumes were found to grow on abandoned soils on which other legumes failed to make impact and maize crops failed to yield any grain.

2.1 Use of legumes in soil fertility restoration

In most smallholder farming systems of Zimbabwe, systematic grain legume-cereal rotations are not feasible due to the difference in areas under legumes and cereals. Studies have demonstrated that legumes in fallows improve nutrient cycling through litter fall and retrieval of subsoil nitrogen and biological N₂-fixation (Palm, 1995; Gathumbi *et al.*, 2004; Mafongoya *et al.*, 2006). Improved fallows with *Sesbania sesban* and *Tephrosia vogelii* have been shown to give maize grain yields of 3 to 4 t ha⁻¹ without supply of mineral fertilizers (Dzowela, 1998). Despite the potential of improved fallows, adoption in most smallholder farming areas remains low and insignificant due to a number of reasons. The high labour demands required in cutting, transporting and managing prunings make improved fallows unpopular with farmers (Jama *et al.*, 1998). Other successful fallow species such as *Sesbania sesban* and *Crotalaria grahamiana* have increasingly become susceptible to pest and diseases or led to outbreaks of new pest and disease (Cadisch *et al.*, 2002).

Despite green manures increasing maize grain yields following incorporation (Marura *et al.*, 2000) adoption still remains low particularly under unimodal rainfall pattern compared to bimodal rainfall pattern. Apart from the possible N losses, seed availability and labour requirements for land preparation and ploughing-under of the green manure become major constraints for most farmers (Muza, 2003). Most soils cultivated by smallholder farmers are exhausted and production of legumes is constrained by poor availability of nutrients, especially P (Giller, 2001). Hikwa *et al.* (1998) showed that rehabilitation of such soils by *Mucuna pruriens* was only possible when P fertilizers were supplied, and in some cases P alone was not enough to stimulate good growth (Zingore *et al.*, 2007). Given that

indigenous legume seed can easily be collected by farmers and that these species are adapted to low P soil the cost associated with seed and P fertilizers might be reduced.

2.2 Species germination and emergence profiles

The necessary activities for a seed to complete the process of germination include water imbibition, germination, radicle entry to the soil and commencement of root growth (Kusekwa and Lwoga, 1985). This is a simple process in a cultivated land where the soil is moist. However, limited soil-seed contacts, light condition on the surface and water availability are some environmental conditions that may limit germination (Ghorbani *et al.*, 1999). For surface sown seeds the relative humidity of the micro-environment surrounding the seed is important. Germination of some seed also requires light but is normally inhibited by vegetation-filtered (far-red) light and enhanced by fluctuations temperature (Alteri and Liebman, 1988). Seed germination at greater sowing depth in the soil may also be prevented by inadequate oxygen, lack of light and low temperature, while delayed emergence is due to the larger distance to extend the coleoptile to the soil surface. If seed is placed just below the surface and receive adequate water, it would emerge using the limited carbohydrate reserves (Ghorbani *et al.*, 1999). Germination and growth amongst relatively small-seeded species such as *Antyllis*, *Hippocrepis* and *Cistus* may be improved by supplying external source of N, P and K because their internal nutrient reserves are low (Fenner and Lee, 1989). Addition of some fertilizers is often essential at sowing as the seedlings have a high requirement for nutrients but have insufficient root growth to compete effectively with the associated grasses (Giller and Wilson, 1991). Phosphorus is the most commonly required nutrient at early root development. However, larger seeded species such as the pine tree (*Pinus brutta*) contain enough essential

minerals to supply the seedling through out the early establishment period. These larger seeded species can also emerge from greater depth.

While emergence profiles may vary from year to year depending upon environmental conditions, the emergence patterns of different species remain relatively consistent in relation to each other (Hartzler, 2000). The size of food reserve in the seed (seed size) provides information on both the length of emergence and distribution of emergence. Some species germinate readily soon after seeding while others germinate a little bit later or do not germinate at all due to difference in genetic makeup. For instance, under laboratory and glasshouse conditions indigenous legume species generally had low germination. Studies by Venge (2003) showed that *Eriosema ellipticum*, a perennial legume in Zimbabwe had the highest while some species such as *Rothia hirsuta* and *Tephrosia radicans* did not germinate at all. Some leguminous species have hard seeded coats, which need to be scarified for them to germinate or to increase germination. This study might provide more information on the factors affecting establishment and populations under natural environment and managed conditions.

2.3 Factors affecting nitrogen fixation and legumes growth

Soil nutrient availability is a primary factor driving nitrogen fixation and legume establishment (Giller, 2001; O'Hara, 2001). Legume-rhizobium symbiosis is often limited by phosphorus, molybdenum (Mo), sulphur (S) and zinc (Zn) deficiencies in soils deficiencies. Calcium is important for root infection and nodule formation in legume BNF while cobalt is required by N₂ fixing bacteria for electron transport. Among the potential nutritional constraints to legume growth, availability of P is often overriding in both agricultural and natural ecosystems (Giller and Wilson, 1991). Phosphorus deficiency

appears to be the most limiting nutrient to legume biomass productivity and N₂-fixation leading to low yield of subsequent cereal crops (Giller, 2001). Phosphate fertilizer application is necessary to support the luxurious growth of green manures. For example, application of 8 kg P ha⁻¹ + 4 kg S ha⁻¹ was shown to improve the biomass of *Mucuna pruriens*, *Cajanus cajan* and *Tephrosia vogelii* in Malawi (Malwanda *et al.*, 2002).

In soil with low N levels, symbiosis is initiated between the legume roots and the rhizobia, causing nodulation and nitrogen fixation to occur. However, in systems dominated by legumes, such as fodder banks, rates of N₂ fixation decline as the system accumulate N in the soil (Vance, 2001). According to Munns (1977) high plant available N in the soil inhibits nodule development, nitrogenase activity and accelerates nodule senescence in the short term. Over long periods, this high available N would promote plant growth which would then deplete the soil mineral N resulting in renodulation of the legumes (Dart, 1977). Toxic levels of aluminum (Al), manganese (Mn) and other heavy metals have been reported to interfere with the process of nodule formation in legumes and survival of N₂-fixing bacteria in acid soils (Giller 2001; Metcalf, 2005). When Al concentration in the soil is high, dry matter production of tropical pastures dependent on symbiotically fixed N was shown to decrease (Carvalho *et al.*, 1981). However, application of 4 t ha⁻¹ of millet straw to a groundnut crop reduced the imbalance caused by soil acidity (Al and Mn toxicity) coupled with increased availability of molybdenum (Mo) resulting in the doubling of accumulated N (Rebafka *et al.*, 1993).

Soil moisture also affects legume performance with both water-logging and drought conditions reducing legume growth (Muza and Mapfumo, 1998). Inadequate rainfall has been reported to affect legume biomass productivity of *Tephrosia vogelii* (Rutunga *et al.*,

1999). Low soil water can reduce nodulation by as much as 50 % and continued water stress can irreversibly damage nodules and bacteria, permanently stopping N₂-fixation (Abdel-Wahab *et al.*, 2002). Low or high temperature also delays the establishment and functioning of the symbioses.

2.4 Biomass productivity of legumes in smallholder farming systems

Most legume-based soil fertility improving technologies have failed to make the desired impact on nutrient-depleted soils partly due to low N₂-fixation rates and poor biomass productivity (Mapfumo, 2000; Nhamo *et al.*, 2002). The impact of legumes on soil fertility restoration depends largely on the amount of biomass the legumes produce. The minimum legume biomass required to make a significant impact on soil fertility is above 2 t ha⁻¹ which generates about 60 kg N ha⁻¹ (Gilbert, 1998). In Western Kenya, Ojiem *et al.* (1998) reported dry matter accumulation of up to 9 t ha⁻¹ for all green manure legumes (*Crotalaria ochroleuca*, *Crotalaria grahamiana*, *Crotalaria incana* and *Mucuna*) while soybean accumulated dry matter of about 2 t ha⁻¹. Kamanga and Shamudzarira (2001) recorded dry matter yield of < 1 t ha⁻¹ for *C. grahamiana*, *Vigna subterranea* and *Vigna unguiculata* in Zimuto Communal Area in Zimbabwe. Such poor biomass production is a major factor undermining the capacity of grain legumes to improve the fertility of sandy soils in Zimbabwe (Mapfumo *et al.*, 1999). Low soil fertility on abandoned fields contributed to poor legume performance compared to homestead fields which are relatively fertile due to a history of manure and household waste applications (Kamanga and Shamudzarira, 2001).

According to Giller (2003) an initial application of 20-30 kg P ha⁻¹ is critical in biomass productivity in most soils. Application of plant residues or manure will provide some P

but mineral P fertilizers are the most effective. However, legumes differ in their ability to utilize available forms of P in the soil and large differences exist between plant species and cultivars within species (Rao *et al.*, 1999). Species growth habits can also influence the biomass contribution in a system despite the soil being fertile. For example Ojiem et al (2000) noted that *Calopogonium mucunoides* and *Mucuna pruriens* produced low biomass due to their low initial growth rates, which increase substantially 2-3 months after planting. This study might bring back abandoned field into production by managing indigenous legume species which are adapted to nutrient depleted soils where other legumes often fail to yield significant biomass.

2.5 The benefits associated with mixed legume fallows

Developing integrated pest management through mixing species has been considered to be an option for increasing benefits associated with most legume based soil fertility technologies (Sileshi *et al.*, 2002). Furthermore, mixing species in fallows provides a better risk management strategy through compensatory biomass and nutrient production gains obtained from the strongly competing species (Gathumbi *et al.*, 2004). For example, indigenous legumes in sole stands would contribute about 3-17 % of the total biomass translating to $< 5 \text{ kg N ha}^{-1}$, while mixing species increases contribution up to 40 % of total biomass which translates to potential N inputs of 6-53 kg N ha^{-1} (Mapfumo *et al.*, 2005). Mixing species also enhances the uptake of soil water and nutrients within the soil profiles due to differences in rooting depth and ability to exploit resources (Farley and Fitter, 1999; Nordin *et al.*, 2001). Mulder et al (2002) showed that the percent legume in plots was the single most important factor-controlling %N, total N and $\delta^{15}\text{N}$. Increased diversity could lead to greater niche complementarity, influencing the N release patterns in the system as a result of different quality of biomass, and extends the time of residual

effect. Mixed fallows of sprouting species such as *Gliricidia sepium* and a non-sprouting species *S. sesban* significantly increased grain yield to 4.8 t ha⁻¹ from single species yield of 3.7 t ha⁻¹ and 4.3 t ha⁻¹, respectively (Mafongoya *et al.*, 2006). Species richness could result in greater microbial diversity and higher decomposition rates, although there is no empirical data to support this hypothesis. The indifallow concept involves using a mixture of indigenous legume species for soil fertility management which might reduce the risk of single species.

2.6 Species interaction in mixed stands

The effects of species interaction in mixed stands can either be negative or positive depending on the competitive utilization of available resources (above and below ground) in relation to the companion species. For example, the accumulated N yield of *Sesbania* was decreased by 54 % and 67 % when mixed with pigeon pea and crotalaria, respectively (Gathumbi *et al.*, 2004). This was attributed to poor initial establishment of *Sesbania* and in about 60 % reduction in biomass productivity due to interspecific competition from the surrounding crotalaria or pigeon pea plants which were stronger competitors in the mixtures. Plantation studies conducted in the humid tropics of Costa Rica also showed that biomass of *Genipa Americana* and *Vochysia ferruginea* trees were reduced by 55-60 % in mixture than in pure stands. In contrast, *Hieronyma alchorneoides* and *Pithecellobium elegans* trees grew 40-50 % more rapidly in mixture (Stanley and Montagnini, 1999). Species interaction in mixtures can be greatly influenced by initial establishment of species, as demonstrated by the low biomass and N yield observed for *S. sesban* in mixed species fallows. Poorly established species in mixtures compete less vigorously than fast growing species and this greatly influences the final benefit of the fallow (Gathumbi *et al.*, 2004).

2.7 Ecology of legumes and grass species in relation to N economy

In natural ecosystems, N_2 -fixation is more important in early successional phases unless other nutrients are strongly limiting, but becomes relatively unimportant as the amount of N in the soil gradually accumulates (Figure 2.1). However, at later stages of primary or secondary succession when the system becomes more abundant in C and limited in N, there would be a resurgence of N_2 -fixation (Gorham *et al.*, 1979). Agricultural systems are also influenced in the same way, and rate of N_2 fixation are largest when N is limiting but other nutrients plentiful.

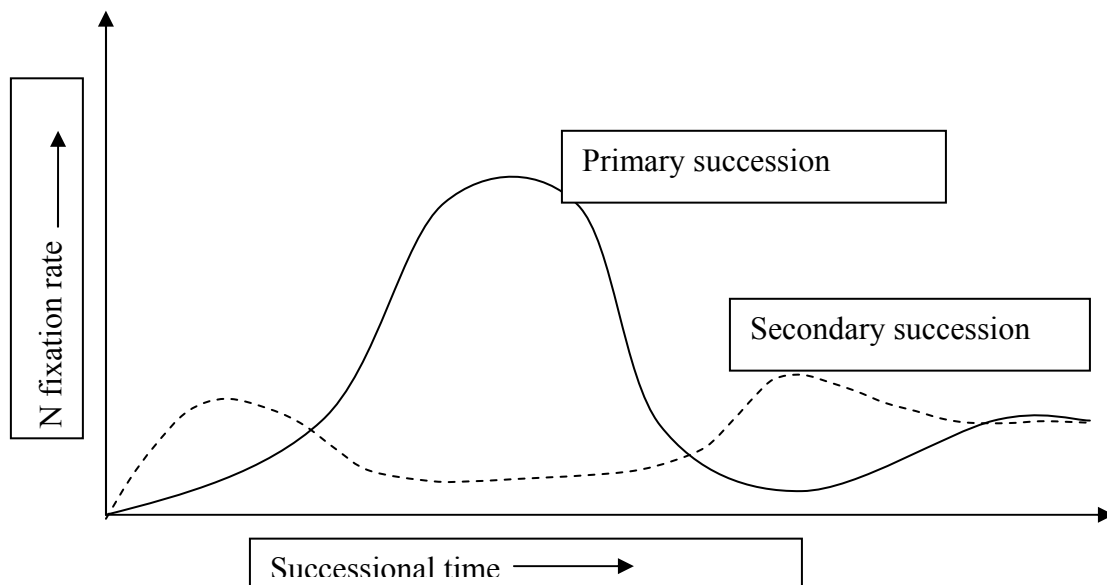


Figure 2.1 Changes in the relative importance of N_2 -fixation at different stages in vegetation succession (After Gorham *et al.*, 1979).

Persistence of a species refers to its ability to repeatedly invade an environment even when it was apparently removed from the scene by man (or any other agent). Both legumes and non-legume species have different mechanisms of persistence. For example high persistence of weeds is attributed to their prolific seed production, dormancy of seed, vegetative propagation and rapid dispersal. The difference in rooting systems of species can also affect persistence of species in a system (Oberson *et al.*, 2001). Currently there is

limited information on the mechanisms that promote indigenous legume persistence in fallow systems and such information is required to fully utilize these legumes for soil fertility management.

2.8 Utilization of phosphate rock (PR) as a source of P in cropping systems

The use of local resources such as Dorowa phosphate rock may be a feasible alternative to satisfy the farmers' needs, both agronomically and economically. However, direct use of Dorowa phosphate rock (DPR) as a P source is limited due to low solubility in neutral and alkaline conditions (Dhliwayo, 1999). Ground phosphate rock has been reported to be beneficial to crops only in acidic soils (Nnadi and Haque, 1988). Current efforts have been directed at composting of phosphate rock with agricultural waste, and results have shown an increase in solubility of phosphate rock (Akande *et al.*, 1998; Akande *et al.*, 2005). Akande *et al.*, (2003) reported an increase in okra (*Abelmoschus esculentus*) yield grown under combination of phosphate rock and poultry manure. However, availability and accessibility of poultry manure is dependent on the number of birds on the household and can be the major limitation to adoption.

Legumes have also been shown to increase the dissolution and utilization of phosphate rock compared with non-legumes mainly due to rhizosphere processes. The combined effect of rhizosphere acidification and higher Ca uptake by lupin (*Lupinus angustifolius*) increased the release of P from PR (Kamh *et al.*, 1999; Horst *et al.*, 2001). There is limited use of Dorowa phosphate rock in Zimbabwe due to its indigenous nature and low solubility despite the vast deposit of the rock. This study seeks to generate information on the role of indigenous legume species in influencing soil P availability from PR.

CHAPTER 3

GENERAL MATERIALS AND METHODS

3.0 Introduction

This chapter gives details of the common methods used in the various parts of this thesis. The study was conducted in two concurrent sets of experiments: (a) laboratory germination tests, and (b) field experiments. The germination tests were conducted at the Seed Services in the Department of Agricultural Research for Development of the Ministry of Agriculture.

3.1.0 Field study sites and farming systems

The study was conducted in 2005/06 and 2006/07 rainfall seasons under smallholder farming conditions at Chinyika Resettlement Area (18°13'S, 32°22'E) and Chikwaka Communal Area (17°44'S, 31°29'E). Parallel studies were also conducted on-station at Domboshawa Training Centre (Domboshawa) (17°35'S, 31°14'E) and Makoholi Experimental Station (Makoholi) (19°47'S, 30°45'E). Domboshawa and Chikwaka which are 30 km and 80 km northeast of Harare respectively are in Agro-ecological Region (NR) II of Zimbabwe which receives over 800 mm of rainfall annually. Chinyika is 250 km east of Harare in NR III (650-750 mm yr⁻¹) and has been under smallholder cultivation since 1983 when farmers were resettled there. The area had been under commercial crop-livestock farming before then. In Chikwaka, experiments were hosted by farmer Nyamayaro while in Chinyika three farmers hosted the experiments namely Mudange, Chikodzo and Masara. Makoholi experiment station is about 300 km southeast of Harare

and in NR IV (450-650 mm of rainfall per annum). Rainfall at all sites follows a unimodal pattern with rains received between November and March.

The soils at all sites are granite-derived sands to loamy sands that are classified as Lixisol under the World Reference Base system (World Reference Base, 1998). The soils are largely depleted of nutrients (Table 3.1). The soils are acidic with pH 4.1 – 4.6 (CaCl₂), low organic carbon (C) = 0.4 – 0.5 %, low available P = 3 – 5 ppm, exchangeable Ca = 0.3 – 0.7 cmol_c kg⁻¹, exchangeable Mg = 0.3 – 0.7 cmol_c kg⁻¹, exchangeable K = < 0.2 cmol_c kg⁻¹ and clay < 8 % (Table 3.1). The soils at Domboshawa and at Chikodzo farm in Chinyika were relatively fertile with available P = 9 - 15 ppm, 22 % and 10 % clay content, respectively (Table 3.1). Apart from Domboshawa and Chikodzo soils, most of the soils had < 0.05 ppm total N (Table 3.1). There is a relationship between high organic C and the mineralizable N in these soils. For example, Domboshawa soil produced the highest mineralizable N (35 mg ka⁻¹) from 0.7 % organic C while Makoholi only manage to give 17 mg kg⁻¹ mineral N from 0.4 % organic C (Table 3.1).

The farming systems in all the areas are maize-based, characterized by crop-livestock interactions and with low legume utilization. Groundnut (*Arachis hypogaea*), bambara (*Vigna subterranea*) and cowpea (*Vigna unguiculata*) are most widely grown as sole legumes but often on small pieces of land (e.g. < 0.3 ha) (Mapfumo *et al.*, 2005). Cattle manure, leaf litter, mineral fertilizers and fallowing are the predominant methods used for soil fertility management in such areas (Mapfumo and Giller, 2001).

Table 3.1 Physical and chemical characteristics of soils at study sites where indigenous legumes were established.

Site	Clay	Sand	Organic C	Total N	Available P	Mineral N	pH	Ca	Mg	K
	(%)	(%)	(%)	(%)	(ppm) ^a	(mg kg ⁻¹) [*]	(0.01 M CaCl ₂)	(cmol _c kg ⁻¹)		
Domboshawa	22	72	0.7 _(0.08)	0.06 _(0.003)	15 _(0.3)	4.8 _(0.15)	4.8 _(0.15)	0.8 _(0.06)	0.4 _(0.01)	0.1 _(0.005)
Makoholi	8	81	0.4 _(0.02)	0.03 _(0.005)	3 _(0.5)	4.6 _(0.13)	4.6 _(0.13)	0.3 _(0.02)	0.3 _(0.02)	0.1 _(0.004)
Chikwaka	8	79	0.4 _(0.06)	0.04 _(0.006)	4 _(0.1)	4.5 _(0.11)	4.5 _(0.11)	0.4 _(0.01)	0.5 _(0.01)	0.2 _(0.001)
Mudange ^{**}	7	89	0.5 _(0.05)	0.05 _(0.005)	5 _(0.4)	4.1 _(0.05)	4.1 _(0.05)	0.7 _(0.01)	0.5 _(0.02)	0.2 _(0.005)
Chikodzo ^{**}	10	86	0.6 _(0.04)	0.06 _(0.002)	9 _(0.2)	4.5 _(0.12)	4.5 _(0.12)	1.0 _(0.02)	0.8 _(0.04)	0.3 _(0.004)
Masara ^{**}	8	75	0.4 _(0.05)	0.04 _(0.007)	4 _(0.6)	4.8 _(0.13)	4.8 _(0.13)	0.6 _(0.03)	0.7 _(0.03)	0.1 _(0.003)

Chikwaka = Nyamayaro field; ^{**} = fields in Chinyika

^{*}Mineralizable N after two weeks of anaerobic incubation.

^aAvailable P measured using the Olsen method.

Figures in parentheses denote standard error.

3.1.1 Initial soil sampling and preparation

Soils were sampled from respective field sites by collecting a total of 5 sub-samples from 0-20 cm depth using an auger. The sub-samples were thoroughly mixed in a clean polystyrene bucket, after which a 1 kg composite sample was withdrawn and put into a polythene bag for laboratory analysis. The air-dried soil samples were characterized for texture, pH, organic carbon (OC), bases, Cation Exchange Capacity (CEC), P and N.

3.1.2 Determination of soil texture

Soil texture was measured using the Hydrometer method (Gee and Bauder, 1986). Air-dried soil (50 g) was weighed into a 600 ml beaker and 100 ml of sodium hexametaphosphate (calgon) added. The beaker was filled to the 500 ml mark with distilled water and the mixture was put on an automatic shaker overnight, and then left to stand for at least 10 minutes. The mixture was transferred into a dispersing cup of an electric mixer and stirred for 5 minutes. Using a plunger, the suspension was thoroughly mixed by moving it up and down for 1 minute. The hydrometer was gently placed into the cylinder, and its reading noted at 40 seconds and 5 hours after plunging. The temperature of the solution was also noted. The hydrometer and temperature readings were then used to calculate the corrected hydrometer.

3.1.3 Determination of soil pH

Soil pH was determined using the CaCl_2 method (Thomas, 1996). To a soil sample weighing 10 g, 25 ml of 0.01M CaCl_2 solution was added. The mixture was shaken for 30 minutes. Prior to taking the pH reading from the pH meter the electrode was thoroughly rinsed free of buffer solution. The suspension was stirred up and the electrode immersed

into the suspension making sure it did not touch the base of the beaker. When the pH reading was stable, the displayed value was recorded (McNeal, 1982).

3.1.4 Determination of soil organic carbon

A modified Walkley-Black dry combustion method was used to determine the percentage of organic carbon in the soil samples (Anderson and Ingram, 1983). About 15 g sucrose was dried at 105 °C for 2 hours and 11.87 g of this were dissolved in water. The solution was made up to 100 ml in a volumetric flask, to make a 50 mg C ml⁻¹ solution. Two and half to 25 ml of the solution were pipetted into labeled 100 ml volumetric flasks, at 7.5 ml intervals, and made to the mark with deionized water. Two milliliters of each of these working standards were pipetted into labeled 150 ml conical flask and dried at 105 °C in an oven.

One gram of air-dried soil sample was weighed into a 150 ml flask to which 10 ml of 1N K₂Cr₂O₇ was added and the contents were gently swirled until the sample was completely wet. This was followed by the addition of 20 ml of concentrated H₂SO₄ with further swirling to ensure thorough mixing of the solution in a fume cupboard. After cooling the solution, 50 ml of 0.4 % BaCl₂ was added. The solution was left to stand over night and the absorbance of the samples and the standards were read at 600 nm on UV visible spectrophotometer (Spectronic-20-Bausch and Lomb).

3.1.5 Determination of exchangeable bases

Total exchangeable bases were determined following extraction of soil by 1M acidified ammonium acetate (Anderson and Ingram, 1993). Air-dried soil samples weighing 10 g were put into 150 ml plastic containers to which 40 ml of ammonium acetate were added.

The containers were tightly closed and put on a reciprocating shaker (Stuart Flask model) for 1 hour. The solution was then filtered through a Whatman number 125 filter paper into 250 ml flasks. The remaining soil was washed using ammonium acetate making the volume in the collecting flask to about 90 ml. Fresh ammonium acetate was used to make the flask to the mark. After leaching the bases, potassium (K) and sodium (Na) emission were read on a flame spectrophotometer with the filter set on either K or Na while magnesium (Mg) and calcium (Ca) absorption were read on an atomic absorption spectrophotometer (AAS) (SpectrAA50 model) using the respective lamps (Thomas, 1982). The concentrations of the bases were then calculated from a standard curve.

3.1.6 Determination of available soil phosphorus

Available soil P was measured using the Olsen method (Olsen *et al.*, 1954). An air-dried soil sample weighing 2.5 g was placed into a 250 ml polythene shaking bottle followed by addition of Olsen's extracting solution (0.5 M NaHCO₃ at pH 8.5). The mixture was shaken on a mechanical shaker for 30 minutes. The resultant suspension was filtered through Whatman No. 42 filter paper. To the filtrate, 5 ml of 0.8 M boric acid and 10 ml of ascorbic acid reagent were added and allowed to stand for 1 hr. The phosphorus content of the sample was then determined colorimetrically from a phosphorusmolybdate complex formed by addition of acidified ammonium molybdate (Okalebo *et al.*, 2002). The absorbance of sample and standards were read at 880 nm wavelength.

3.1.7 Determination of total soil nitrogen

Total N was determined using the semi-Kjeldhal method as described by Anderson and Ingram (1983). Soil samples were digested using a digestion solution made up of selenium powder (being the catalysts), lithium sulphate (to raise the boiling temperature) and in

concentrated sulphuric acid. An air-dried soil sample weighing 0.5 g (0.1 g for ground plant material) was weighed into a digestion tube followed by addition of 4.4 ml of digestion mixture. The resultant mixture was placed on a digester at 360°C for 2 hours. Three reagent blanks were included to each batch of the samples. Afterwards, the solution was allowed to cool and 25 ml of distilled water added. A further 75 ml of distilled water was added and the solution allowed to settle.

Standards were prepared by oven drying 7g of ammonium sulphate ((NH₄)₂SO₄) at 105 °C for 2 hours. About 4.714 g of dry ammonium sulphate was dissolved in 1000 ml of deionized water (1000 mg N/litre) and 50 ml of the solution was pipetted into a 500 ml volumetric flask. Zero, 2.5, 5.0, 7.5, 10, 15, 20 to 25 ml of the 50 ml solution in volumetric flask was poured into 100 ml. About 2.5 ml of digested blank was added to each flask before marking it, to the mark with distilled water. To 0.1 ml of the sample or standard solution, 5 ml of reagent N1 (34 g sodium salicylate, 25 g sodium citrate and 0.12 g sodium nitroprusside dissolved 1000 ml deionised water) was added. After 15 minutes, 5 ml of reagent N2 (30 g NaOH, 750 ml water and 10 ml sodium hypochlorite in 240 ml deionised water) was added. The solution was mixed well and left for color development. Total N in the sample was then determined colorimetrically from the clear solution against a set of standards at an absorbance of 655 nm (Anderson and Ingram, 1993).

3.2 Evaluation of indigenous legume seed germination

Fifteen species targeted for establishment of indigenous legume fallows (indifallows), namely, *Crotalaria laburnifolia* (L.), *C. ochroleuca* G. Don, *C. cylindrostachys* Welw.ex Baker, *C. pallida* (L.), *C. pisicarpa* Welw.ex Baker, *C. glauca* Willd, *Eriosema ellipticum* Welw.ex Baker, *Neonotonia wightii* (Wight & Arn.) J.A. Lackey, *Chamaecrista*

mimosoides (L.), *C. absus* (L.), *Indigofera arrecta* Hochst. Ex A. Rich., *I. astragalina* DC and *Rothia hirsuta*, *Tephrosia radicans* Welw.ex Baker and *T. purpurea* (L.) were tested for germination under laboratory conditions. Before the germination tests, different scarification treatments were employed:

- i. Sulphuric acid (H₂SO₄) submersion
- ii. Hot water at 70 °C for 15 minutes and at 80 °C for 10 minutes
- iii. Control

Preliminary results on H₂SO₄ treatments have shown no significant differences in time of seed submersion into the acid. Sulphuric acid treatment involved submersion of 400 seeds in 100 ml of 98 % concentrated H₂SO₄ for 30 minutes at room temperature. The mixture was occasionally stirred using a glass rod. The seeds were then removed from sulphuric acid and rinsed under running water for one minute before being air-dried (Rodrigues *et al.*, 1990).

Hot water treatment involved subjecting 400 seeds to 70 °C for 15 minutes and to 80 °C for 10 minutes (Kak *et al.*, 2006), after which the seeds were air dried. Unscarified seeds were included as a control. A sub-sample of 50 seeds per species per treatment was tested for germination. Germination tests involved evenly distributing seeds on top of wet filter papers and covering with cups prior to incubation at 20 – 30 °C in a water bath under light (two florescence lamps, daylight type, 40w) (International Rules for Seed Testing, 2007). The experiment was laid out in randomised complete block design (RCBD) with four replicates, with an existing gradient of light intensity being the reason for blocking. Germinating species were counted by destructive sampling, with all the germinated seeds removed on each day of counting.

3.3 Field determination of species emergence

Plant emergence was estimated from a 0.5 m x 0.5 m quadrat replicated three times within each plot (Mapfumo *et al.*, 2005). Three quadrats were randomly selected from a total of 144 grids from each plot. Species emergence was determined at 3-days intervals for the first 3 weeks and then at 1-week interval for a further 4 weeks, effectively spreading the monitoring period over two months. Individual plants belonging to the same species were counted and recorded for each quadrat. To evaluate the effects of soil disturbance on indifallow establishment, indigenous legume species were broadcast on the surface of disturbed and undisturbed soil, and their emergence patterns also monitored.

3.4 Species biomass productivity and abundance

The identification of the indigenous legumes species had already been done in previous studies (Mapfumo *et al.*, 2005). The scientific identification of grass and non-legume broadleaved species was done with the assistance of botanists from the National Herbarium and Botanic Gardens under the Department of Agricultural Research for Development of the Zimbabwe's Ministry of Agriculture. To determine the biomass productivity, a random quadrat sampling strategy was used. The quadrat measuring 0.5 m x 0.5 m was made using a 5 mm diameter wire. The quadrat was used to randomly sample for species (legumes and non-legumes) biomass productivity with at least 3 replicates sampled from each plot. Legume biomass production was monitored twice between 3 and 6 months after indifallow establishment.

All biomass in the quadrats was cut just above the soil surface, separated into individual species and then oven-dried to constant weight at 60 °C before the biomass yield was

calculated. To estimate species abundance within the system, the species yield was divided with the total system biomass.

3.5 Estimation of N₂-fixation of indigenous legume species under field conditions

The nitrogen difference (ND) method was used for estimating N₂-fixation of indigenous legumes between 3 and 6 months after seeding. Non-leguminous species from natural fallow plots were used as reference plants. The ND method measures N₂-fixation by comparing N accumulated in a N₂-fixing plant with that taken up by a non-fixing reference plant of corresponding growth habit. The difference between N accumulated by the fixing legume and a non-fixing reference crop is considered as the N derived from fixation (Peoples *et al.*, 1989). Because different legume species exhibited different growth patterns, several reference plants of corresponding growth habits of individual species were used in this study. Plant species were cut above the soil surface line and separated into species before being oven-dried to constant at 60 °C. The dried biomass samples were then ground in a Wiley Mill to pass through a 1 mm sieve. A semi-Kjeldhal digestion method was used to determine the total N content in the samples (Anderson and Ingram, 1993). The difference between N accumulated by the fixing legumes and a non-fixing reference plant was assumed to be the N derived from fixation.

3.6 Determination of total plant nitrogen

Total plant N was determined using the Kjeldhal method as describe by Anderson and Ingram (1983). To a mass of 0.02 g of the sample, 5 ml of concentrated sulphuric acid and selenium mixture was added. The mixture was digested at about 70 ° C until the solution was clear to pale yellow and then cooled for 10 minutes. The contents of the digestion flask were transferred into the distillation flask by rinsing twice with distilled water and

the sidearm replaced. To the distillate, 20 ml of 50% NaOH was steadily introduced to liberate NH_3 from the solution which was cooled and absorbed in 5 ml of boric acid indicator until the solution reaches the 50 ml mark. Total nitrogen was then determined by titration with standardised sulphuric acid (H_2SO_4). The titre value is the N content of the sample.

3.7 Determination of total plant phosphorus

About 0.5 g of ground plant samples were digested using the digested method described in section 3.17. To a 5 ml sub-sample of the digested sample and standard in a 50 ml volumetric flask, 20 ml of distilled water followed with 10 ml of ascorbic acid were added starting with standards. The volumetric flask was then filled to the mark with distilled water. Total phosphorus was then determined colorimetrically at 880 nm wavelength (Anderson and Ingram, 1993).

CHAPTER 4

ESTABLISHMENT AND BIOMASS ACCUMULATION OF INDIGENOUS LEGUME SPECIES UNDER INDIFALLOW SYSTEMS ON NUTRIENT DEPLETED SOILS^{1,2}

4.1 Abstract

Studies in Southern Africa have shown the potential of indigenous N₂-fixing legumes to improve soil productivity and reclaim nutrient-depleted fields abandoned by smallholder farmers. The emergence and growth patterns of fifteen selected indigenous legume species were evaluated under smallholder farm conditions in Zimbabwe. *Crotalaria pallida* and *C. ochroleuca* were the first to emerge within 14 days from seeding while emergence for other species was late and spread over two months. Emergence for *Eriosema ellipticum*, *Crotalaria ochroleuca* and *C. pallida* was above 15 % compared with lowest values of < 10 % for *Tephrosia radicans* and *Indigofera astragalina*. Low emergence rates were attributed to the seed hardness and seed viability, which accounted for > 50 % and 10 - 30 % of germination failure, respectively. Scarification with concentrated sulphuric acid significantly ($P < 0.05$) increased germination by > 60 %, reducing seed hardness to < 15 % for most species. Responses to hot water treatment were insignificant in all species. Annual herbs such as *C. cylindrostachys* and *C. glauca* had the shortest vegetative period of 3 months, yielding about 0.5 t ha⁻¹ (dry weight) biomass. In contrast, fast growing erect annuals, *C. ochroleuca* and *C. pallida*, attained maximum biomass of about 5 and 9 t ha⁻¹, respectively within a growth period of six months. Biennials (*Neonotonia wightii*, *E. ellipticum* and *Tephrosia radicans*) exhibited slow growth rate and only attained maximum biomass in the second season with seasonal yields not exceeding 2 t ha⁻¹. An exception was *Indigofera arrecta* which accumulated up to 5 t ha⁻¹ in the second season. About 50 % of the sown species successfully persisted and established on undisturbed soil in the second season. Successful establishment of indigenous legume species was influenced by wide variability of species germination profiles, emergence patterns which were spread over time and different growth habits resulting in distribution of species biomass into the system in space and time.

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²Tauro, T.P., Nezomba, H., Mtambanengwe, F. and Mapfumo, P. 2009. Germination, field establishment patterns and nitrogen fixation of indigenous legumes on nutrient-depleted soils, *Symbiosis*, 48:92-101.

4.2 Introduction

Soils in the smallholder farming area of Zimbabwe are inherently poor in fertility, being deficient in both macro- and micronutrients, are often abandoned or fallowed after some years of cropping. Most of the fallowed land is composed of common grass species which can not build up meaningful soil fertility over a short fallowing cycle (Mapfumo and Giller, 2001). Efforts to build fertility of these soils using livestock manure, leaf litter and termitarium soil is limited by low quantity and poor quality resources available to farmers. In the wake increasing population pressure, the main challenge is to find technologies that can regenerate some of the fallowed land for crop production.

Introduction of legumes in fallows have been shown to improve the fallow system through nutrient cycling, litterfall, biomass input and biological nitrogen fixation (Palm, 1995; Gathumbi *et al.*, 2004; Mafongoya *et al.*, 2006). Although some legume-based soil fertility restoration options have shown great potential in Sub-Saharan Africa (Jama *et al.*, 1998), most of them have not been integrated in smallholder farming system due to various reasons. The use of leguminous species (trees, shrubs and herbs) have failed to be an integral pathway for revitalizing degraded soil in Sub-Saharan Africa due to the costs involved for adoption.

According to Giller (2001), successful establishment of legumes is determined by adaptation, biomass productivity, amount of N₂-fixed, weed suppression and persistence in a given environment. However, the major drawback of some grain legume species have been poor stand establishment, giving low biomass of < 2 t ha⁻¹ due to severe fertility constraints in fields often cultivated by smallholder farmers (Mapfumo *et al.*, 1999;

Kamanga and Shamudzarira, 2001). In such soils, productivity of legumes and N₂-fixation is limited by availability of nutrients especially P (Giller, 2001), thus reducing the biomass and N inputs into the system. Since most grain legumes have failed to make a significant contribution to fertility restoration of depleted soils, new legume innovations are required. In Zimbabwe, selection of legumes for use in most farming systems has focused on grain legumes for human consumption and pasture reinforcement options for livestock feed (Clatwothy and Thomas, 1972; Maclaurin and Grant, 1985) with little attention on legumes for soil fertility management.

Recently, work in Zimbabwe by Mapfumo et al. (2005) has identified over 36 different indigenous legumes species mainly of the genera *Crotalaria*, *Indigofera* and *Tephrosia* across different agro-regions. These indigenous legumes established and grew on nutrient-depleted soils where common agricultural crops often fail to yield anything. Seed collection for most of the identified indigenous legume species was done by farmers from natural stands following some training on identification procedures (Mapfumo *et al.*, 2005). This reduced the constraints related to seed costs and availability associated with other legume-based technologies. Integrating N₂-fixing indigenous legumes has potential to contribute to the alleviation of major agricultural constraints associated with nitrogen (N) inputs in smallholder farming in many parts of Sub-Saharan Africa. However, there is limited information on the establishment patterns, growth habits and biomass accumulation of these species when planted in mixtures on nutrient depleted soils. This chapter focuses on the following specific objectives:

1. To establish germination profiles, emergence and establishment patterns of indigenous legumes under field and laboratory conditions

2. To determine biomass accumulation patterns of different indigenous legumes and non-leguminous species grown in mixtures under indifallow (indigenous legume fallow) systems in comparison with natural fallows

4.3.0 Materials and Methods

4.3.1 Field sites

Fields abandoned by farmers due to poor soil fertility were identified and used for the study using a criterion developed by Mtambanengwe and Mapfumo (2005). Field sites included Domboshawa, Makoholi, Chikwaka and Chinyika, which have been described in Chapter 3. In Chikwaka, experiments were hosted by farmer Nyamayaro while farmers Mudange, Chikodzo and Masara hosted the experiment in Chinyika.

The study was conducted in two concurrent experiments that were: (a) a field investigation on establishment patterns and biomass accumulation, and (b) a laboratory germination test conducted at Seed Services under the Department of Agricultural Research for Development of Zimbabwe's Ministry of Agriculture.

4.3.2 Seed germination tests

Seed was subjected to various scarification methods before germination tests were done under laboratory conditions. Apart from the control, the scarification methods used included sulphuric acid submersion and hot water treatments (at 70 °C for 15 minutes and at 80 °C for 10 minutes) as described in section 3.2. Germinating species were counted by destructive sampling, where all the germinated seeds were removed on each day of counting.

4.3.3 Determination of species emergence patterns

Indifallows were established by broadcasting mixtures of *Crotalaria laburnifolia*, *C. ochroleuca*, *C. pallida*, *C. pisicarpa*, *C. cylindrostachys*, *Eriosema ellipticum*, *Neonotonia wightii*, *Chamaecrista mimosoides*, *C. absus*, *Indigofera astragalina* and *I. arrecta* seeds at a seeding rate of 120 seeds m⁻² species⁻¹ during the 2005/06 rainy season. Seeding rates were based on preliminary seed viability results by Venge (2003). Planting were done on: (a) plots where soil had been disturbed by hand hoeing, and (b) plots with undisturbed soil. The experiment was laid out as a randomised complete block design (RCBD) with three replicates per treatment. The treatments were established in plots measuring 6 m by 4.5 m. Emergence was estimated in quadrats randomly selected within the plots and this involved counting individual plants belonging to the same species.

4.3.4 Monitoring of species growth habits

Species were monitored from emergence to senescence over two years using an existing observation scheme. The scheme included recording qualitative description of growth patterns, time to sprout, days to physiological maturity and measurement of biomass accumulation as described in section 3.4. Identification of non-legumes in indifallows was done with the assistance of botanist while biomass of non-legumes was also quantified using the quadrat method. The following treatments were effected:

- i. 1-year Indifallow (established during 2005/06 season)
- ii. 2-year Indifallow (established during 2004/05 season)

4.3.5 Statistical analysis

Data was analyzed using GENSTAT statistical package (GENSTAT, 2005). Mean comparisons for abundance and productivity of legumes and grasses were done using t-test. All the mean comparisons were done at 0.05 % significance level and all the biomass is reported on a dry matter basis.

4.4.0 Results

4.4.1 Germination of indigenous legume species

Eriosema ellipticum and *Crotalaria pallida* had the highest germination of >40% compared with 10-20% for *C. ochroleuca*, *C. laburnifolia*, *Chamaecrista mimosoides* and *I. astragalina*. *Crotalaria piscarpa*, *C. glauca*, *C. absus*, *N. wightii*, *I. arrecta* and *R. hirsute* had the lowest final germination of <10 % (Table 4.1). Seed hardness was a major constraint to germination for most species, accounting for >50% of cases of germination failure. Apart from seed hardness, lack of viability accounted for 10-30% of species germination failure (Table 4.1). Scarification using concentrated sulphuric acid significantly ($P<0.05$) increased germination by ~60% and reduced seed hardness to less than 15% for most species. However, submersing *E. ellipticum* and *C. mimosoides* for 60 minutes in acid caused germination failure. Hot water treatment had no significant ($P>0.05$) effect on species germination (Table 4.1).

Table 4.1 Germination (%) of indigenous legume species following different scarification methods under laboratory conditions

Indigenous legume species	Treatment			
	Control	Concentrated Sulphuric acid*	Hot water 70°C for 15 min.	Hot water 80°C for 10 min.
<i>Crotalaria pisicarpa</i>	6(2.7)	91(1.7)	16(2.5)	16(2.5)
<i>Crotalaria pallida</i>	40(2.5)	90(1.7)	33(0.1)	45(5.5)
<i>Indigofera astragalina</i>	10(1.9)	79(1.9)	7(1.0)	20(5.9)
<i>Indigofera arrecta</i>	3(1.3)	64(4.7)	4(1.4)	31(4.7)
<i>Eriosema ellipticum</i>	57(4.1)	0	38(7.4)	38(7.4)
<i>Rothia hirsuta</i>	5(1.0)	59(3.5)	8(1.6)	21(2.1)
<i>Chamaecrista absus</i>	6(1.0)	0	0	0
<i>Crotalaria cylindrostachys</i>	7(1.9)	84(2.6)	6(1.3)	7(1.0)
<i>Crotalaria laburnifolia</i>	10(3.2)	87(2.6)	nd	nd
<i>Crotalaria ochroleuca</i>	13(1.9)	73(3.9)	nd	nd
<i>Crotalaria glauca</i>	7(1.0)	74(3.6)	nd	nd
<i>Neonotonia wightii</i>	8(1.8)	50(6.0)	nd	nd
<i>Chamaecrista mimosoides</i>	19(4.3)	0	nd	7(0.5)
<i>Tephrosia radicans</i>	nd	nd	19(2.2)	16(1.8)
<i>Tephrosia purpurea</i>	nd	nd	21(2.1)	18(4.2)

nd = not determined; * = species seed scarified in acid for 30 minutes; min = minutes; Figures in parentheses denote standard errors.

4.4.2 Species emergence in indifallow systems

There was wide variability in indigenous legume species emergence and establishment. *Crotalaria pallida* and *C. ochroleuca* were the first to emerge in about 14 days, while emergence was spread over two months for other species. By 21 days, 90% of *Eriosema ellipticum* emerging seedlings had been recorded. For *Tephrosia radicans*, *Indigofera astragalina* and *Indigofera arrecta* 90% of the emerging seedlings were recorded 5 weeks after sowing.

Across all sites, *Eriosema ellipticum* had the highest emergence (>20 %). *Crotalaria ochroleuca* and *C. pallida* had medium emergence of 3 – 15% compared with lowest values of 1 – 10% for *Tephrosia radicans*, *Indigofera astragalina* and *Indigofera arrecta* (Table 4.2). Soil disturbance significantly ($P<0.05$) increased emergence of *Crotalaria pisicarpa*, *C. laburnifolia*, *Eriosema ellipticum*, *Indigofera arrecta* and *I. astragalina* both at Domboshawa and Chikwaka (Figure 4.2). However, the emergence of *C. pallida*, *C. cylindrostachys*, *Tephrosia radicans*, and *Chamaecrista mimosoides* was not significantly affected by soil disturbance (Figure 4.2).

Table 4.2. Field emergence (%) of selected indigenous legume species on sandy soils under different rainfall regions in Zimbabwe.

Indigenous legume species	Makoholi (450-650 mm yr ⁻¹) (608 mm)**	Chinyika (650-750 mm yr ⁻¹) (583 mm)**	Domboshawa (>750 mm yr ⁻¹) (1042 mm)**	Chikwaka (>750mm yr ⁻¹) (600 mm)**
<i>Eriosema ellipticum</i>	40(6.3)	45(7.0)	18(4.0)	22(4.0)
<i>Crotalaria ochroleuca</i>	3(0.4)	15(3.0)	13(3.3)	8(3.0)
<i>Crotalaria pallida</i>	4(1.5)	nd	9(2.6)	10(4.1)
<i>Crotalaria cylindrostachys</i>	4(0.4)	3(0.1)	8(1.4)	7(0.9)
<i>Indigofera arrecta</i>	1(0.4)	8(1.8)	10(1.8)	10(1.4)
<i>Indigofera astragalina</i>	2(0.8)	5(1.1)	0	3(0.8)
<i>Tephrosia radicans</i>	2(0.5)	5(1.3)	2(1.1)	3(1.5)

nd = not determined; ** = rainfall that had been received at time of evaluation; Figures in parentheses denotes standard error

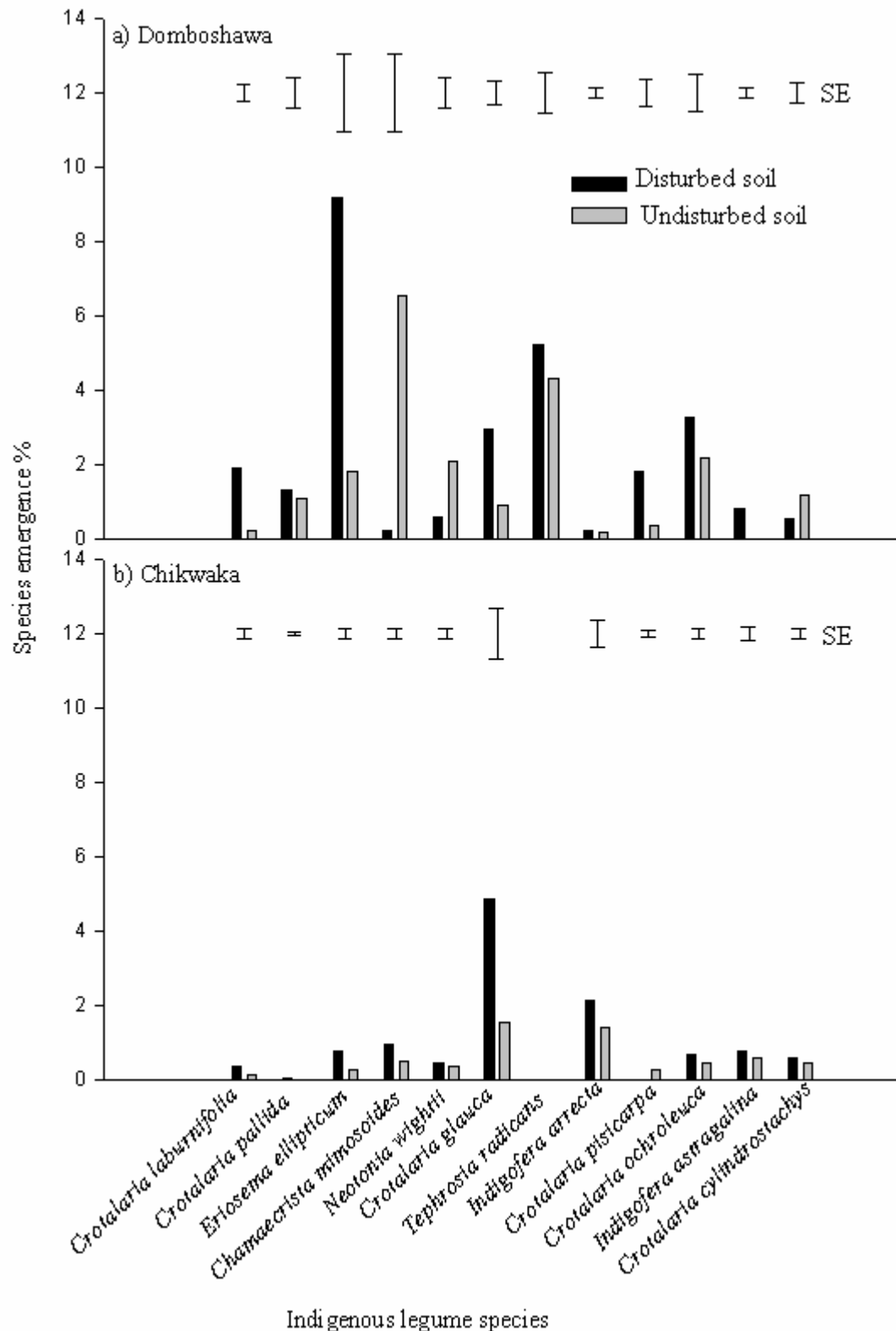


Figure 4.1. Effects of soil disturbance on species emergence of early planted species, under high rainfall conditions on-station at Domboshawa (a) and on-farm Chikwaka (b), Zimbabwe during 2006/07 season. SE denotes standard error.

4.4.3 Species growth habits

The indifallow system was a mixture of annuals, biennials and perennials of both legume and non-legumes species of complementary growth habits resulting in the distribution of biomass inputs in space and time into the system (Table 4.3). Of the three groups, there was variation of growth rates and traits. Annuals included *Crotalaria pallida*, *C. ochroleuca*, *C. cylindrostachys*, *C. glauca*, *C. pisicarpa*, *Indigofera astragalina*, *Chamaecrista mimosoides*, *C. absus*, *Tephrosia longipes* and *T. purpurea*. *Crotalaria pallida* and *C. ochroleuca* are erect legume shrubs that exhibited fast growth habits and attained maximum biomass of about 9 and 5 t ha⁻¹, respectively within a growth period of six months (Figure 4.2). They were distinctively taller in stature exceeding a height of 1.5 m, and had a longer vegetative phase compared to all other erect legumes in the indifallow system. While the two had similar growth habits, *C. ochroleuca* had prolific branching at the base of main stem just above the ground, while *C. pallida* started branching midway along the main stem all the way to the growing tip (Table 4.3).

Crotalaria cylindrostachys, *C. pisicarpa* and *C. glauca* are annual herbs with a vegetative period that only lasted 3 months, yielding about 0.5 t ha⁻¹ biomass on a dry weight basis (Figure 4.2). However, *C. cylindrostachys* had more leafy biomass and it completely senesced all its biomass as seed matured. *Crotalaria pisicarpa* is a slow growing legume and exhibited a dual growth habit. The lower branches had a prostrate growth habit while the upper branches and main stem were erect. It also reached its peak biomass after 3 months. *Indigofera astragalina*, *Chamaecrista mimosoides*, *C. absus*, *Tephrosia longipes* and *T. purpurea* are annual herbs which accumulated an average of 350-450 kg

biomass per month over a growth period of 6 months. In the second season, *Indigofera astragalina*, *Tephrosia longipes* and *T. purpurea* resprouted from the root crown.

Biennials included *Neonotonia wightii*, *I. arrecta*, *Tephrosia radicans* and *E. ellipticum*. Most of these indigenous legumes had a slow initial growth rate, dying back after six months of establishment and only resprouting from stems to reach a maximum biomass of up to 2 t ha⁻¹ in the second season. An exception was *I. arrecta*, which attained about 5 t ha⁻¹ in the second season (Figure 4.2). During the second season, these biennials vigorously resprouted and had a relatively faster growth rate as compared to that observed in the first season, mostly likely due to an improved rooting environment (Figure 4.2). While most of the species sprouted from the root crown, *Indigofera arrecta* and *E. ellipticum* sprouted from the standing stems. *Tephrosia radicans* and *Neonotonia wightii* had prostrate and trailing growth habits, respectively. The perennial species was *Crotalaria laburnifolia* which had an erect growth habit, reaching a height of ~1 m and also resprouting from stems. It attained maximum biomass of about 3.5 t ha⁻¹ in the second season (Figure 4.2).

The majority of non-legume species were annual grasses, sedges and broadleaf weeds that had fast initial growth rates, attaining peak biomass at 3 months and then dying back (Figure 4.2). Maximum total legume biomass of up to ~13 t ha⁻¹ was attained under 1-year indifallow (Figure 4.3). Non-legumes species only managed to attain a maximum of ~ 4 t ha⁻¹ under 1-year indifallow. However, in the second season, non-legumes species biomass reached a peak of ~ 7.5 t ha⁻¹, out-competing most indigenous legume species which attained < 5 t ha⁻¹ of biomass (Figure 4.3).

Table 4.3. Growth habits and patterns of different indigenous legume species studied under smallholder farm conditions in Zimbabwe

Species	Description	Growth habit	Time to flowering period	Sprouting
<i>Crotalaria pallida</i>	Annual	Erect, about 1 metre tall in stature	180	ns
<i>Crotalaria laburnifolia</i>	perennial	Erect, about 1 metre tall in stature	119 and 147 days	Mid October
<i>Crotalaria ochroleuca</i>	Annual	Erect, about 2 metre tall in stature, prolific branching	77 days	ns
<i>Crotalaria pisicarpa</i>	Annual	Erect and prostate	65 days	ns
<i>Crotalaria cylindrostachys</i>	Annual	Herb	70 days	ns
<i>Crotalaria glauca</i>	Annual	Herb	60 days	ns
<i>Eriosema ellipticum</i>	Biennial	Erect	In second season	Mid October
<i>Neonotonia wightii</i>	Biennial	Trailing	In second season	December, after the rains
<i>Chamaecrista mimosoides</i>	Annual	Herb	90 days	ns
<i>Chamaecrista absus</i>	Annual	Herb	90 days	ns
<i>Indigofera arrecta</i>	Biennial	Erect	In second season	Early November
<i>I. astragalina</i>	Annual	Erect herbs first season then erect and prostate in second season	119 day	December, after the rains
<i>Tephrosia radicans</i>	Biennial	Prostate	In second season	December, after the rains
<i>Tephrosia longipes</i>	Annual	Herb, with longer internodes	90 days	December, after the rains
<i>Tephrosia purpurea</i>	Annual	Herb, with shorter internodes	90 days	December, after the rains

ns= non-sprouting species

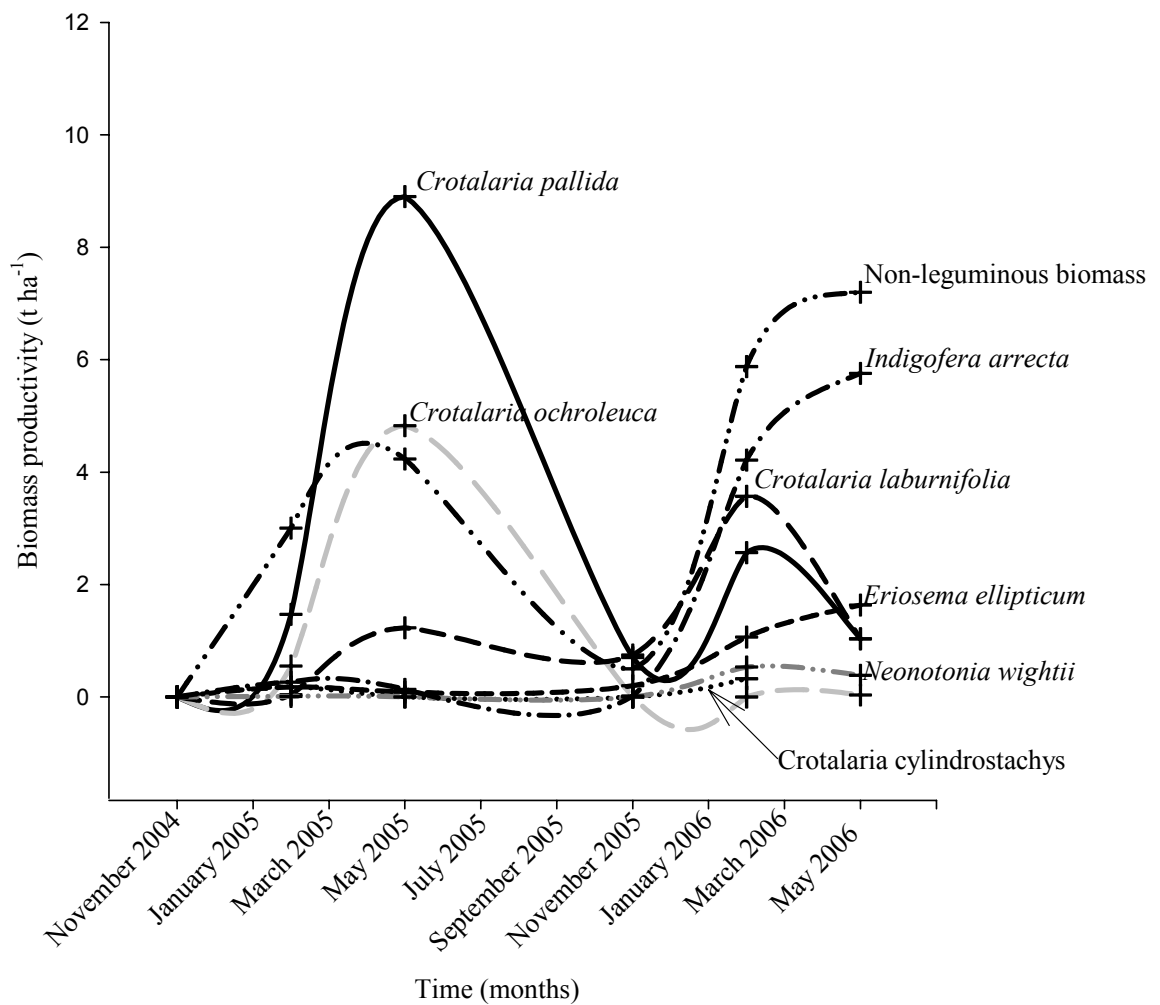


Figure 4.2. Biomass accumulation patterns of indigenous legume species over two seasons under high rainfall conditions at Domboshawa, Zimbabwe during 2004/05 and 2005/06 seasons.

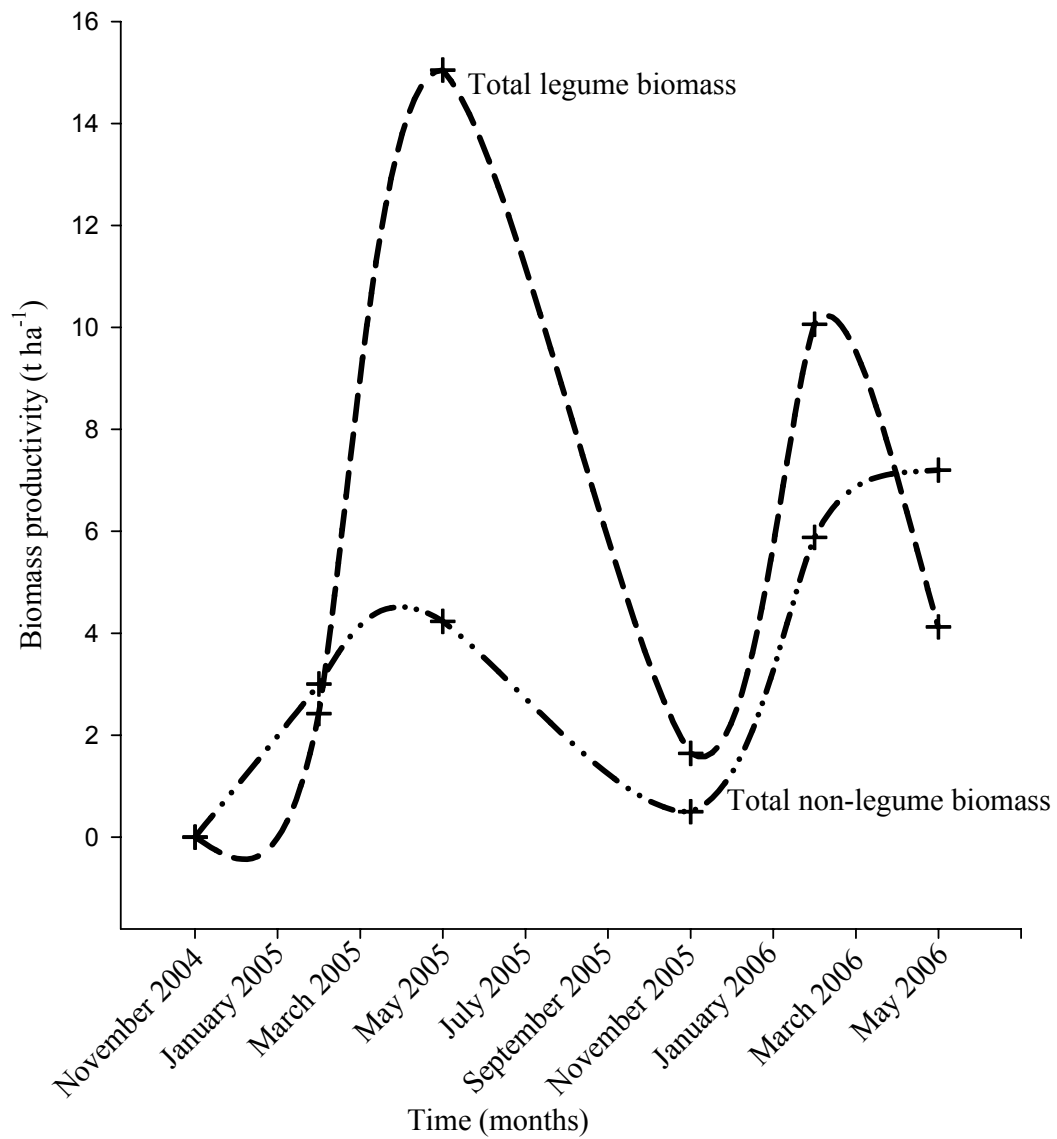


Figure 4.3. Biomass accumulation patterns of total leguminous and non-leguminous species over two seasons under high rainfall conditions (>750 mm yr⁻¹), at Domboshawa, Zimbabwe during 2004/05 and 2005/06 seasons.

4.5.0 Discussion

4.5.1 Species germination and emergence under indifallows

The low rate of emergence of the majority of the indigenous legumes may be attributed to the seed hardness caused by the impermeability of seed coat that maintains the quiescence of the embryo by preventing imbibition of water (Russ, 1993). Germination tests of these species showed that seed hardness was the major constraint for germination of most indigenous species, accounting for >50 % of cases of germination failure for most species. Consistent with findings from this study Loi et al (1999) also reported the existence of seed hardness among species even of the same genera. Most wild or indigenous legumes such as *Crotalaria laburnifolia*, *C. medicaginea*, *C. pallida* and *C. retusa* have been shown to possess physical dormancy (Venge, 2003; Kak *et al.*, 2006). Such dormancy results in erratic stand establishment as shown by the low emergence under field conditions. Apart from seed hardness, seed mortality accounted for 10 – 15 % of species failure under field conditions.

Sulphuric acid scarification significantly increased germination. Similar results have been reported (Rodrigues *et al.*, 1990; Mackay *et al.*, 1995; Mapfumo, 1999). However, the practicality of this procedure under smallholder farming conditions poses a challenge. For instance, a shorter time of soaking in sulphuric acid may be required for *Chamaecrista absus* and *C. mimosoides* to avoid loss of seed viability. As the intensity of seed hardness varies among legume species (Kelly *et al.*, 1992), it is likely that indigenous legume species under study responded differently to acid treatments. Hot water scarification might have been a practical option for most farmers; however this simple treatment had no effect on species germination. The results are contrary to findings by Kak et al (2006), who

reported enhancement germination of *C. laburnifolia*, *C. medicaginea*, *C. pallida* and *C. retusa* using hot water treatment. Therefore for practical purposes farmers may need to further increase their seeding rate to cater for the seed physical dormancy. There also need to monitor if natural process of heat and fluctuating moisture conditions may influence germination.

The high emergence observed both under field and laboratory conditions for *E. ellipticum* suggest that it is free from physical dormancy and does not need scarification. Sunnhemp (*Crotalaria juncea*), which has found widespread use as a green manure and cover crop in cropping systems is known to have high germination (Kak *et al.*, 2006). The variation in emergence of species over time ensured successful establishment of indifallows against species failure from adverse weather conditions or poor early growth. The result also indicated that increasing the seeding rate (Venge, 2003) alone may not produce a good stand hence the need to consider mechanisms to reduce seed hardness.

Soil disturbance enhanced the emergence of indigenous legume species suggesting that there was better seed-soil contact for species germination. Clatworthy and Thomas (1972) had previously highlighted the importance of disturbing the soil to set back grass growth and competition during pasture establishment. However, there was no significant effect of disturbing the soil on species emergence of *C. pallida*, *C. cylindrostachys*, *T. radicans*, and *C. mimosoides* in the high rainfall areas of Domboshawa and Chikwaka and this was attributed to adequate surface soil moisture at planting and during the germination phase. This is in agreement with observations made by Lwoga (1983) who noted that when surface soil moisture was not limiting, oversown seeds germinated well.

4.5.2 Species growth habits

In general, *Crotalaria* species were fast growing and performed better in terms of biomass accumulation than *Indigofera* and *Tephrosia* species suggesting that *Crotalaria* species were stronger competitors in the mixtures. However, species such as *C. ochroleuca* only made a significant contribution in the first season and disappeared in the second season, and for that reason there is a need to have persistent species such as *E. ellipticum* and *I. arrecta* in indifallows. *Crotalaria laburnifolia* regenerated through reseedling and resprouting, and therefore persisted well. The ability of some species to persist into the second season also suggests that these species required little maintenance once they have established, conforming to findings by Metcalf (2005). According to Piano (1993), short lived species such as *C. cylindrostachys*, *C. pisicarpa* and *C. glauca* have an advantage in marginal areas where rainfall ends abruptly since they are able to produce mature seed faster than slow-flowering and long maturity species. Conversely, in high potential areas, high rainfall after the vegetative cycle would favour pathogen and saprophyte attack on mature seeds of short duration species while late maturing species are likely to escape attack (Sulas *et al.*, 2000).

Biennial species such as *N. wightii* and *E. ellipticum* apparently exhibited the “suffretex” habit (Maruzane and Ziobwa, 2002). Suffretex habit enables seedling otherwise thought to be dead to recover when conditions improve, owing to the persistence of rootstock in the ground. These species had an early season die back as they developed a good rooting system to support the shoot development in the next season. As biennials, *N. wightii* and *E. ellipticum* would not be suitable for 1-year fallows. For longer term fallows, mixing

species with different growth habits would ensure that species biomass contributions into the system are spread over time.

Mixing indigenous legume species of different growth habits ensured successful establishment of indifallows by safeguarding against single species failure and guaranteeing distribution of species contribution into the system in space and time. Mixing species with complementary growth traits has also been reported to produce a more diverse fallow system and also maximize biomass productivity (Cadisch *et al.*, 2002). Gathumbi *et al.* (2004) showed that mixed species fallows provided a better risk management strategy through compensatory biomass and nutrient production gains obtained from the strongly competing species. *Crotalaria laburnifolia* and *C. ochroleuca* produces a dense canopy cover, which can shade off other species such as *T. radicans* and *C. pisicarpa* thereby reducing their contribution in the system. Therefore in terms of establishment options, species with a prostrate growth habit such as *T. radicans* and a slow growth rate such as *C. pisicarpa* should be seeded at a higher rate and early before fast growing species such as *C. laburnifolia* and *C. ochroleuca*.

Over time, indigenous legumes out-competed non-legume species despite having a slow initial growth rate because the system was N deficient which affected non-legume growth while these legumes were using biological nitrogen fixation to meet their N needs. The dominance of grasses which then eclipsed most annual legumes in the second season of indifallow might be associated with an improved N environment following decomposing legume residues from the first season. With this indifallow system, it then possible to reduce the labour related to weeding associated with other legume-based technologies during establishment as non-legumes have no effect on the legumes biomass inputs.

4.6 Conclusions

Indigenous legume species had different establishment patterns being influenced by wide variability of species germination profiles, emergence patterns and different growth habits. Low germination rate are related to seed coat hardness but increasing seeding rate can result in desired plant population. Acid scarification significantly increased species germination by ~60% where as hot water pre-treatment had no effect. Mixing indigenous legume species resulted in distribution of species biomass into the system across time, with *Crotalaria cylindrostachys*, *C. pisicarpa* and *C. glauca* attaining peak biomass (0.5 t ha^{-1}) over 3 months, while others (*Crotalaria pallida* and *C. ochroleuca*) gave maximum biomass ($5\text{-}9 \text{ t ha}^{-1}$) at 6 months and *Indigofera arrecta* attained maximum biomass (5 t ha^{-1}) in the second season after resprouting. Total legume biomass out-yielded non-legumes in indifallow but non-legumes reached a peak of 7.5 t ha^{-1} in the second season as a result of rotational benefits from the N inputs from decomposition of N-rich litter of short lived indigenous legume species. Mixing indigenous legume species of different growth habits ensured successful establishment of indifallows by safeguarding against single species failure and guaranteeing distribution of species biomass contribution into the system in space and time.

CHAPTER 5

CHANGES IN PLANT SPECIES COMPOSITION AND ABUNDANCE IN INDIFALLOW SYSTEMS

5.1 Abstract

Legume-based soil fertility innovations that offer alternative N nutrient sources to address soil fertility challenges for resource-constrained farmers are being sought by smallholder farmers in many sub-Saharan countries. Studies were conducted under low (450-650 mm yr⁻¹) to high (> 800 mm yr⁻¹) rainfall areas in Zimbabwe to investigate the changes in species composition within indigenous fallows (indifallows) established on nutrient depleted soils. The indigenous legume seed was broadcasted in mixtures at 120 seed m⁻² species⁻¹ over two growing seasons. In the first season, *Eriosema ellipticum* was the most dominant legume species having a population of 42 plants m⁻² (8 %) while *Crotalaria pallida*, *Crotalaria cylindrostachys*, *Crotalaria ochroleuca* and *Indigofera arrecta* each had population of < 23 plants m⁻² (5 %). Over time there was a significant ($P < 0.05$) decrease in the population of *E. ellipticum* and *Neonotonia wightii* as a result of low survival rates as competition increased. Introduction of indigenous legume species suppressed the abundance of predominant non-legume species such as *Cynodon dactylon* and *Richardia scabra* to 17 % and 7 % respectively, while the abundance of the same species in natural fallows increased to 47 % and 11%, respectively. Overall, the most abundant species were *C. pallida* and *C. ochroleuca* having dense canopy cover. The two species yielded 9 and 5 t ha⁻¹ of biomass respectively, translating to approximately 48% and 26% of indifallow biomass. There was a significant change in non-leguminous species composition and abundance in the second season. Abundance of annual legume species such as *C. pallida*, *C. ochroleuca* and *C. cylindrostachys* decreased to < 2% in the second season while there was a disappearance of *Richardia scabra*, *Bulbostylis hispidula* and *Nicandra physalodes*. There was significant ($T_{(obs)} > 1.96$) decrease in legume species diversity into the second season. Non-legume species diversity decreased as *C. dactylon* dominated in the second season apparently associated with improved N economy where indigenous legumes once dominated. This study suggest that establishment of these species in degraded soils can influence changes in non-legume composition from legume competition and resultant increase of N in the system while the changes in legumes population and abundance was influenced by species emergence, competitiveness and growth trait.

5.2 Introduction

In many parts of tropical Africa, much of the land cleared for agriculture is abandoned after a few years, due to invasion of aggressive weeds or a drastic decline in soil fertility (Donfack *et al.*, 1995). Resources for the management of soil fertility and weeds are generally scarce in most smallholder farming areas raising the need for soil fertility options that complement weed management. However, most resource-constrained farmers depend on traditional technologies such as natural grass fallows and other locally derived nutrient resources to manage soil fertility (Mtambanengwe and Mapfumo, 2005; Mafongoya *et al.*, 2006). Most of these methods have consistently shown little impact while efforts to use some potential legumes such as mucuna (*Mucuna pruriens*) and pigeon pea (*Cajanus cajan*) have been hindered by poor establishment (Hikwa *et al.*, 1998; Mapfumo *et al.*, 1999).

Successful establishment of legumes is determined by weed suppression and persistence in a given environment (Peoples *et al.*, 1995). Past studies on legume-based technologies have focused on biomass productivity and residual fertility benefits (Hooper and Vitousek, 1998; Mafongoya *et al.*, 2006), with little attention on the population dynamics of both legumes and non-legume species contributing to the total system biomass. Species diversity and functional composition have been confined to forage legumes in pastures (Clatworthy and Thomas, 1972; Barker *et al.*, 2002; Guretzky *et al.*, 2005), but there has been little of such information on unpalatable legumes for soil fertility management.

Mapfumo *et al.* (2005) advocated for the use of well-adapted indigenous legume species found across different agro-regions in Zimbabwe for soil fertility management option for poor households. Most of such legumes have been ignored in the past as a result of being

unpalatable despite their ability to grow on degraded soils on which other legumes failed to make impact. However, when unchecked, such wild plant species can become troublesome weeds once integrated in farming systems. For example, species such as *Lantana camara* and *Pinus patula* in Zimbabwe have posed serious problems to conservationists, forestry managers, farmers and land owners because of their invasiveness (Maroyi, 2006). It is therefore imperative to gain more information about indigenous legume species dynamics and factors driving persistence under the indifallow system.

There has been a general focus on implications of N management on species composition and community structure in natural systems and agricultural systems (Wilson and Tilman, 1993; Clements *et al.*, 1994). Little information exists on species competitive ability and shading characteristics within indigenous fallows (indifallows). Before integrating indifallows into farming system, there is need to understand how species composition and abundance changes over time within indifallows and how best to manage indigenous legume species for use as a soil fertility management resource. This study investigated the changes in species composition under 1 and 2 year indifallows on nutrient depleted soils. This chapter focuses on the following specific objectives:

1. To investigate changes in abundance of N₂-fixing indigenous legumes seeded in mixtures and grown over one- to two-cropping seasons.
2. To evaluate the influence of mixed indigenous legume stands on composition and abundance of non-leguminous species after two years in comparison to natural fallows

5.3.0 Materials and methods

5.3.1 Determination of species abundance

Relative species abundance under indifallow and natural fallow systems was estimated on the basis of individual species biomass productivity in relation to total system biomass. Species biomass sampling was done 3, 6, 15 and 20 months spreading over two rainy seasons using a random quadrat method. Following individual species biomass quantification, species abundance was calculated (Mapfumo *et al.*, 2005).

5.3.2 Monitoring changes in species composition over time

The following treatments were effected to investigate changes in species composition over time in both indifallow and natural fallow systems:

- i. 1-year Indifallow
- ii. 2-year Indifallow
- iii. 1-year natural fallow
- iv. 2-year natural fallow

Indifallows were established at Domboshawa and Makoholi through mixtures of indigenous legume species as earlier described in Chapter 3. Control plots were disturbed by ploughing and left to natural fallow. The experiment was laid out in randomized complete block design (RCBD) with three replicates per treatment. Plots were 36 m² and blocking was based on soil fertility within the fields. Species population and biomass was quantified by sampling three replicate quadrats per plot between 3 and 20 months spreading over two rainy seasons. The quadrats measured 0.5 m x 0.5 m and all legume species plants were counted before all plant biomass was cut at soil surface, dried and weighed as earlier described in Chapter 3 (section 3.4).

5.3.4 Statistical analysis

Data was analyzed using GENSTAT statistical package (GENSTAT, 2005). Mean comparison for legumes and grasses abundances and productivity was done by t-test. The Shannon-Wiener diversity index (H') was used to test for diversity changes over time and comparisons of system diversity was done at critical t value of 1.96 and 774 degrees of freedom (Guretzky *et al.*, 2005). Species evenness was calculated with the formula: $E = H' / \ln S$, where S was the number of species present. All the mean comparisons were done at 0.05 % significance level and all the biomass is reported on a dry matter basis while species abundance is reported in percentages of plant species per plot.

5.4. Results

5.4.1 Changes in indigenous legume species composition in indifallows

The indifallow system at Domboshawa was comprised of fourteen indigenous legume species. The predominant non-legume species in the system included the grasses *Cynodon dactylon*, *Eragrostis patens*, *Bulbostylis hispidula*, a sedge *Cyperus esculentus* and broadleaved species such as *Commelina benghalensis*, *Bidens pilosa* and *Richardia scabra* (Figures 5.1). *Eriosema ellipticum* was the most dominant legume species having a population of 42 plants m^{-2} (8%) while *Crotalaria pallida*, *Crotalaria cylindrostachys*, *Crotalaria ochroleuca* and *Indigofera arrecta* each had populations of < 23 plants m^{-2} (5%) (Table 5.1). However, *E. ellipticum* accumulated insignificant biomass resulting in *C. pallida* and *C. ochroleuca* being the most abundant species which attained 9 and 5 t ha^{-1} of biomass respectively, representing 48% and 26% of total indifallow biomass. Indifallow at 3 months had the highest Shannon-Wiener index (H') and evenness (E) than

at 6, 15 and 18 months after establishment indicating more diverse and greater legume species evenness (Table 5.1).

Over time there was a significant ($T_{observed} > 1.96$) decrease in legume species diversity from 6 months after establishment into two-year indifallow. However, there was no significant ($T_{obs} < 1.96$) difference in legume species diversity at 6 and 15 months after establishment. There was a substantial decrease in the population of *E. ellipticum*, *C. pallida*, *C. ochroleuca* and *C. cylindrostachys* into the second season. *Indigofera astragalina*, *T. radicans* and *C. pisicarpa* did not persist into the second cropping season (Table 5.1). Annual legume species such as *C. pallida*, *C. ochroleuca* and *C. cylindrostachys* decreased in abundance from 48% to 0.9%, 26% to 2.2% and 3.5% to 0.2% respectively into the second season (Figure 5.2). However, *I. arrecta*, *N. wightii* and *Chamaecrista mimosoides* persisted into the second season without any changes in species population over the growing seasons. Overall, about 50 % of the sown species successfully persisted and established on undisturbed soil in the second season.

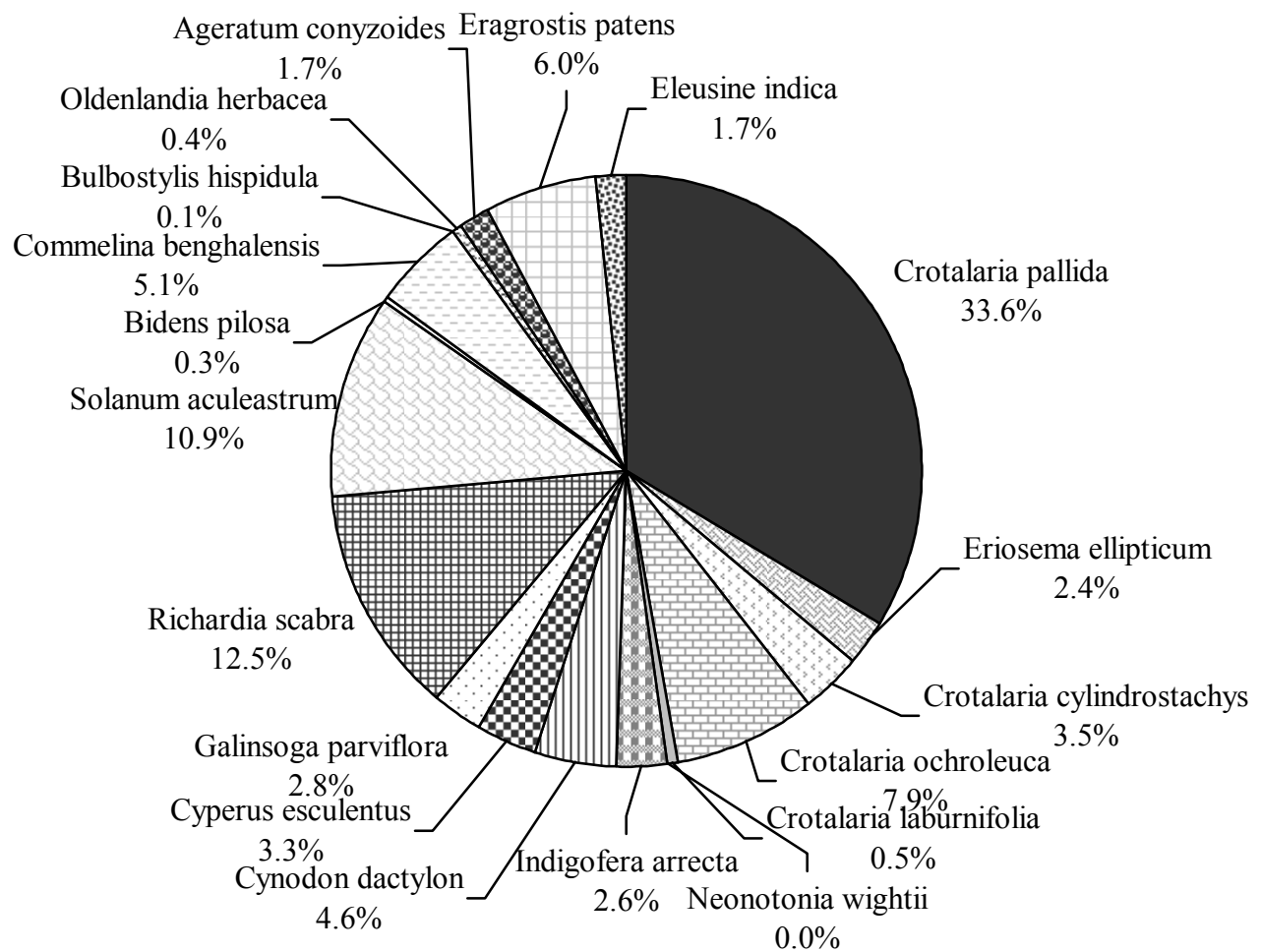


Figure 5.1. Relative abundance of legume and non-legume species at 3 months after establishment of indifallows at Domboshawa ($>800 \text{ mm yr}^{-1}$), in the 2005/06 season.

Table 5.1. Changes in indigenous legume species population over time at Domboshawa, Zimbabwe.

Indigenous legume species	Population in indifallow system (plants m ⁻²)			
	Months after planting			
	3	6	15	18
<i>Crotalaria laburnifolia</i>	12(2.1)	4(2.3)	38(12.7)	17(5.7)
<i>Crotalaria pisicarpa</i>	3(1.3)	ni	ni	ni
<i>Crotalaria pallida</i>	26(7.1)	40(5.4)	8(1.2)	4(2.3)
<i>Crotalaria ochroleuca</i>	26(12.3)	10(2.0)	7(3.5)	3(1.6)
<i>Crotalaria cylindrostachys</i>	14(4.4)	8(1.2)	4(2.4)	ni
<i>Neonotonia wightii</i>	13(5.3)	4(2.3)	9(2.9)	8(4.1)
<i>Indigofera astragalina</i>	3(1.3)	ni	ni	ni
<i>Indigofera arrecta</i>	20(5.3)	15(8.1)	14(5.3)	14(1.3)
<i>Eriosema ellipticum</i>	42(12.2)	17(2.8)	13(0.8)	8(2.7)
<i>Chamaecrista mimosoides</i>	3(1.3)	3(1.7)	4(0.3)	6(2.0)
<i>Tephrosia radicans</i>	6(4.2)	ni	ni	ni
<i>Tephrosia purpurea</i>	12	11	8(0.4)	7(2.4)
<i>Tephrosia longipes</i>	8	7	4(2.3)	6(1.2)
Shannon-Wiener diversity index (H')	2.29	2.00	2.01	2.07
Evenness (E)	0.89	0.87	0.88	0.88

ni = not identified in the indifallow system; Figures in parentheses denotes standard errors.

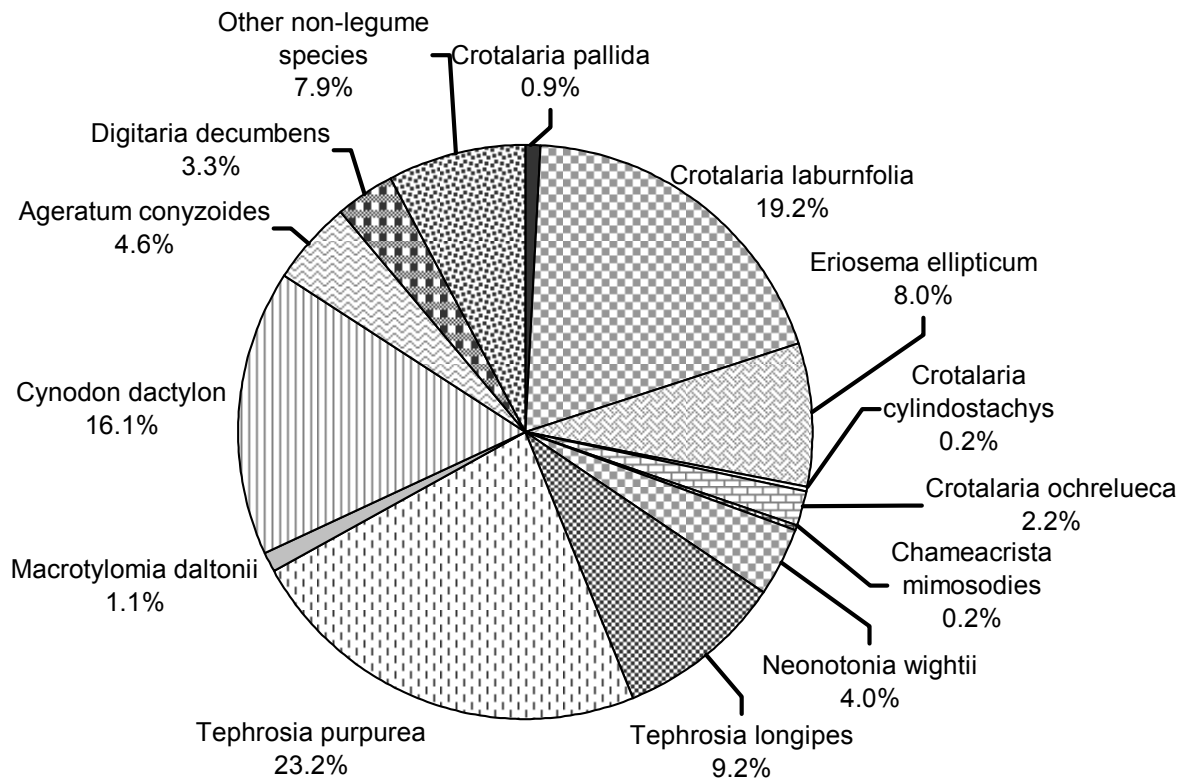


Figure 5.2. Relative abundance of legume and non-legume species at 15 months of a two year indifallow Domboshawa (annual rainfall = 1400 mm yr⁻¹), in the 2005/06 season.

On a nutrient depleted soil at Mudange farm, the indifallow was comprised of seventeen species, eight being non-leguminous species while the remaining nine were indigenous legume species. The predominant non-leguminous species included *Richardia scabra*, *Eragrostis patens*, *Bulbostylis hispidula*, *Commelina benghalensis*, *Hibiscus meeusei* and *Cyperus esculentus*, showing close similarities with observations at Domboshawa despite the relatively less annual rainfall in Chinyika. Domboshawa has an average annual rainfall of > 800 mm yr⁻¹ compared with 650 - 750 mm yr⁻¹ for Chinyika. Consistently, *Eriosema ellipticum* was the most dominant legume species having a population of 79 plant m⁻² (16 %) while *C. ochroleuca*, *C. cylindrostachys*, and *I. arrecta* had population of < 20 plant m⁻² (5 %) each (Table 5.2). Overall, the most abundant species in the indifallow system was

C. ochroleuca, which attained a maximum of 7.7 t ha⁻¹ (Table 5.3). Similarly, indifallow at 3 months had the highest Shannon-Wiener index (H') indicating more diverse system but indifallow after 15 months had greater species evenness.

Indigofera arrecta, *I. astragalina*, *T. radicans* and *Chamaecrista mimosoides* persisted into the second season without any apparent changes in species population while *Crotalaria ochroleuca* and *C. glauca* did not persist (Table 5.2), most likely linked to growth habits and competition from non-legume biomass. There was a significant ($T_{(obs)} > 1.96$) decrease in H' over time into the second (Table 5.2). There was a significant ($P < 0.05$) decrease in *E. ellipticum* and *N. wightii* populations as a result of low survival rates over the growing season, while the population of *C. cylindrostachys* significantly ($P < 0.05$) increased in the second season (Table 5.2) probably from the existing soil seed reserve since the species is prevalent in Chinyika. About 50 % of the sown species successfully persisted and established on undisturbed soil in the second season.

Table 5.2. Changes in indigenous legume species population over time at Mudange, Zimbabwe.

Indigenous legume species	Population in indifallow system (plants m ⁻²)		
	Months after planting		
	3	6	15
<i>Crotalaria ochroleuca</i>	20(9.2)	28(11.6)	ni
<i>Crotalaria glauca</i>	8(2.3)	12(2.1)	ni
<i>Crotalaria cylindrostachys</i>	5(1.3)	3(1.3)	14(1.6)
<i>Neonotonia wightii</i>	6(3.5)	ni	ni
<i>Indigofera astragalina</i>	5(3.5)	5(1.3)	8(2.3)
<i>Indigofera arrecta</i>	13(5.2)	5(0.7)	12(4.1)
<i>Eriosema ellipticum</i>	74(16.7)	48(5.1)	25(6.6)
<i>Chamaecrista mimosoides</i>	10(2.3)	6(0.8)	5(2.9)
<i>Tephrosia radicans</i>	11(1.3)	7(2.7)	5(1.3)
Shannon-Wiener diversity index (H')	1.70	1.64	1.63
Evenness (E)	0.78	0.79	0.91

ni = not identified in the indifallow system; Figure in parentheses denotes standard error

Table 5.3. Biomass productivity of indigenous legumes species at 6 months after sowing, under high and medium rainfall conditions in Zimbabwe during the 2005/06 rainfall season.

Indigenous legume species	Biomass productivity (t ha ⁻¹)		
	(> 750 mm yr ⁻¹)		(650 -750 mm yr ⁻¹)
	Domboshawa	Chikwaka	Chinyika
<i>Crotalaria pallida</i>	8.9	3.4	np
<i>Crotalaria ochroleuca</i>	4.1	0.5	7.7
<i>Crotalaria cylindrostachys</i>	0.2	0.5	0.2
<i>Eriosema ellipticum</i>	0.7	0.1	0.07
<i>Indigofera arrecta</i>	<0.1	ni	ni
<i>Indigofera astragalina</i>	ni	ni	0.3
LSD	3.1	2.2	5.2

np = not planted during establishment of indifallow; ni = not identified in the indifallow system

5.4.2 The effect of indigenous legume species on non-legume species composition

In the first year, introduction of indigenous legumes resulted in the abundance of common species being suppressed. For example, at Domboshawa the abundance of *Cynodon dactylon* and *Richardia scabra* was ~5% and ~13 % in indifallows while the same species constituted 12% and 18% of total biomass under natural fallow (Figure 5.3). Similar trends were also observed at Makoholi, Chikwaka and Chinyika despite having different non-legume compositions. Within one season, abundance of *Cynodon dactylon* increased by 12% in indifallows, while that of *Eleusine indica*, *Acanthospermum hispidum* and *Cyperus esculentus* decreased by 6 - 9%.

In the second season, there was a disappearance of species that included *Richardia scabra*, *Bulbostylis hispidula* and *Nicandra physalodes* while the abundance of *Cynodon dactylon* increased by 42%. In contrast, *Cynodon dactylon* abundance only increased by 2% in the second season under natural fallow. The abundance of *Cynodon dactylon* translated to increase in non-legume biomass in the second season which resulted in a significant decrease in non-legume diversity.

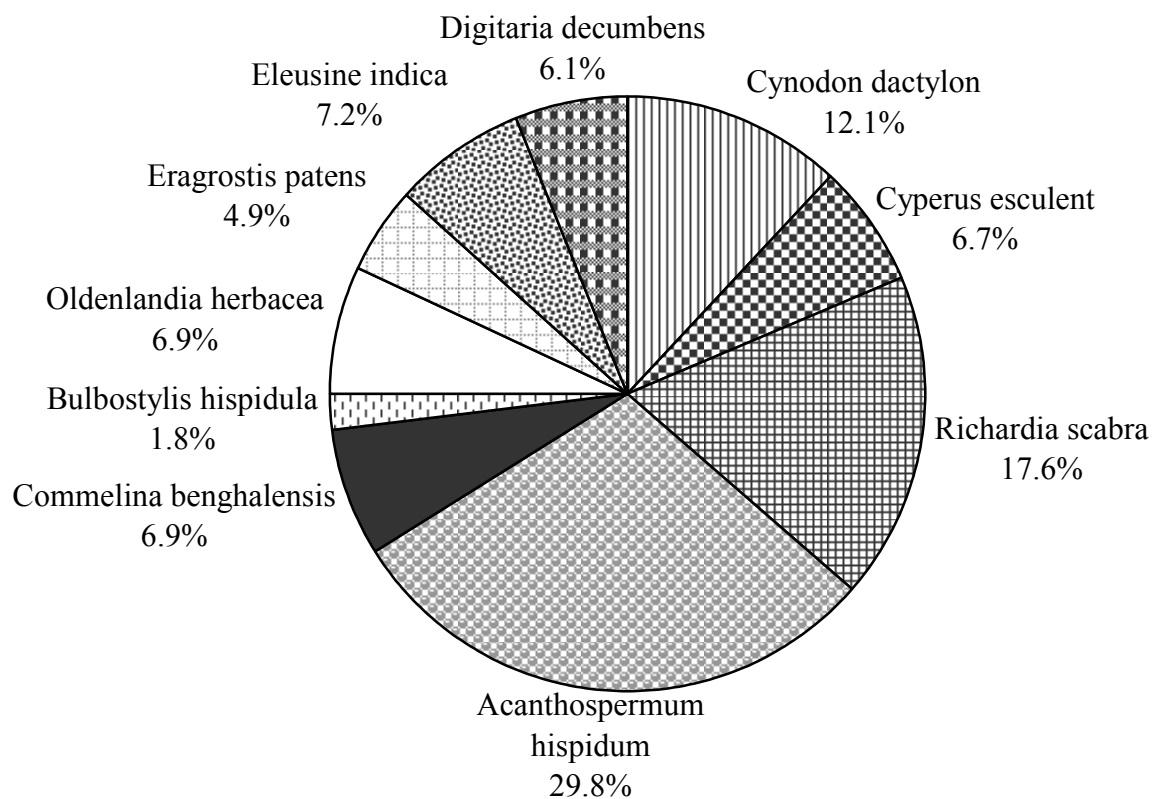


Figure 5.3. Relative abundance of non-legume species at 3 months in natural fallow systems, expressed as % of total biomass per unit area at Domboshawa (>800 mm yr⁻¹), in the 2005/06 season.

5.5.0 Discussion

5.5.1 Species dynamics in an indifallow system

Changes in indigenous species composition were influenced by seed germination, competitiveness and regenerative ability of species within the indifallow. The high population of *Eriosema ellipticum* in indifallow than other species across all study sites was consistent with germination tests findings (Venge, 2003; Tauro *et al.*, 2007). The decrease in the population of *E. ellipticum* observed in the second season might indicate its low survival potential implying reduced species biomass contribution into the system during this phase. According to Cook (1980), survival of individual legumes is influenced by its ability to withstand competition from the existing vegetation and to tolerate other environmental stress. Disturbing the soil during planting suppressed the growth of non-legume species while promoting the emergence of indigenous legume species, but was apparent that competition would occur as soon as the native vegetation began to emerge resulting in species such as *E. ellipticum* dieing off within the system.

Despite *Crotalaria* species having low population density in the indifallow system, they had superior survival ability compared with *E. ellipticum*, suggesting that *Crotalaria* species were stronger competitors in the mixtures. Comparable biomass accumulations amounting to 9 t ha⁻¹ for *Crotalaria ochroleuca*, *C. grahaminia* and *C. incana* have been reported in western Kenya (Ojiem *et al.*, 1998). The decrease in population and abundance during the second season for annual legume species such as *C. ochroleuca*, *C. pallida* and *C. cylindrostachys* could be attributed to their growth traits and poor emergence. *Crotalaria cylindrostachys* and *C. ochroleuca* are non-sprouting and have high seed dormancy which resulted in a reduction in species abundance and population in the second year. Similar results have been reported in *Sesbania sesban* improved fallows where a

negative biomass accumulation was observed after fallow termination (Mafongoya *et al.*, 2006). The significant increase in population of *C. cylindrostachys* at Mudange might be from the existing soil seed banks. *Crotalaria cylindrostachys* had previously been reported to contribute about 25% of the total legume biomass under natural system in Chinyika area (Mapfumo *et al.*, 2005). Apart from seed dormancy and species growth traits, the decrease of legume species population might be associated with increased N availability (Nezomba, 2009) leading to non-legume species dominance. Application of N in pasture was also reported to result in selective invasion of non-legume species as it affects nodule formation and inhibits N₂-fixation of legumes (Heichel, 1985; Guretzky *et al.*, 2005).

Indigofera arrecta, *E. ellipticum* and *C. laburnifolia* were able to persist into the second season by resprouting from standing stems while *T. radicans*, *T. longipes*, *T. purpurea* and *N. wightii* regenerated from rootstocks. This resulted in little change in species composition in the second season. The die back of most annuals then provided a window for most biennials and perennials apparently exhibiting the suffretex habit to persist into the system. These resprouting species also lead to maintenance of indigenous species diversity under indifallow systems, showing the potential of indifallow systems than improved fallow of *Sesbania sesban*, *Tephrosia vogellii*, *Tephrosia candida* and *Cajanus cajan* which depend on fresh supply of seedling or seed (Mafongoya *et al.*, 2006).

5.5.2 Influence of indigenous legume and non-legume species in cropping systems.

Indigenous legume species were able to suppress non-leguminous species within the system as previously reported in sole and mixed legume species fallows (Anoka *et al.*, 1991; Niang *et al.*, 2002). Some problem weeds such as *Eleusine indica*, *Acanthospermum*

hispidum and *Cyperus esculentus* that exist in most cropping system disappeared under indifallows. The increase in populations of some non-legume species in natural fallows also confirmed the ability of indigenous legume species to suppress weeds. *Crotalaria pallida* and *C. ochroleuca* which attained peak biomass at six months (Tauro *et al.*, 2007) suppressed non-legume species during the establishment. Furthermore, resprouting species such as *C. laburnifolia*, *I. arrecta*, *Tephrosia longipes*, and *T. purpurea* further reduced non-legume species diversity in the second season.

At the beginning of the indifallow, the soils were N-depleted and legumes were more competitive than non-legume species because of their ability to fix nitrogen. According to Barrios *et al.*, (2000) natural and agricultural systems respond simultaneously to degradation and regeneration processes through natural succession. Similarly, the peak biomass productivity and increase in abundance of non-legumes which eclipsed most annual legumes in the second season of indifallow establishment might be associated with N release from decomposing legume residues. The dominance of grass, *Cynodon dactylon* in the system was associated to the soil N availability and its growth traits. Similarly, nitrogen addition in mixed species grassland has been reported to change species composition and increase the dominance of *Cynodon dactylon* with an overall loss in species richness (Humphrey, 1977; Mamolos *et al.*, 1995). According to Horowitz (1973), *C. dactylon* was considered as a problem weed due to its open growth pattern and lack of seasonality. Despite *C. dactylon* being termed a problem weed, it could be a useful indicator species for fertility restoration under indifallow systems. According to Mairura *et al.*, (2007), tapping such knowledge may be used as a cheaper alternative by resource-constrained farmers since laboratory procedures are time consuming and costly.

5.6 Conclusions

Changes in indigenous legumes species population, composition and abundance within the indifallow system were influenced by species emergence, competitiveness and growth traits. High emergence of *Eriosema ellipticum* ensured high species population of > 42 plants m^{-2} but contributed insignificant biomass compared to *Crotalaria pallida* and *C. orcholeuca* which had a low species population (< 23 plants m^{-2}). Low survival rate of *E. ellipticum* and the disappearance of *C. pallida*, *C. orcholeuca* and *C. cylindrostachys* contributed to decrease in species populations into the second season. Re-sprouting species such as *Indigofera arrecta*, *E. ellipticum* and *C. laburnifolia*, *Tephrosia radicans*, *T. longipes*, *T. purpurea* and *N. wightii* maintained species diversity under the indifallow system. The most appropriate legume species would be those with high survival, persistence and at the same time contributing more biomass into the system. Introduction of indigenous legume species on nutrient depleted soils contributed to changes in non-legume species composition with well adapted species such as *Cynodon dactylon* becoming dominant resulting from legume competition effects and changes in soil characteristics, particularly increased soil N where indigenous legumes once dominated. This study suggest that establishment of these species in degraded soils can influence changes in non-legume composition from legume competition and resultant increase of N in the system while the changes in legumes population was influenced by species emergence, competitiveness and growth trait.

CHAPTER 6

INFLUENCE OF PHOSPHORUS IN INDIFALLOWS MANAGED FOR RESTORING FERTILITY OF DEGRADED SOILS ON SMALLHOLDER FARMS¹

6.1 Abstract

Developing alternative soil fertility management options is vital for increasing food security in many parts of Africa where soil productivity is constrained by nitrogen (N) and phosphorus (P) deficiencies. This study investigated the P response of indigenous legumes as organic nutrient sources in smallholder farming systems of Zimbabwe. Single super phosphate (SSP) and Dorowa phosphate rock (DPR) were broadcast and incorporated to 20 cm depth at 26 kg P ha⁻¹ before mixtures of indigenous legume species were broadcast on the surface at 120 seeds m⁻² species⁻¹ on disturbed soil. The study was conducted during 2005/06 and 2006/07 rainfall season under low (450-650 mm yr⁻¹) to high (>800 mm yr⁻¹) rainfall conditions. Indigenous legumes responded significantly ($P < 0.05$) better to SSP as a source of P than DPR. Application of SSP or DPR had no significant ($Tobs < 1.96$) effect on legume species composition and establishment patterns but SSP significantly increased biomass productivity by between 20-60%. Single super phosphate influenced ($Tobs > 1.96$) the composition and biomass yield of non-legume species. Abundance of non-legume common broad-leaves weeds *Commelina benghalensis*, *Richardia scabra*, and *Solanum aculeastrum* was reduced by between 5-20% while that of *Cynodon dactylon* a grass, increased with SSP application, leading to a significant ($P < 0.05$) increase in overall non-legume biomass. Indigenous legumes derived 61 – 90% of their N from biological nitrogen fixation with amounts fixed ranging between 5 – 120 kg N ha⁻¹ under semi-arid conditions and between 78 – 267 kg N ha⁻¹ under high rainfall. There was selective response to SSP application among indigenous legume species, with only *Crotalaria cylindrostachys*, *C. ochroleuca* and *C. pallida* increasing biomass accumulation thereby increasing the amount of N fixed by 2, 27 and 51 kg N ha⁻¹, respectively, hence raising the total N fixed within the system. However, non-legumes species responded to SSP application and recovered more P apparently due to their rooting system. The combined effect of P and N from decomposing legume residues resulted in high biomass productivity of non-legumes in the second season thereby out-competing legumes. Application of SSP is critical to increase the N₂-fixation of indigenous legume species.

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6.2 Introduction

Apart from mineral fertilizers, legumes have been known to make net N additions to cropping systems through biological nitrogen-fixation (BNF) and increase maize yields by two to three times (Niang *et al.*, 2002). However, the productivity and nitrogen fixation of most legumes in smallholder farming system of Zimbabwe are constrained by poor nutrients availability, especially phosphorus (P) (Giller, 2001). Biomass generated from such soils is less than 2 t ha⁻¹ and yielding < 60 kg N ha⁻¹ required to make significant impact on productivity (Gilbert, 1998). Supply of P would boost early root development resulting in take up of other soil nutrients for plant development. Most of the locally available resources for smallholder farmers such as cattle manure, crop residues, termitaria and leaf litter supply no more than 15 kg N t⁻¹ and 1.5 kg P t⁻¹ (Giller *et al.*, 1997; Mapfumo and Giller, 2001). When these resources are applied in modest amounts of 3-5 t ha⁻¹ dry matter, N supplied is sufficient to produce a 2 tonne maize crop but their N: P ratio is too high to supply required P for legumes production (Vanlauwe and Giller, 2006). In this case, addressing such soil fertility challenges for smallholder farmers of Southern Africa requires external supply of P or new technical innovations.

Recent findings have identified indigenous legume species capable of establishing on soil with low clay content (< 100 g kg⁻¹ soil), low soil organic carbon (~4 g C kg⁻¹ soil) and < 5 mg kg⁻¹ available P, (Mapfumo *et al.*, 2005). Such soils are often abandoned by farmers due to frequent failure of crops such as maize and soyabean. One way of increasing the N economy of most depleted soils could be through harnessing of these indigenous legumes into cropping system. It is likely that the problem of P deficiencies would not be adequately addressed. Unlike N, biological mechanisms to improve the availability of P

are limited thus application of P containing fertilizers is vital during the restoration of degraded soils. Despite the potential of these indigenous legumes, there is paucity of information on the influence of P application on population dynamics, N₂-fixation and biomass productivity.

In the wake of increasing cost of P fertilizers, a lot of interest has emerged for the use of phosphate rock available in many countries in Sub-Saharan Africa (Akande *et al.*, 1998). According to Dhliwayo (1999), utilization of Dorowa phosphate rock (DPR) satisfies both agronomic and economic farmers' needs, particularly the resource-constrained. Since the indifallow is a low cost technology in terms of establishment and management, use of DPR would integrate well into this concept. Indifallows (indigenous fallows) involves establishing various naturalized indigenous legume species in dense stands in order to improve soil N of natural fallows. Encouraging results have been reported from composting of rock phosphate with agricultural waste (Akande *et al.*, 2005) resulting in increased solubility of phosphate rock but little has been done in utilization of phosphate rock in improved fallows.

Most studies have focused on the influence of P on biomass productivity in improved fallows and yield of the subsequent crop (Chikowo *et al.*, 1999; Akande *et al.*, 2005), with little attention on population dynamics and N₂-fixation of the legumes in the system. This study investigated the population dynamics and P response of indigenous legumes as organic nutrient sources in smallholder farming systems of Zimbabwe. This chapter focused on the following specific objectives:

1. To evaluate the differential response of leguminous and non-leguminous plant species to P application under indifallow and natural systems.

2. To determine the effect of Single Super Phosphate (SSP) and Dorowa Phosphate Rock (DPR) on N₂-fixation by indigenous legume species and biomass productivity of indifallow systems.

6.3.0 Materials and methods

6.3.1 Evaluating species response to phosphorus application under indifallow and natural fallow systems

The following treatments were effected to investigate response of species under indifallow and natural fallow systems to P application:

- i. Indifallow
- ii. Indifallow + Single Super Phosphate (SSP)
- iii. Indifallow + Dorowa Phosphate Rock (DPR)
- iv. Natural fallow
- v. Natural fallow + SSP
- vi. Natural fallow + DPR

The experiment was carried out at Domboshawa and Makoholi experimental stations using both SSP and DPR while at Chikwaka and Chinyika smallholder farming areas SSP was the only P source used. The plots were established by broadcasting and incorporating SSP or DPR to a 20 cm depth at 26 kg P ha⁻¹. A rate between 20 and 30 kg P ha⁻¹ has been used for other grain legumes (Ojiem *et al.*, 2000). Natural fallows were established by disturbing the land by hand hoeing and then allowing naturalized species to reestablish. The experiment was laid out in randomized complete block design (RCBD) with three replicates per treatment. Plots were 36 m² and blocking was based on soil fertility within the fields.

6.3.2 Determining the effect of P application on species abundance and biomass productivity

A 0.5 m x 0.5 m quadrat was used to randomly determine species biomass productivity at 3, 6, 15 and 20 months spreading over two rainy seasons as described in Chapter 3 (section 3.4). The species biomass yield was then divided with the total system biomass to estimate species abundance. After abundance estimation, the dried legume and non-legumes plant biomass were separately ground in a Wiley Mill to pass through a 1 mm sieve followed by total P analysis using the colorimetric method (Anderson and Ingram, 1993). Phosphorus uptake by legume and non-legume species was obtained by multiplying the tissue P concentration by the corresponding biomass. Following individual species P uptake quantification, system total P uptake was calculated as:

$$\text{System total P uptake} = \text{Average \% P of the system} * \text{Total system biomass} \quad (1)$$

6.3.3 Determining the effect of P application on BNF

The N-difference (ND) method, as described in Chapter 3 was used for estimating N₂-fixation of indigenous legumes between 3 and 6 months after seeding. Appropriate non-leguminous reference plants for the different indigenous legumes species were selected from natural fallow plots. The tissue N concentration in both legume and selected reference species were determined using the semi-Kjeldhal digestion method (Anderson and Ingram, 1993). The accumulated N was obtained by multiplying the tissue N concentration by the corresponding species biomass quantity. The difference between N accumulated by the fixing legume and a non-fixing reference plant was considered as the N derived from fixation (Peoples *et al.*, 1995).

6.3.4 Statistical analysis

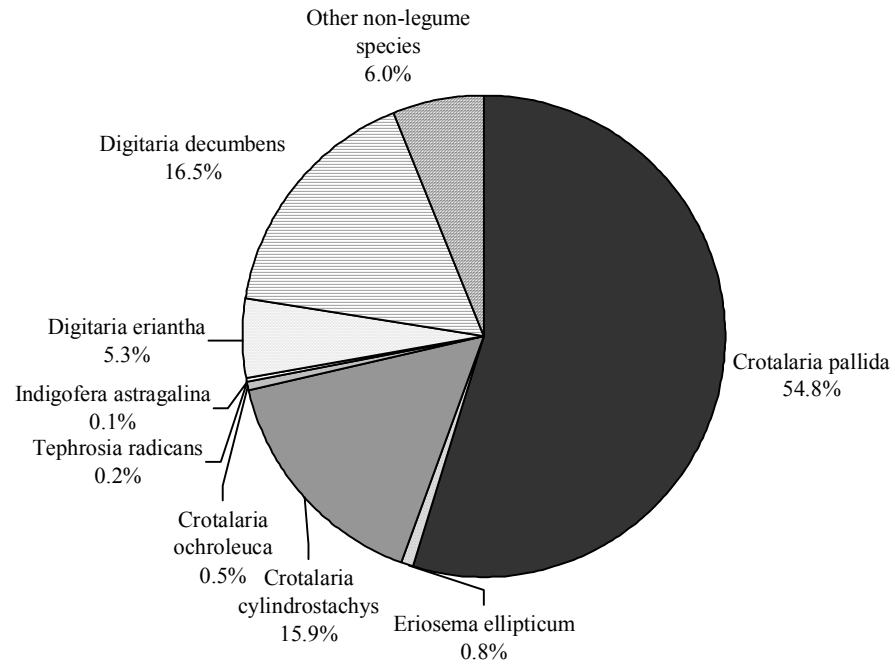
Data was analyzed by analysis of variance and mean comparisons using GENSTAT statistical package (GENSTAT, 2005). Mean comparison for legumes and non-legume productivity were done by t-test. The Shannon-Wiener diversity index (H') was used to test for diversity changes and comparisons of system diversity (Guretzky *et al.*, 2005). Comparisons of system diversity were done at t critical of 1.96 and 774 degrees of freedom. All the mean comparisons were done at 0.05 % significance levels. All the biomass is reported on a dry matter basis while species abundance is reported in percentages of individual plant species per plot.

6.4.0 Results

6.4.1 Influence of P fertilization on species composition in indifallows and natural fallows

Application of SSP or DPR had no significant effect on legume species composition. The abundance of *C. pallida* was increased by ~ 30% at Makoholi and ~ 20% at Domboshawa with SSP application (Figure 6.1), though there was no significant ($P>0.05$) increase in biomass yield.

a) Indifallow



b) Indifallow + SSP

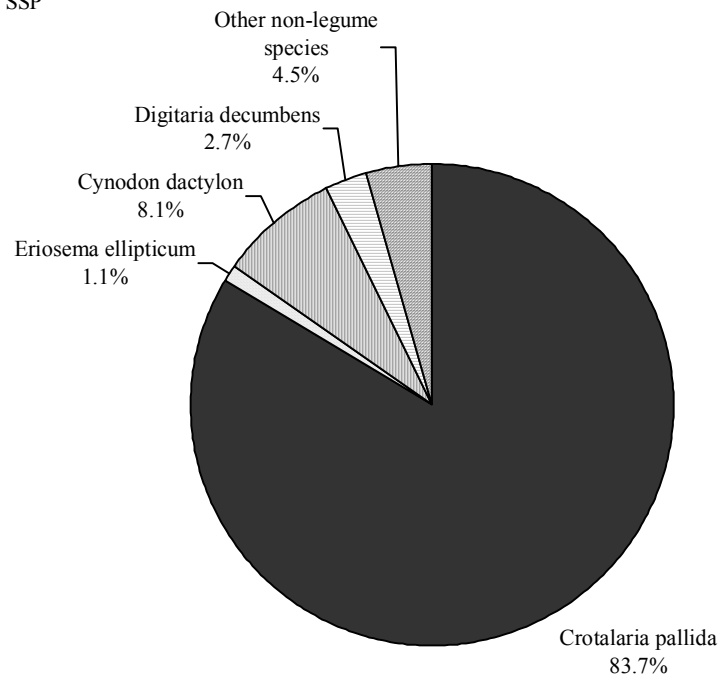


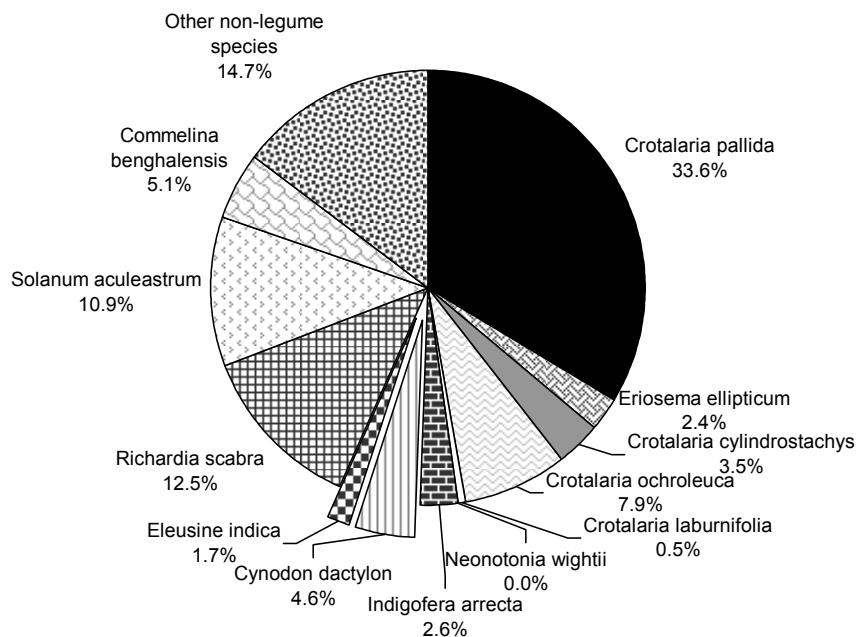
Figure 6.1 Relative abundance of indigenous legume and non-legume species at 6 months in (a) indifallow and (b) indifallow + SSP systems under low rainfall (450-650 mm yr⁻¹), Makoholi in the 2005/06 season.

At Domboshawa and Chikwaka, there was no significant difference ($T_{(obs)} < 1.96$) in non-legume species diversity in indifallow system regardless of P application after 3 months of establishment (Table 6.1). However, application of SSP increased the abundance of *Eleusine indica* and *Cynodon dactylon* by about 10% and 4% in indifallow resulting in abundance decline of *Richardia scabra*, and *Solanum aculeastrum* by about 6% and 8%, respectively (Figure 6.2). Six months after establishment, natural fallow was significantly ($T_{(obs)} > 1.96$) high in non-legumes species diversity than the indifallow system. Following SSP application, both indifallow and natural fallow systems had the highest Shannon-Wiener index (H') and evenness (E) indicating highest diversity and greater non-legumes species evenness, respectively though not significantly different (Table 6.1). Indifallow with SSP was more diverse than indifallow and indifallow + DPR while there was no significant difference in non-legumes species composition among natural fallow system regardless of P source. Consistently, at Chikwaka indifallow + SSP had significantly ($T_{obs} > 1.96$) high species diversity than natural fallow + SSP six months after establishment (Table 6.1). This was due to increased non-legume species diversity under indifallow while non-legume species diversity under natural fallow was reduced following SSP application.

At Makoholi, natural fallow had the highest H' and E than indifallow 3 months after establishment indicating more diverse and greater species evenness, though not significantly ($T_{obs} < 1.96$) different from indifallow system. Application of either SSP or DPR had no significant ($T_{obs} < 1.96$) effect on non-legume species diversity at 3 months after establishment under the indifallow system while application of SSP significantly ($T_{obs} > 1.96$) increased species diversity under natural fallow system (Table 6.1). Six months after establishment, there was significant ($T_{obs} > 1.96$) difference in non-legumes

species diversity under indifallow and natural fallow system. Indifallow had the highest H' and E indicating a more diverse and greater species evenness. Application of SSP significantly ($T_{obs} > 1.96$) increased and reduced species diversity under natural fallow and indifallow system, respectively. Non-legume species diversity was significantly ($T_{obs} > 1.96$) reduced following DPR application under both natural fallow and indifallow systems (Table 6.1). Species diversity under natural fallow + SSP was significantly different from indifallow + SSP. Generally, application of SSP increased the abundance of most non-legume species under indifallow and also led to the appearance of new species namely *Conyza sumatrensis* and *Ageratum conyzoides*.

a) Indifallow



b) Indifallow + SSP

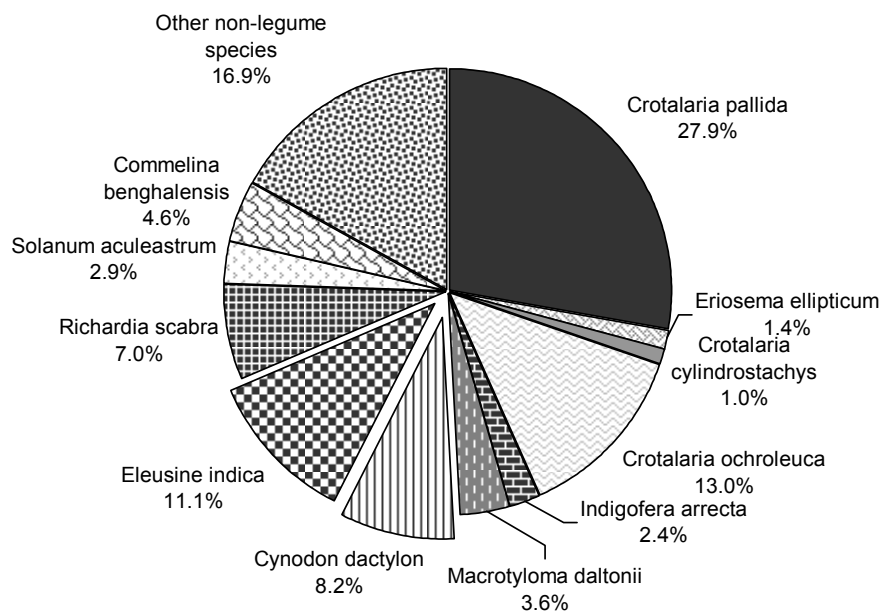


Figure 6.2. Relative abundance of indigenous legume and non-legume species at 3 months in (a) indifallow (b) indifallow + SSP systems under high rainfall ($>800 \text{ mm yr}^{-1}$), Domboshawa in the 2005/06 season.

Table 6.1. Shannon-Wiener diversity index (H') and Evenness index (E) for non-legume species at 3 and 6 months after establishment under indifallow and natural fallow system with or without P at Domboshawa, Makoholi and Chikwaka in the 2005/6 rainfall season.

Treatment	Domboshawa				Makoholi				Chikwaka			
	3 months		6 months		3 months		6 months		3 months		6 months	
	H'	E	H'	E	H'	E	H'	E	H'	E	H'	E
Indifallow	1.78	0.62	0.49	0.25	1.20	0.67	1.74	0.97	1.81	0.79	1.69	0.77
Indifallow + SSP	1.63	0.56	1.27	0.55	0.83	0.46	1.59	0.77	1.55	0.74	1.99	0.90
Indifallow + DPR	1.80	0.62	1.08	0.49	1.04	0.58	1.06	0.60	nt	nt	nt	nt
Natural fallow	2.00	0.69	1.10	0.44	1.57	0.71	1.65	0.69	1.91	0.80	2.01	0.87
Natural fallow + SSP	1.79	0.62	1.41	0.51	1.84	0.71	1.71	0.88	1.78	0.77	1.88	0.76
Natural fallow + DPR	1.67	0.58	1.12	0.47	0.69	0.38	1.58	0.64	nt	nt	nt	nt

nt = not established, H'= Shannon-Wiener diversity index, E= Species evenness index

In the first growing season, non-legume species had peak biomass at 3 months while legumes attained maximum yield at 6 months after sowing thereby suppressing most of the non-legume species. During the second growing season, the abundances of *Cyperus esculentus* and *R. scabra* was reduced possibly due to competition from increased abundance of *C. dactylon*. In the second season non-legumes species out-competed indigenous legumes species as a result of P application (Figure 6.3). Non-legume species were dominant in the system through-out the second growing season (Figure 6.3).

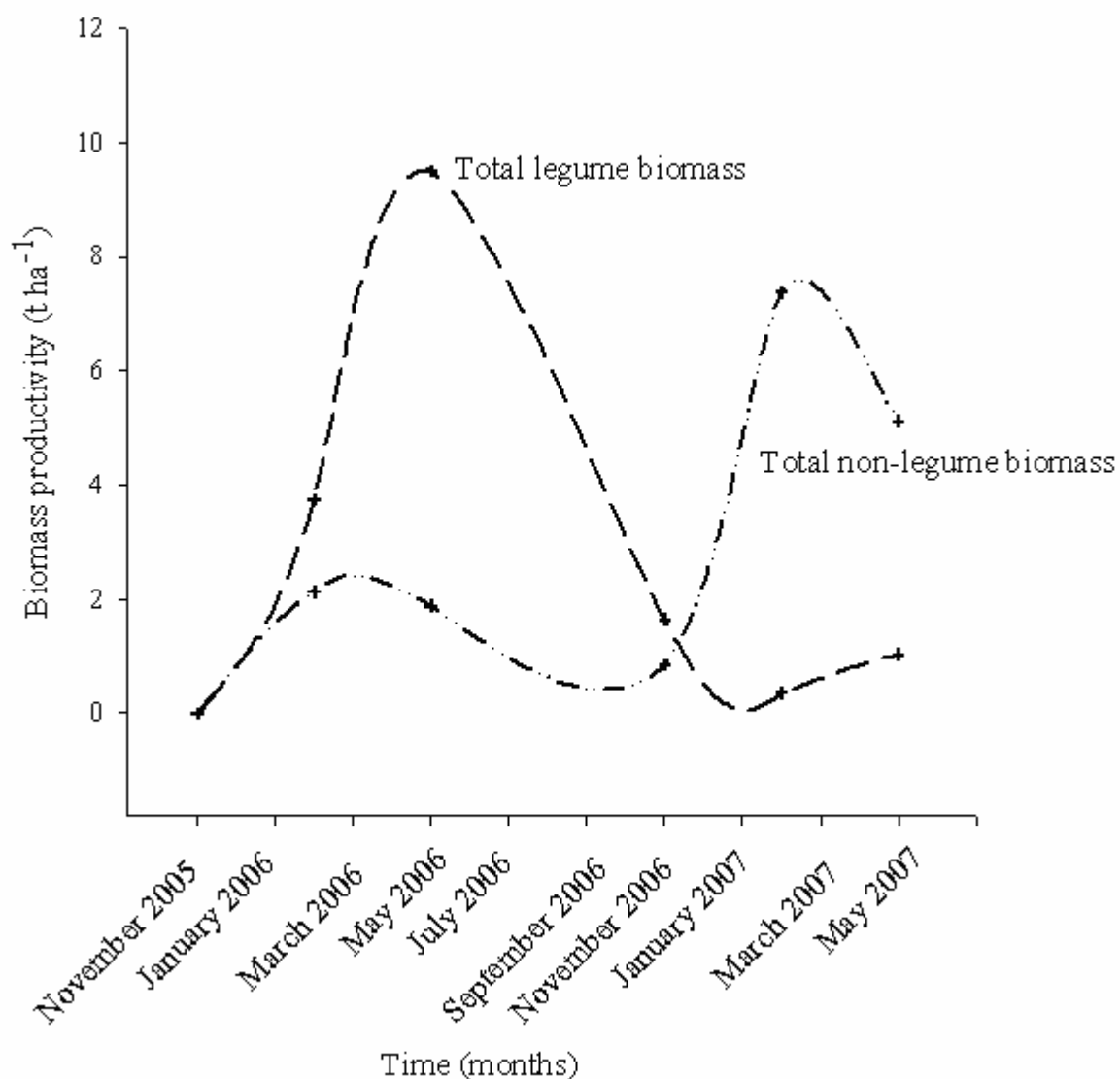


Figure 6.3. Biomass accumulation patterns of leguminous and non-leguminous species biomass under indifallow + SSP over two seasons at Domboshawa (>800 mm yr⁻¹), Zimbabwe during 2005/06 and 2006/07 seasons.

6.4.2 Influence of P application on indifallow and natural fallow productivity

At 3 month, P application regardless of source had no significant effect on total legume biomass productivity under indifallows while there was a significant increase in biomass under natural fallows. Of the three legume species (*Crotalaria cylidrostrachys*, *C. glauca*

and *C. pisicarpa*) which had peak biomass at 3 month, only *C. cylindrostachys* responded to SSP application at Chikwaka. Application of SSP increased *C. cylindrostachys* biomass from 0.2 t ha⁻¹ to 0.4 t ha⁻¹. At 6 months after establishment indifallow biomass productivity increased significantly between 20% and 60% as a result of SSP application across sites. *Crotalaria pallida* significantly responded to SSP application while slow growing biennials such *N. wightii*, *I. arrecta* and *E. ellipticum* did not respond (Table 6.2). At both Makoholi and Domboshawa, *C. pallida* increased yield by 0.2 and 0.3 t ha⁻¹, respectively with SSP application (Table 6.2). Generally indifallow biomass productivity (legume and non-legume) increased with the addition of SSP at both sites. Similar six months after establishment, *Crotalaria pallida* and *C. cylindrostachys* increased biomass by about 1.0 and 0.8 t ha⁻¹ at Chikwaka, respectively, following SSP application. Response to SSP addition was also evident for *C. ochroleuca* which accumulated an additional 0.1 t ha⁻¹ at Chikwaka due to poor initial establishment and 3.1 t ha⁻¹ at Mudange.

Dorowa phosphate rock showed contrasting effects on biomass productivity across sites. There was no significant ($P>0.05$) difference in biomass productivity with application of SSP or DPR at 6 months after establishment at Domboshawa (Table 6.2). Conversely at Makoholi, addition of DPR to indifallows resulted in low yield of indigenous legume species compared with yield in indifallow with SSP over the 6 months period. *Crotalaria pallida* and *C. cylindrostachys* only accumulated 0.6 t ha⁻¹ and 0.9 t ha⁻¹ following DPR application compared with 7.6 t ha⁻¹ and 0.9 t ha⁻¹ without supply of P (Table 6.2).

Shoot P concentration of the legumes was particularly low, ranging from a mean value of 0.05 % for *C. cylindrostachys* to 0.09 % for *E. ellipticum* and *C. pallida*. In contrast, non-

legume species had slightly higher shoot P concentration of 0.12 %. Regardless of P source, there was no significant difference ($P>0.05$) in the total P uptake of the indigenous legume species (Figure 6.4). In contrast, there was an increase in total P uptake for non-legume species in both indifallow and natural fallow systems as a result of DPR or SSP application at Domboshawa (Figure 6.4). Despite the application of P, the accumulated P ranged from 9 to 11 kg ha⁻¹ and 2 to 7 kg ha⁻¹ at Domboshawa and Makoholi, respectively. The total P uptake of non-legumes was reduced with DPR application in both indifallow and natural fallow system at Makoholi a more depleted soil (Figure 6. 4). At Makoholi, application of SSP increased the total P uptake in indifallow from 4 kg ha⁻¹ to 7 kg ha⁻¹ while the total P uptake indifallow was reduced to <1.5 kg ha⁻¹ with application of DPR (Figure 6.4).

Table 6.2. Effect of phosphorus application on biomass productivity (t ha⁻¹) of indigenous legumes at 6 months after establishment under low rainfall (Makoholi) and high rainfall (Domboshawa), in the 2005-06 season.

Indigenous legume species	Makoholi				Domboshawa			
	SSP	DPR	No P	SED	SSP	DPR	No P	SED
<i>Crotalaria pallida</i>	7.8	0.6	7.6	2.10	9.2	9.2	8.9	2.70
<i>Crotalaria ochroleuca</i>	np	np	np	-	0.3	4.5	4.0	1.88
<i>Crotalaria cylindrostachys</i>	0.5	0.1	0.9	0.10	0.7	0.07	0.2	0.53
<i>Eriosema ellipticum</i>	0.1	0.1	0.1	0.04	0.04	0.01	0.5	0.27
<i>Indigofera arrecta</i>	ni	ni	ni	-	ni	0.08	0.04	-
<i>Indigofera astragalina</i>	0.08	0.2	0.1	0.03	ni	ni	ni	-

np = not planted during establishment of indifallow; ni = not identified in the indifallow system

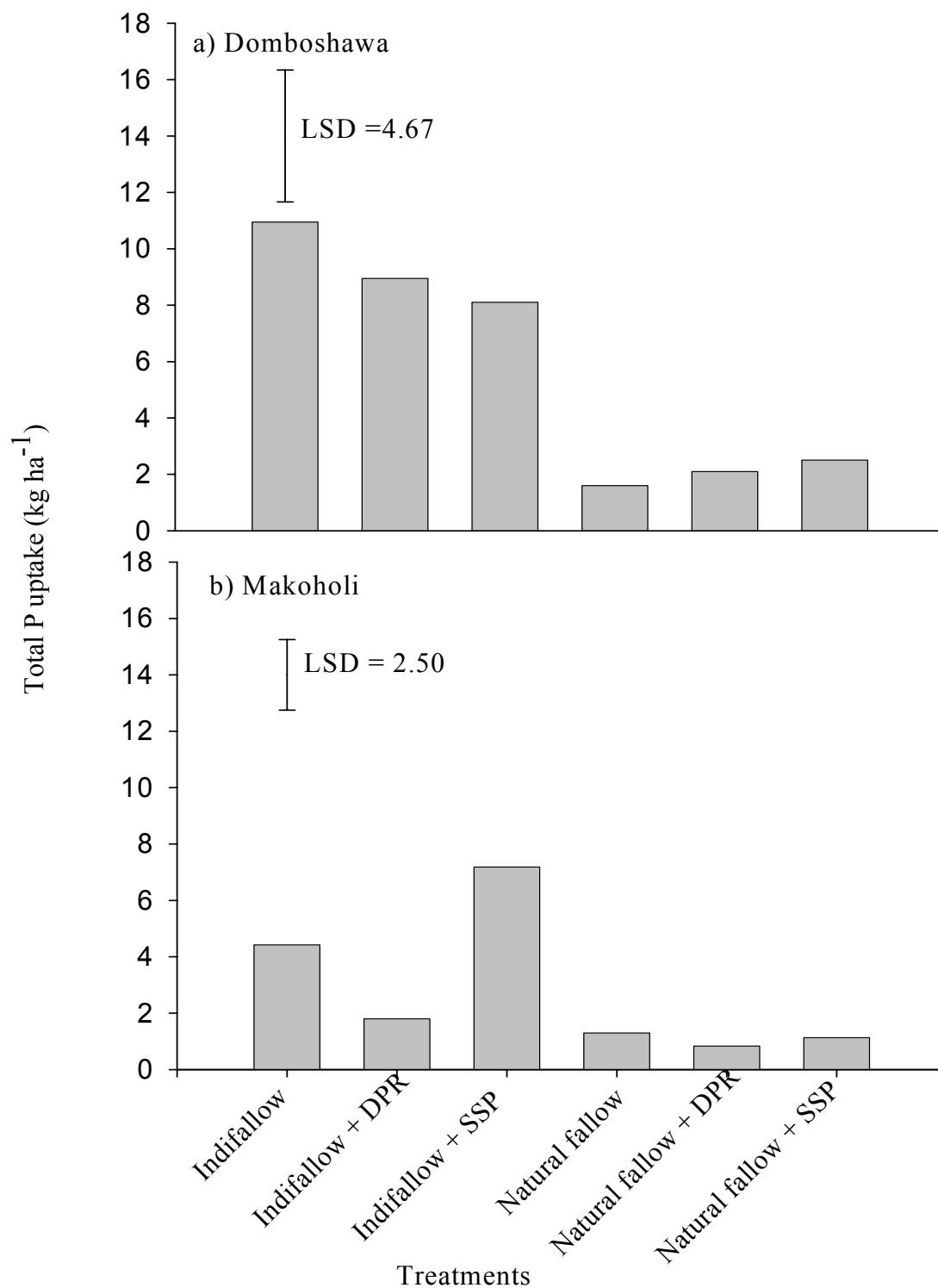


Figure 6.4. Total phosphorus uptake in indifallow and natural fallow biomass after 6 months of establishment under (a) high rainfall conditions at Domboshawa (750 mm yr⁻¹) and (b) low rainfall conditions at Makoholi (450-650 mm yr⁻¹) in the 2005-06 season.

6.4.3 Effects of P application on N₂-fixation of indigenous legumes

Generally, addition of SSP increased N fixation by indigenous legume species across the rainfall zones, except at Makoholi which was severely depleted (Table 6.3). Addition of SSP increased the total amount of N fixed at Domboshawa and Chinyika by 43 %, yielding 120 kg N ha⁻¹ and 81 % yielding 26 kg N ha⁻¹, respectively. The amount of N fixed at Makoholi following application of SSP decreased by 47 % yielding 63 Kg N ha⁻¹ instead of 90 kg N ha⁻¹. At Domboshawa, there were no significant ($P>0.05$) differences in amount of N fixed as a result of SSP or DPR application. In contrast, DPR application significantly ($P<0.05$) reduced the amount of N fixed at Makoholi. The greatest increase in N fixation was at Chikwaka where application of SSP to indifallows led to a 141 % increase in N fixation (Table 6.3).

Most indigenous legumes significantly ($P<0.05$) fixed more N after the addition of SSP (Table 6.3). Addition of SSP significantly increased the amount of N fixed by *C. ochroleuca* (18 %) and *C. pallida* (26 %) (Table 6.4). However, addition of SSP did not significantly increase the amounts of N fixed by the legume species in cases where overall biomass accumulation remained poor, suggesting that there were other limiting factors apart from P.

Table 6.3. Total amount of N₂-fixed (kg N ha⁻¹) in indifallows plots under different rainfall conditions at 3 months after establishment in the 2005-06 season.

Site	Treatments			SED
	Indifallow	Indifallow Plus SSP	Indifallow Plus DPR	
Domboshawa (>750 mm yr ⁻¹)	84	120	123	21.0
Makoholi (450-650 mm yr ⁻¹)	91	63	11	37
**Chikwaka (>750 mm yr ⁻¹)	5.4	13	np	7.3
*Chinyika (650-750 mm yr ⁻¹)	14.4	26.1	np	6.5

**Nyamayaro, *Mudange, np = not planted during establishment of indifallow

Table 6.4. N₂-fixation patterns of different indigenous legume species between 3 and 6 months of growth on poor soils, with and without SSP application under different rainfall conditions in Zimbabwe

Study site (rainfall zone)/ Indigenous legume species	N ₂ -fixed (kg N ha ⁻¹)		% N from fixation (%Ndfa)	Reference plant
	Minus P	Plus P		
Chinyika (450-650 mm yr ⁻¹)				
<i>Crotalaria pallida</i>	140(23.8)	nd	99	<i>Ageratum conyzoides</i>
<i>Crotalaria ochroleuca</i>	150(31.5)	177(4.0)	95-97	<i>Leucus martinicensis</i>
<i>Crotalaria cylindrostachys</i>	7(1.20)	9(0.5)	68-74	<i>Richardia scabra</i>
<i>Eriosema ellepticum</i>	15(1.4)	9(0.2)	93-95	<i>Ageratum conyzoides</i>
<i>Indigofera arrecta</i>	0.5(0.1)	2(0.7)	61-78	<i>Ageratum conyzoides</i>
<i>Indigofera astragalina</i>	1.5(0.3)	5(0.3)	59-75	<i>Richardia scabra</i>
<i>Tephrosia radicans</i>	1.4(0.1)	nd	99	<i>Ageratum conyzoides</i>
<i>Chamaecrista mimosoides</i>	3.4(2.4)	1(0.2)	62-87	<i>Ageratum conyzoides</i>
*Domboshawa (>750 mm yr ⁻¹)				
<i>Crotalaria pallida</i>	193(6.2)	244(27.7)	99	<i>Ageratum conyzoides</i>
<i>Crotalaria ochroleuca</i>	70(2.8)	76(2.0)	93-99	<i>Ageratum conyzoides</i>
<i>Crotalaria cylindrostachys</i>	3(1.05)	nd	66	<i>Richardia scabra</i>
<i>Eriosema ellepticum</i>	11(0.2)	3(0.2)	99	<i>Ageratum conyzoides</i>
<i>Indigofera arrecta</i>	6(0.3)	5(0.5)	70-84	<i>Bidens pilosa</i>
Chikwaka (>750 mm yr ⁻¹)				
<i>Crotalaria pallida</i>	89(10.2)	82(14.3)	87-95	<i>Bidens pilosa</i>
<i>Crotalaria ochroleuca</i>	2.6 (0.3)	3.9 (0.9)	72-80	<i>Bidens pilosa</i>
<i>Crotalaria cylindrostachys</i>	5.2 (0.3)	8.8 (0.2)	84-89	<i>Richardia scabra</i>
<i>Eriosema ellepticum</i>	nd	nd	nd	
<i>Indigofera arrecta</i>	nd	nd	nd	

* Domboshawa soils have 22 % clay compared with <10 % for Chikwaka; nd = not determined; Figure in parentheses denotes standard errors

6.5.0 Discussion

6.5.1 Species composition as affected by P application in indifallows

The response of non-legume species such as *Cynodon dactylon* and *Eleusine indica* to P application can be attributed to their fibrous rooting systems, which enable their ready access to soil P (Cadisch *et al.*, 1998). This could account for increased non-legume species diversity under both indifallow and natural fallow following P addition. However, the increase in non-legume species diversity under indifallow can also be partly due to increased availability of N as a result of contributions from N₂ fixation by the legumes. Lack of seasonality and open growth pattern of *C. dactylon* also attributed to the response to P application while other species were being out-competed in the first season. The dominance and competitiveness of *C. dactylon* contributed to the reduction in abundance of *Cyperus esculentus* and *R. scabra* in the indifallow. The combined effect of P and N from decomposing legume residues could have resulted in high biomass productivity of non-legumes in the second season. However, at Makoholi lack of response by non-legume species to P application at seemingly high rate of 26 kg P ha⁻¹ suggests that nutrients other than P were also limiting. The soils at Makoholi are also highly prone to nutrient leaching (Mtambanengwe and Mapfumo, 2006), which might have attributed to lack of responsiveness of non-legume species.

According to Tauro *et al.*, (2007) indigenous legume species composition is governed by germination and emergence but these results showed that the application of P influenced species composition in the system. Changes in species abundance following P application contributed to changes in species composition. Even though legumes have

high P requirement than grasses (Cassman *et al.*, 1981; Giller and Wilson, 1991), most of indigenous legumes had a slow initial growth rate, resulting in poor early response to SSP application. The result also showed that most indigenous legume species except *C. cylindrostrachys*, *C. pallida* and *C. ochroleuca* are adapted to low soil available P.

6.5.2 Influence of P on biomass productivity under indifallow system

Indifallows produced high biomass at Domboshawa (~15 t ha⁻¹) and Chinyika (Chikodzo) (~7 t ha⁻¹) sites despite these soils having 5 mg kg⁻¹ available P, suggesting that such low P levels might be adequate to support indigenous legume species establishment and growth. Furthermore, the particularly low P content (P < 0.09%) of these indigenous legume species and low total P uptake of indifallow systems confirm that these legumes utilize low P from the soil and may not respond to P application. Application of either SSP or DPR at Domboshawa had no significant effect on biomass accumulation. These results support similar findings by Mapfumo *et al.* (2005) who identified these species to be growing in P deficient soils where maize could not yield 1 tonne of grain.

Despite ground phosphate rock being beneficial in acidic soils (Nandi and Haque, 1988), application of DPR depressed the growth of the legumes species such as *C. pallida* at Makoholi. The low supply of P for legume utilization might be attributed to the low solubility of the material (Dhliwayo, 1999) and short time of fallowing which was unlikely to benefit the DPR. In another study by Muza and Feresu (1998), velvet bean, sunnhemp and cowpea did not respond to direct application of DPR or Pelleted Phosphate Rock (PPR). According to Dhliwayo (1999), DPR might need to be beneficiated with organic materials prior to use in order to release the locked P implying that despite being a

cheaper source of P, DPR might not provide the immediate benefits which most farmers expect. However, DPR still remains a cheap source for improving soil P capita for most resource-constraint farmers. Therefore there is need to understand the long term effects of applying DPR to indifallows.

Varied responses among legume species to SSP application can be attributed to their growth traits and different P requirements. Slow growing biennials species such as *I. arrecta*, *N. wightii* and *E. ellipticum* did not respond to SSP as they had early die back compared to *Crotalaria pallida* and *C. ochroleuca*. Such a phenology may help to explain why the effect of SSP on legume biomass productivity was evident at 6 months after legume establishment. The responsiveness of *C. pallida* and *C. ochroleuca* to P application among the *Crotalaria* genera provides evidence of different P response even among species of the same genera. Similarly, Rao et al. (1999) reported that plants differ in their ability to utilize available forms of P in the soil and large differences exist among species even of the same genera.

6.5.3 Importance of P in N₂-fixation of indigenous legumes

The increases in N₂-fixation with application of SSP at Chikwaka suggest that P was a limiting nutrient to N₂-fixation of indigenous legumes. Phosphorus application is a major requirement for N₂-fixation and biomass productivity in both cropping and natural systems when soil P is low (Giller, 2001). Despite most indigenous legume species adapted to soil with low available P, application of P increased biomass productivity and N₂-fixation of *C. ochroleuca* and *C. pallida*. Indifallows without P will not attain the addition benefits from responding species suggesting that P application is critical. The poor response in N₂-

fixation of indigenous legumes following P application at Makoholi suggest that indigenous legumes may be limited by nutrients other than N, which is consistent with findings by Grime and Curtis (1976) and Tilman (1982). Similar challenges have been cited in efforts to enhance productivity of soyabean and other grain legumes under severely depleted soil in sub-Saharan Africa (Snapp *et al.*, 2002; Giller, 2003). According to Ritchie and Tilman (1995), other nutrients such as calcium and manganese may be necessary for optimum performance of wild legumes. To increase fixation of indigenous legumes on such depleted soils, cattle manure or other organic resources might need to be applied to improve the supply of bases, micronutrient and reduce soil acidity. Working on similar depleted soils, Zingore et al. (2007) reported a yield of 44 kg N ha⁻¹ for soyabean amended with manure compared to 25 kg N ha⁻¹ following SSP application.

6.6 Conclusions

Indigenous legume species responded significantly to SSP as a source of P than DPR. Phosphorus application to indigenous legume fallows influenced non-legume species composition but did not affect establishment and composition of the legume species. There was an apparent low P requirement by indigenous legume species. Different legume species of the same genera responded differently to P application, exhibiting the advantage of sowing them in mixtures. Application of P significantly increased total biomass productivity and N₂-fixation of indifallows. The study demonstrates that phosphorus remains a strategic nutrient input in stimulating restoration of sand soil productivity using indigenous legume species. However, the realisation of P benefits is apparently limited by multi-nutrient deficiency in sand soils.

CHAPTER 7

OVERALL DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS

7.1 Introduction

Much of the previous soil fertility research has targeted legume-based technologies to increase maize yields with little attention on restoration of nutrient depleted soils. This study evaluated the establishment and management of indigenous legumes in indifallow systems, which is a potential integrated soil fertility management (ISFM) option. The data presented here is from three different agro-ecological regions of Zimbabwe and may apply to other farming systems in sub-Saharan Africa where such indigenous legume resource can be found.

7.2 Establishment of indigenous species

This study has demonstrated that mixing indigenous legume species ensured successful establishment of indifallows for soil fertility amelioration as it provides insurance against germination or emergence failure and competition. Acid scarification of the seed and disturbing the soil at planting increased the emergence of indigenous legume species resulting in successful indifallow establishment. However, there is need to explore alternative mechanisms that are acceptable to farmers for increasing species emergence apart from acid scarification, as acid is not readily available in rural outlets. It was evident that *Eriosema ellipticum* showed no signs of dormancy while other species had seed dormancy being expressed. Apart from seed dormancy, lack of viability also affected species germination in the system resulting in poor stand establishment. The most ideal planting time for the species is at the onset of the rains when there is adequate moisture for seed germination.

Most legume-based technologies have failed to make an impact due to high establishment and maintenance cost. However, this new innovation requires no weeding once the species have established. Since labour shortage is common in communal areas, this might be a good option for soil fertility management particularly for resource-constrained farmers. Establishment of the 2-year indifallows is mainly through resprouting species with little influence of seed from the first season. Disturbing the soil in the second season might improve species germination due to improved seed soil contact. On the other hand, collection of indigenous seed from the 1-year indifallows might increase the availability of the seed for use on other plots and at the same time save time of collecting seed from the wild.

7.3 Biomass accumulation of indigenous legume species

Mixing various indigenous legume species in the indifallow systems ensured species contribution to biomass could be spread over time. *Crotalaria* species such as *C. pallida*, *C. ochroleuca* and *C. laburnifolia* attained $> 5 \text{ t ha}^{-1}$, showing superiority in biomass productivity in relation to *Indigofera* and *Chamaecrista* species, which might be related to their high N_2 -fixation capacity. However, most of these species did not persist into the second season and needed to be complemented. Most biennial species such *Neonotonia wightii*, *Tephrosia radicans* and *E. ellipticum* only managed to attain about 2 t ha^{-1} , which might be low amounts but critical contributions in increasing residual benefit associated with biomass inputs in the system.

Given that most locally derived organic nutrients are often of poor quality, particularly low in N, synchronization of nutrient release and crop demand is normally poor. In addition, unavailability and inaccessibility to most nutrients resource limits farmer's

capacity to manipulate the synchronization. The indifallow concept can potentially address such challenges through the inputs of different quality biomass into the system. A regular supply of high and low quality organic materials to sandy soils have been shown to improve the fertility status and improve maize yields (Mtambanengwe and Mapfumo, 2005). An accumulation of 7-15 t ha⁻¹ of biomass without P application and low requirement of P by indigenous legumes makes them suitable for use in fertility restoration purposes in most depleted soils of Zimbabwe.

7.4 Population dynamics within indifallow systems

In the first season, *Eriosema ellipticum* was the most dominant legume species having a population of 42 plants m⁻² while *Crotalaria pallida*, *C. cylindrostachys*, *C. ochroleuca* and *Indigofera arrecta* each had populations of < 23 plants m⁻². As the season progressed, there was a significant decrease in the population of *E. ellipticum* and *Neonotonia wightii* due to low survival rates as competition increased. This showed that population of indigenous legumes species is governed by species germination, emergence, ability to withstand competition from non-legume species and growth habit. Monitoring of changes in species composition in the indifallow systems revealed that annuals are abundant in the first season and could not persist into the second season. On the contrary biennials and perennials persisted, attaining their maximum biomass in the second season. The generative capacity of indigenous legume species through resprouting resulted in maintenance of legume species diversity in the systems. Indigenous legume species influenced changes in non-legume species diversity. This was indicated by the smothering effect of the species, suggesting that weeding might not be necessary thereby reducing the maintenance costs of the indifallow systems.

On the other hand, the increase in the N economy of the system resulted in the increase in abundance of non-leguminous species in the second season. The rapid dominance of *Cynodon dactylon*, a grass weed with high nutrient requirements suggests that it took advantage of increased nutrient levels particularly N. Such competitive dynamics for N may act as indicators for the restoration process of degraded soils. According to Promsakha na Sakonnakhon et al. (2005) non-legumes species are likely to immobilize applied nitrogen due to their high C: N ratio. However, the quality of non-legumes species under indifallow systems is likely to be high due to accumulation of nitrogen from decomposing legumes which reduces the C: N ratio and can release nitrogen to subsequent crop. Overall, the combination of N and organic matter inputs could be vital in addressing the depleted soils in Sub-Saharan Africa to bring them back into productivity.

7.5 Response of indigenous legumes to P application

The two sources of P (SSP and DPR) varied in quality and their effectiveness within the soil matrix was probably governed by their solubility and availability to crops. Both sources had no effect on the abundance and diversity on indigenous legume species in the systems. It was evident that these indigenous legume species are adapted to low P soil and most did not respond to P application in term of biomass productivity. The increase in abundance of non-legume species with SSP application might be linked to the readily available P from SSP compared to DPR. Despite having no effect on legume species composition, addition of SSP increased the amount of N fixed by most indigenous legume species across sites except at Makoholi where deficiencies of other nutrients could have been limiting N₂-fixation.

The practicality of P application in indifallows under smallholder farming conditions poses a challenge given that fertilizers are expensive and limited for most resource-constrained farmers. However, the P application is critical under indifallow as it increases the benefit associated with indigenous legume species by increasing biomass productivity and N₂-fixation of selective species. Farmers tend to allocate the limited fertilizers to cereal crops which might not ensure household food security when the soils are depleted. Since P is not lost through leaching the farmer will benefit more after the N economy of the system has improved by indigenous legume species. According to Muza (2003), the application of P to green manure crops such as sunnhemp and velvet bean almost doubled the subsequent maize grain yields. Phosphorus application is a pre-request in increasing the benefits associated with indigenous legumes species and in restoration of abandoned soils.

Short term benefits of DPR were not evident in the study, which could be attributed to its low solubility and short time of fallowing. Further research is required to quantify potential P benefits to subsequent cereal crops and to determine the long term effects of DPR application in indifallow systems. Apparently, beneficiating the DPR with organic materials or manure might be the best way to improve the release of the P into the system (Dhliwayo, 1999). Most of these indigenous legumes had low P uptake from the system and since P is not very mobile in soils DPR can then contribute to the P recapitalization in most of depleted soils.

7.6 Area for further research

The indifallow systems can potentially address most challenges of resource constrained farmers in restoring fertility of their abandoned fields. An understanding of indigenous legume species establishment patterns, population dynamics and P management response in indifallows is useful in the integration of indifallows into farming systems. However, there is still a scarcity of information on:

- The effect of indigenous legume species competition on biomass productivity and N fixation within the indifallow systems. To understand the nature of competition among species in the indifallow there is need to study the species in their sole stands.
- Factors affecting emergence of indigenous legume seed in the second season, despite the prolific seed production in the first season.
- Ways to make indigenous legume seed available to most farmers and at the same time improving the quality of seed to ensure high emergence during establishment.
- The potential P benefits to soil fertility and the subsequent cereal crops.
- Opportunities for incorporating legumes in land rehabilitation programs.
- Issues of species invasiveness.

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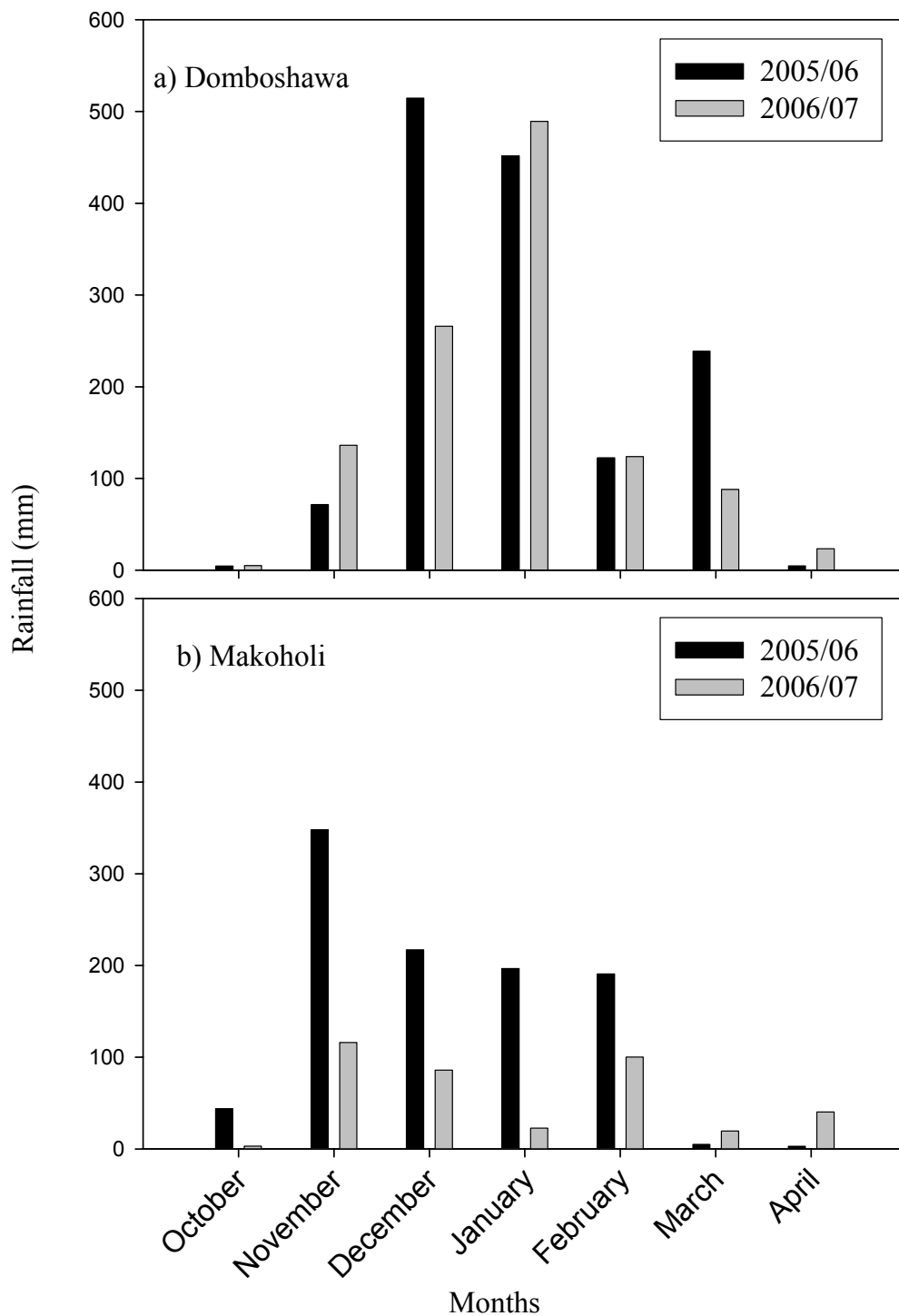
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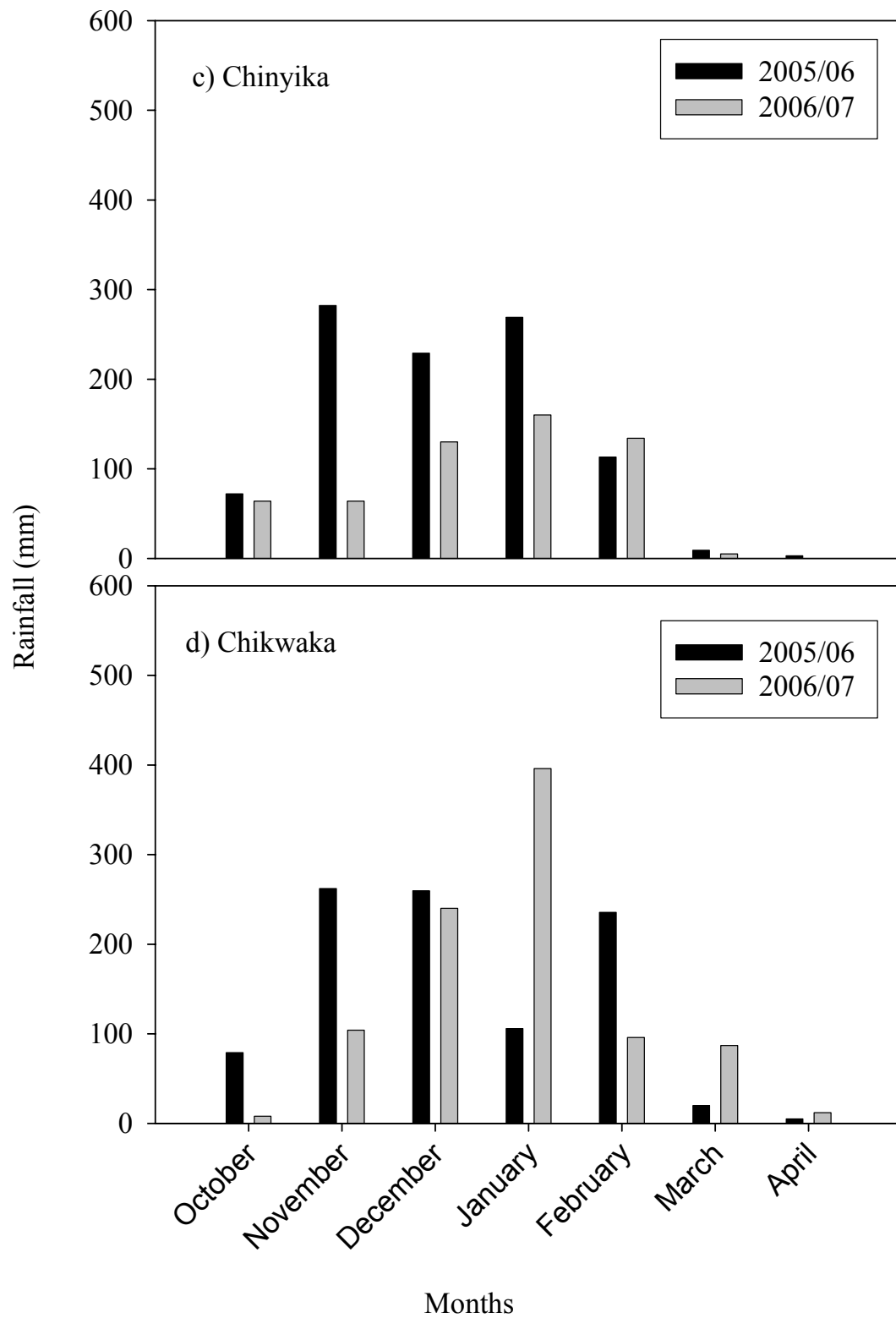
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Appendix A. Rainfall data for 2005/06 and 2006/07 season





Appendix B. List of publications from this thesis

1. Mapfumo, P., Nezomba, H., **Tauro, T.P.** and Mtambanengwe, F. 2006. N₂-fixing indigenous legumes: From the wild to farmers' fields. Abstract presented at the 1st International conference on indigenous vegetables and legumes, ICRISAT Campus, Patancheru, Hyderabad, India, 12-15 December 2006.
2. **Tauro, T.P.**, Nezomba, H., Mtambanengwe, F. and Mapfumo, P. 2007. Field emergence and establishment of indigenous N₂-fixing legumes for soil fertility restoration. *African Crop Science Conference Proceedings* **8**: 1929-1935.
3. **Tauro, T.P.**, Nezomba, H., Mtambanengwe, F. and Mapfumo, P. 2007. Responses of indigenous legumes species to mineral P application for soil fertility restoration in smallholder farming systems of Zimbabwe. Abstract published in the proceedings of African Network for Soil Biology and Fertility (Afnet) -SOFECSA International Symposium titled "*Innovations as Key to the Green Revolution in Africa: Exploring the Scientific Facts*", 17-21 September, 2007, Arusha, Tanzania.
4. **Tauro, T.P.**, Nezomba, H., Mtambanengwe, F. and Mapfumo, P. 2009. Germination, field establishment patterns and nitrogen fixation of indigenous legumes on nutrient-depleted soils, *Symbiosis*, **48**:92-101.

Appendix C. Statistical analysis outputs

(i) Domboshawa *C. pallida* biomass productivity at 6 months after establishment

TREATMENTS

1. Indifallow
2. Indifallow + SSP
3. Indifallow + RP

***** Analysis of variance *****

Variate: Biomass

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	5.23	2.62	0.24	
Block.*Units* stratum					
Treatment	2	0.16	0.08	0.01	0.993
Residual	4	43.85	10.96		
Total	8	49.25			

***** Tables of means *****

Variate: Biomass

Grand mean 9.1

Treatment	1	2	3
	8.9	9.2	9.2

*** Standard errors of means ***

Table	Treatment
rep.	3
d.f.	4
e.s.e.	1.91

*** Standard errors of differences of means ***

Table	Treatment
rep.	3
d.f.	4
s.e.d.	2.70

*** Least significant differences of means (5% level) ***

Table	Treatment
rep.	3
d.f.	4
l.s.d.	7.51

(ii) Domboshawa *C.ochroleuca* biomass productivity at 6 months after establishment

TREATMENTS

1. Indifallow
2. Indifallow + SSP
3. Indifallow + RP

***** Analysis of variance *****

Variate: Biomass

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	6.472	3.236	0.61	
Block.*Units* stratum					
Treatment	2	24.763	12.382	2.33	0.213
Residual	4	21.251	5.313		
Total	8	52.486			

***** Tables of means *****

Variate: Biomass

Grand mean 2.64

Treatment	1	2	3
	4.02	0.31	3.59

*** Standard errors of means ***

Table	Treatment
rep.	3
d.f.	4
e.s.e.	1.331

*** Standard errors of differences of means ***

Table	Treatment
rep.	3
d.f.	4
s.e.d.	1.882

*** Least significant differences of means (5% level) ***

Table	Treatment
rep.	3
d.f.	4
l.s.d.	5.225

(iii) Domboshawa *E.ellipticum* biomass productivity at 6 months after establishment

TREATMENTS

1. Indifallow
2. Indifallow + SSP
3. Indifallow + RP

***** Analysis of variance *****

Variate: Biomass

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	0.3192	0.1596	1.50	
Block.*Units* stratum					
Treatment	2	0.3084	0.1542	1.45	0.336
Residual	4	0.4258	0.1065		
Total	8	1.0534			

***** Tables of means *****

Variate: Biomass

Grand mean 0.19

Treatment	1	2	3
	0.45	0.04	0.09

*** Standard errors of means ***

Table	Treatment
rep.	3
d.f.	4
e.s.e.	0.188

*** Standard errors of differences of means ***

Table	Treatment
rep.	3
d.f.	4
s.e.d.	0.266

*** Least significant differences of means (5% level) ***

Table	Treatment
rep.	3
d.f.	4
l.s.d.	0.740

(iv) Domboshawa *C.cylindrostachys* biomass productivity at 6 months after establishment

TREATMENTS

1. Indifallow
2. Indifallow + SSP
3. Indifallow + RP

***** Analysis of variance *****

Variate: Biomass

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	0.1609	0.0804	0.19	
Block.*Units* stratum					
Treatment	2	0.3592	0.1796	0.43	0.675
Residual	4	1.6553	0.4138		
Total	8	2.1754			

***** Tables of means *****

Variate: Biomass

Grand mean 0.39

Treatment	1	2	3
	0.16	0.65	0.36

*** Standard errors of means ***

Table	Treatment
rep.	3
d.f.	4
e.s.e.	0.371

*** Standard errors of differences of means ***

Table	Treatment
rep.	3
d.f.	4
s.e.d.	0.525

*** Least significant differences of means (5% level) ***

Table	Treatment
rep.	3
d.f.	4
l.s.d.	1.458

(v) Makoholi C.pallida biomass productivity at 6 months after establishment

TREATMENTS

1. Indifallow
2. Indifallow + SSP
3. Indifallow + RP

***** Analysis of variance *****

Variate: Biomass

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	7.334	3.667	2.01	
Block.*Units* stratum					
Treatment	2	23.200	11.600	6.34	0.057
Residual	4	7.315	1.829		
Total	8	37.850			

***** Tables of means *****

Variate: Biomass

Grand mean 2.71

Treatment	1	2	3
	3.81	3.88	0.44

*** Standard errors of means ***

Table	Treatment
rep.	3
d.f.	4
e.s.e.	0.781

*** Standard errors of differences of means ***

Table	Treatment
rep.	3
d.f.	4
s.e.d.	1.104

*** Least significant differences of means (5% level) ***

Table	Treatment
rep.	3
d.f.	4
l.s.d.	3.066

(vi) Makoholi *I. astragalina* biomass productivity at 6 months after establishment

TREATMENTS

1. Indifallow
2. Indifallow + SSP
3. Indifallow + RP

***** Analysis of variance *****

Variate: Biomass

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	0.0020792	0.0010396	2.93	
Block.*Units* stratum					
Treatment	2	0.0077415	0.0038707	10.92	0.024
Residual	4	0.0014180	0.0003545		
Total	8	0.0112387			

***** Tables of means *****

Variate: Biomass

Grand mean 0.0397

Treatment	1	2	3
	0.0038	0.0397	0.0756

*** Standard errors of means ***

Table	Treatment
rep.	3
d.f.	4
e.s.e.	0.01087

*** Standard errors of differences of means ***

Table	Treatment
rep.	3
d.f.	4
s.e.d.	0.01537

*** Least significant differences of means (5% level) ***

Table	Treatment
rep.	3
d.f.	4
l.s.d.	0.04268

(vii) Makoholi *E.ellipticum* biomass productivity at 6 months after establishment

TREATMENTS

1. Indifallow
2. Indifallow + SSP
3. Indifallow + RP

***** Analysis of variance *****

Variate: Biomass

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	0.0015423	0.0007712	1.13	
Block.*Units* stratum					
Treatment	2	0.0006344	0.0003172	0.47	0.658
Residual	4	0.0027247	0.0006812		
Total	8	0.0049014			

***** Tables of means *****

Variate: Biomass

Grand mean 0.0527

Treatment	1	2	3
	0.0501	0.0641	0.0440

*** Standard errors of means ***

Table	Treatment
rep.	3
d.f.	4
e.s.e.	0.01507

*** Standard errors of differences of means ***

Table	Treatment
rep.	3
d.f.	4
s.e.d.	0.02131

*** Least significant differences of means (5% level) ***

Table	Treatment
rep.	3
d.f.	4
l.s.d.	0.05916