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Prevention of *Imperata* invasion in upland cultivated fields in the montane forest of Central Sulawesi, Indonesia

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In remembrance to the confusion I caused and to the love I gave to the person who touched and challenged my whole being while doing this piece of work.

ABSTRACT

The invasion of *Imperata* in upland agriculture areas in tropical Asia is a serious land degradation problem. Substantial investigations and recommendations have been made to manage areas infested with *Imperata*. However, the question still remains whether the initial degradation into *Imperata* grasslands can be slowed down or avoided in former forest areas utilized for agriculture by the development of sustainable food-crop-based production systems alone. In this study, selected *Imperata* control as land and crop management practices were investigated to find a suitable cultivation management option for food-crop-based production systems in currently cultivated forest margins vulnerable to *Imperata* invasion. Field experiments were conducted in upland fields in the montane forest of Central Sulawesi, Indonesia, in maize-based production systems with different levels of *Imperata* infestation and soil fertility conditions.

Findings reveal that *Imperata* invasion can be combated and suppressed by an appropriate combination of land preparation and cropping management. When the field is highly dominated by *Imperata* with well-established rhizomes, the most effective control strategy is either deep hoeing or herbicide application combined with mineral fertilizer application. When *Imperata* has just newly established in the field, shallow hoeing combined with mineral fertilizer application is feasible. As an alternative to mineral fertilizer application, mucuna as a relay crop is also a viable control strategy provided that mucuna is prevented from suppressing the maize.

Imperata invasion can be avoided when soil fertility is maintained or improved at the onset of cropping so that nutrients do not become a limiting factor for crop productivity. In fields already infested with *Imperata*, appropriate soil fertility enhancement management or the right kinds and amounts of fertilizer should be applied so that the crop can compete with the weed and produce a reasonable yield.

The research findings provide evidence that maize dry matter and grain production in the study fields highly infested with *Imperata* were limited by potassium deficiency.

Verhinderung von *Imperata*-Aufkommen in bewirtschafteten Hochlandfeldern im montanen Regenwald von Zentralsulawesi, Indonesien

KURZFASSUNG

Das großflächige Ausbreiten von *Imperata* auf landwirtschaftlich genutzten Flächen in den tropischen Regionen Asiens ist ein ernsthaftes Problem im Hinblick auf Landdegradation. Dazu sind bisher zahlreiche Untersuchungen durchgeführt und verschiedenste Vorschläge zur Bewirtschaftung von *Imperata*-Flächen gemacht worden. Es ist jedoch ungeklärt, ob eine beginnende Degradation durch *Imperata* alleinig durch die Entwicklung von nachhaltigen landwirtschaftlichen Produktionssystemen verlangsamt oder vermieden werden kann. Die vorliegende Studie untersuchte Maßnahmen zur Kontrolle von *Imperata* sowie Anbauverfahren für eine geeignete Bewirtschaftung für Flächen an landwirtschaftlichen genutzten Tropenwaldrändern, die für ein *Imperata*-Aufkommen anfällig sind. Feldversuche wurden in Maisanbausystemen im montanen Central Sulawesi, Indonesien, mit unterschiedlicher *Imperata*-Bedeckung und einer Reihe von Land- und Bodenbedingungen angelegt.

Die Ergebnisse zeigen, dass *Imperata* durch geeignete Bodenvorbereitung und angepasstes Anbaumanagement bekämpft und unterdrückt werden konnte. Die effektivste Kontrolle bei flächendeckendem Aufkommen mit gut entwickelten Rhizomen war entweder tiefes Hacken oder Herbizidbehandlung in Kombination mit mineralischer Düngung. Hatte sich jedoch *Imperata* im Feld erst neuerlich etabliert, reichte ein flaches Hacken, ebenfalls in Kombination mit Düngung aus. Als Alternative zu mineralischer Düngung war der begleitende Anbau von Mucuna ebenfalls eine erfolgreiche Strategie, vorausgesetzt es wurde verhindert, dass Mucuna das Maiswachstum vermindert.

Das Eindringen von *Imperata* konnte verhindert werden, wenn Maßnahmen zur Verbesserung der Nährstoffbedingungen im Boden gleich zu Beginn des Anbaues vorgenommen wurden, um zu vermeiden, dass Nährstoffmangel die Produktivität einschränkt. In Feldern, in denen sich bereits *Imperata* ausgebreitet hat, sollten fehlende Nährstoffe zugeführt werden, damit die Anbaupflanzen mit dem Gras konkurrieren und ausreichend Erträge produzieren können.

Die Ergebnisse zeigen außerdem, dass Maistrockenmasse und -körnerertrag stark durch das Aufkommen von *Imperata* und einen damit verbundenen Kaliummangel beeinträchtigt wurden.

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LIST OF ABBREVIATIONS AND SYMBOLS

AE	Atom excess
A-Low	Low-*Imperata* infested field
Al	Aluminum
ANOVA	Analysis of variance
Avg.	Average
B	Biomass sample size
BD	Bulk density of the soil
B-Medium	Medium-*Imperata* infested field
BNF	Biological Nitrogen Fixation
BS	Base saturation
C	Control
Ca	Calcium
$CaCl_2$	Calcium Chloride
CEC	Cation exchange capacity
C-High	High-*Imperata* infested field
cm	centimeter
CMTr	Crop management strategy as superimposed treatment
CN ratio	Carbon to nitrogen ratio
DAAD	Deutscher Akademischer Austausch Dienst
DAS	Days after seeding of maize
DAP	Days after planting of mucuna
DH	Deep hoeing
DM	Dry matter
Dw	Dry weight
DwG	Dry weight grain
DwS	Dry weight stover
DwL	Dry weight leaves
F	Fertilizer
FAO	Food and Agriculture Organization
Fe	Iron
Fw	Fresh weight
FwG	Fresh weight grain
FwL	Fresh weight leaves
FwS	Fresh weight stover
GDM	Grain dry matter
GLM	General linear model
h	height
HA	Herbicide application
HI	Harvest index
IAT	Institute of Tropical Agriculture
ICAE	*Imperata* shoots counts after experimentation
ICAH1	*Imperata* shoots counts after first maize cropping harvest
ICBE	*Imperata* shoots counts before experimentation
IDM	*Imperata* dry matter
IRDM	*Imperata* rhizome dry matter

IRRI	Indonesian Rubber Research Institute
ISDM	*Imperata* shoots dry matter
ISSFN	Institute of Soil Science and Forest Nutrition
K	Potassium
KCL	Potassium chloride
K_2O	Muriate of potash (0-0-60)
l	Liter
LDM	Leaves dry matter
LMTr	Land preparation method as treatment
LSD	Least Significant Difference
m	Meter
m asl	Meter above sea level
Mg	Manganese
ml	Milliliter
Mn	Magnesium
M	Mucuna relay
MTDM	Maize total dry matter
Mu	Mucuna DM
N	Nitrogen
N_2	Nitrogen fixation
Ndfa	Nitrogen derived from air
Ndff	Nitrogen derived from fertilizer
Ndfs	Nitrogen derived from soil
NFPs	Non-forest products
nleaves	Number of leaves
NH_4^+	Ammonium
NO^{-3}	Nitrate
NRI	Natural Resources Institute
nPlant	Number of plant
Nu	% nutrient concentration
P	Phosphorous
POP	Population density
PPI	Potash and Phosphate Institute
S	Sulphur
(s)	sample
(ss)	subsample
SDM	Stover dry matter
SOM	Soil organic matter
SP/ P_2O_5	Superphosphate (0-31-0-5)
STORMA	Stability of Tropical Rainforest Margin
UNu	Nutrient uptake
V	Volume
WAE/wae	Weighted atom excess
ºC	degree Celsius
^{15}Nae	^{15}N atom excess

1 INTRODUCTION

Southeast Asia's agriculture is at a crossroads. It is reported that about 21% (~91 Mha) of the land of the region is used for agriculture, 36 % (~33 Mha) of which is classified as ´lowland´. Half of the lowland agriculture is occupied by irrigated rice system that cannot be increased easily. Further, large areas of land under rice cultivation are also converted to industrial use and housing each year. The greatest potential for future increases in agriculture production in the region lies only in the remaining 64 % (~58 Mha) of agricultural land classified as ´upland´ or ´rainfed land´ (Dierolf et al., 2001).

With the increasing population and the fact that additional suitable land for intensive lowland agriculture is no longer available, forest encroachment for agricultural land utilization remain unabated. Increasingly, forests lands are being cleared and cultivated for continuous food production, especially those areas that are accessible to farming communities. Farmers already occupying land adjacent to and within the forest zones continue to move and expand further into the forest for cultivation. Due to lack or inaccessibility of primary forest, people now clear secondary forest at different stages of succession.

Among the cereal crops worldwide, maize ranks third economically, after rice and wheat. In Southeast Asia, maize is the second most important cereal as a staple food and as a major component of animal feeds. As the demand for maize in the region is rapidly outpacing the supply, farmers are growing more maize in the upland and marginal lands (CIMMYT, 1999).

In tropical upland soils such as in Southeast Asia, especially on soils that are generally acidic and lose fertility within a relatively short period, the cultivation for agricultural food crops using low-level inputs has been shown to collapse because of weed infestation (Sanchez et al., 1987; von Uexküll, 1995). A common phenomenon is the invasion of *Imperata cylindrica*, the most pandemic weed in tropical areas. It is reported that the invasion of *Imperata* in the uplands is a huge land degradation problem already affecting millions of hectares (Giller, 2003).

The expansion of *Imperata* areas has been attributed primarily to shifting cultivation practice, and as a consequence of continuous cultivation with annual crops but without fertilizer inputs (e.g., a cropping pattern based on maize/upland rice, cassava or horticulture plantation crops) and no permanent vegetation cover (Eussen and Wirjaharja, 1973). When forest areas are cleared for agricultural crop production and without the permanent vegetative cover, *Imperata* seeds find ideal condition to germinate. With the slash-and-burn method of cultivating the infested fields and without fertilizer inputs, the farmers may only have one or two harvests (e.g. maize or upland rice) before *Imperata* completely covers the land (van Noordwijk et al., 1997).

Once *Imperata* infested the field, it strongly competes with crops leading to declining yield. When crop production is low, the farmer has little incentive to weed infested fields. Thus, *Imperata* becomes firmly established. Also, it is indicated that unless high rates of fertilizer are applied, the continuous cultivation of these areas prone to *Imperata* for annual crops over four to five years results in soil degradation (Zaini and Lamid, 1993; Santoso et al., 1994; van Noordwijk et al., 1997).

In mid 1990s, 4 % (~35 Mha) of the total land area in Southeast Asia were already *Imperata* grasslands (Garrity et al., 1997). Indonesia is the country with the largest land area (~8.5 Mha) covered by *Imperata* (Soekardi et al., 1993). *Imperata cylindrica* is considered one of the ten worst weeds in the world (Holm et al., 1977). It is a pernicious perennial grass, native to Southeast Asia (MacDonald, 2004), and is widely spreading in tropical and sub-topical regions (Garrity et al., 1997), especially in areas under slash-and burn agriculture (Chikoye et al., 2000).

Imperata infestation is not restricted to poor soils since it occupies both fertile (e.g. Inceptisols and Andisols) and infertile soils (e.g. Ultisols and Oxisols) (Moeljadi and Soepraptohardjo, 1975; Soerianega, 1980; Garrity et al., 1997). Rather, soils with declining fertility as a result of agricultural management practices where crop production is based on the natural fertility of the soil are dominated by *Imperata cylindrica* (Moeljadi and Soepraptohardjo, 1975; Soerianega, 1980; Menz et al., 1998).

Imperata invasion poses major difficulties to restore the land for crop production, since the weed is well adapted to poor soil, drought conditions, and frequent fire regimes (MacDonald, 2004). The process is exacerbated because *Imperata* competes most effectively for nutrients and water, particularly in soils at lower fertility levels (van Noordwijck et al., 1997). It rapidly regenerates after burning (Wibowo et al., 1997) from its underground rhizomes, which is the main mechanism for its survival and spread (Chikoye et al., 2005). However, it is susceptible to shading (Macdicken et al., 1997; Terry et al., 1997).

Research on the biology and the control of *Imperata* has advanced to a point that the weed need not be a problem provided resources are available for its management (Terry et al., 1997). As summarized by Menz et al. (1998), *Imperata* control can be by physical (manual, mechanical or animal powered), chemical (herbicide use), cultural (intercropping with cover crops) or ecological (shading by competing plants), and/or the combination of the control methods (e.g. physical, chemical and ecological/cultural). Integrated approaches that combine a variety of options are always emphasized, since there is no single method that can control *Imperata* in a sustainable manner (Menz et al., 1998; MacDonald, 2004; Chikoye, 2005).

In the past, studies on *Imperata* have focused on the plant as a weed, and the prospective solutions have often been viewed as a weed control problem. Substantial investigations have been made and solutions recommended to control and manage *Imperata*. However, much of the attention has been given to existing *Imperata* grasslands (from reclamation and rehabilitation to intensified use), while inadequate attention has been given to factors involved in the evolution of *Imperata* grasslands (Garrity, 1997). The prevention of *Imperata* invasion in upland cultivated fields (from recently cleared primary or secondary forests) with agricultural annual crops remains poorly studied. So, the question posed by van Noordwijk et al. (1997) remains open and unanswered, on whether the initial degradation into *Imperata* grasslands can be slowed down or avoided when the forest is first opened, either by the development of sustainable food-crop based production systems alone, or food crops in association with tree crops production

It is generally accepted that sustained crop production depends on good soil fertility management. The spread of *Imperata* is often linked to the loss of soil fertility. The maintenance of an adequate soil nutrient status is considered one of the keys for preventing *Imperata* encroachment and stabilizing crop productivity. Also, it is indicated that *Imperata* is not a serious problem in intensively managed agricultural lands where repeated tillage or herbicide applications are practiced. But, there is still a need to integrate proven *Imperata* control and crop management strategies into the farming system so they are acceptable to the farmers and adapted to specific site conditions.

In this study, it is hypothesized that appropriate field cultivation practices could suppress *Imperata* weed infestation, such as with minimum tillage in combination with cultural control management such as fertilizer application and relay cropping with leguminous cover crops when the infestation is still below a critical level. Above that critical level, radical methods are required, which are the combinations of intensive land preparation by manual/physical or chemical control strategies with cover cropping or planting trees/shrubs to shade-out the *Imperata*. But, the effectiveness of any control strategies is likely to vary by soil types, cropping system and the level of *Imperata* infestation. To date, little is known on the site and system specificity of the combinations of *Imperata* control strategies.

Therefore, the aim of this study is to investigate the effectiveness of such combinations as land preparation and crop management practices. To know whether the degradation into *Imperata* grasslands can be slowed down or avoided in forest areas, which are recently cleared and utilized for agriculture food production. Likewise, whether maize-based cultivation systems at different levels of *Imperata* infestation can be reclaimed or protected from turning into *Imperata* grasslands.

Specifically, the study aims:

1) To investigate the feasibility of selected land preparation practices in controlling *Imperata* in fields with different levels of *Imperata* infestation and soil fertility conditions;
2) To investigate the feasibility of selected cropping management options to enhance soil fertility and at the same time control/suppress *Imperata* and weeds other than *Imperata* in cultivated fields;
3) To determine the threshold levels for the effectiveness of *Imperata* control strategies as a function of degree of *Imperata* infestation and soil fertility status and;
4) To evaluate the combinations of land and crop management strategies that enhance soil fertility, control/suppress *Imperata* infestation and increase the productivity of cultivated fields.

The research focus on the rainforests margins in Central Sulawesi, Indonesia, utilized for agrocrop production, and practically prone to *Imperata* invasions.

2 LITERATURE REVIEW

This chapter reviews the theoretical perspectives of various authors regarding the following topics that are directly related to this research.

2.1 Forest land-use change in the tropics

Worldwide, forests cover about 30% of the total land area. It is reported that total forest areas as of 2005 were already less than 4 billion hectares and continue to decrease due to deforestation. Agricultural expansion is the major contributing factor for deforestation. About 13 Mha^{-1} of forests areas were mainly converted to agricultural land (FAO, 2005).

Forests cannot be seen as stand alone systems when they are accessible to the surrounding communities. Generally, the forest is another source of food and income – forest and other non-forest products (NFPs). To farming communities, a natural forest is regarded as a resource with open access for utilization with potential areas for agricultural production. Farming activities exist around and within the forest, frequently in the forest margins. The shifting cultivation together with the ´slash and burn´ practiced by the farmers is often blamed for deforestation and its eventual degradation.

The unsustainable land management where food production is left to the natural fertility of the soil is a common forest farming practice especially in tropical countries. When the fallow periods for fertility restoration are shortened due to increasing land pressure, it resulted to land-use problems such as soil fertility depletion and weed invasion (Hartemink and Bourke, 2000). Driven by diverse socio-economic and ecological factors, forest conversion is continuing and landscapes are changing.

2.1.1 Vegetation change: forests – agriculture – grasslands

One of the clearest examples of the vegetation change (Potter, 1997) is the replacement of the forest tree cover with agro-crops, but eventually taken over by an invasive grassy weeds. The process of change starts when the trees are cut and used for timber and the remaining vegetation is cleared for agricultural purposes (primarily for agro-cropping systems). However, due to inappropriate land management and unsustainable cultivation practices, soil fertility declines to the point where the area becomes infested with persistent weeds.

Shifting cultivation has become the most practical way for farmers to escape weed problems and declining soil fertility after cropping periods. When crop production is very low and continuous cultivation eventually resulted to further decline or crop failure, the patch of cultivated land is either left fallow or totally abandoned. When crop field is unused, persistent weeds completely invade, and the fields often turn into grassland. Most especially, when the farmers are not able to cope with the persistent weeds, and continued cultivation no longer provides sufficient economic returns (Nye and Greenland, 1960; Van Noordwijk et al., 1997; Chikoye, 2005). Such changes in the vegetative cover lead to economic drawbacks and ecological changes (Eussen and Wirjahardja, 1973; Soerianegara, 1980; Van Noordwijk et al., 1997). This is particularly true after forest or long fallow (bush) clearance, followed by a cropping cycle, a duration that kills most of the tree stumps and thus slows down regeneration into bush and forest (Garrity et al., 1997; Santoso et al., 1997; Snelder, 2001).

2.1.2 Declining soil fertility and weed invasion

With the new land-use and the ecological disturbance through agricultural activities, the closed nutrient cycle of the forest becomes open to nutrient flows, with an increasing imbalance between nutrient uptake and return to the soil (Hairiah et al., 2000). As Bationo and Vlek (1997) indicated, in many cropping systems little or no agricultural residues are returned to the soil. The nutrient cycle is interrupted by the export of nutrients out of the system during harvest and burning. The removal of harvested products and movement of fertile topsoil out of the field through erosion and leaching increases the nutrient losses. This is mostly observed in the uplands of humid tropical regions such as in Southeast Asia, where runoff/erosion and leaching has caused N, Mg, Ca, K and S deficiency (Härdter and Fairhurst, 2003).

The continuous cultivation without nutrient returns eventually resulted to nutrient depletion of initially fertile soil. The soil organic matter content declines with time while this reduction in fertility leads to a poorer structure, water holding capacity and lower biological activity, and thus in lower soil productivity and crop yield.

Overall, the soil characteristics of the area change rapidly (Schoenau and Campbell, 1996; Vlek et al., 1997; Derksen et al., 2002).

With low soil organic matter content, there is often a rapid and persisting weed growth. In time, certain species tend to predominate as they win the struggle for space. Repeated soil cultivation causes suppression of typical fallow species and favors the growth of adapted arable weed species, thus changing the vegetation composition (Nye and Greenland, 1960; Sanchez, 1976; Macdicken et al., 1997).

2.2 Agricultural food production and *Imperata* invasion

According to von Uexküll and Mutert (1995), the acid soil land areas in the tropics represent the last and largest reserve of potential agricultural land in the world. Most of these lands are classified as forests areas and provided a temporary subsistence to small farmholders practicing shifting cultivation. It can not sustain continuous agriculture with conventional low-input techniques. Once the forest cover is removed, most of these acid soils quickly lose their residual fertility and thus abandoned after only a few years of cropping.

According to the Potash and Phosphate Institute (PPI) (http//:www.ppi.org), the major soil nutrient problems of these acid upland soils are the low N, P and K status and Al toxicity. Further indicated that K and Mg are particularly deficient in soils that have been cropped for several seasons, where crop residues have been removed, and little or no K and Mg fertilizer has been applied.

Each farming system produces its typical weed population as a result of cultivation practices, local climate and soil conditions. Under tropical conditions, *Imperata cylindrica* is one of the worst weeds and is considered the most serious noxious weed in many countries of Southeast Asia (Garrity et al., 1997; Potter, 1997; MacDonald, 2004). *Imperata* invasion and low production after some years of continuous cultivation is common in Southeast Asia´s agricultural upland food production systems (van Noordwijk et al., 1997) and a serious land degradation problem that are already affecting millions of hectares (Giller, 2003).

In tropical areas like in Southeast Asia, vast tracts of land with previously productive forest cover have degraded to anthropogenic savanna after clearing for agricultural cultivation (von Uexküll and Mutert, 1995). Garrity et al. (1997) estimated that about 35 million hectares (4 % of the total land area) in the region were already covered with *Imperata* grasslands. Countries with the largest area of *Imperata* grasslands are Indonesia (8.5 million ha) and India (8.0 million ha). Countries with the largest proportion of the land covered with *Imperata* grassland are Sri Lanka (23 %), the Philippines (17 %), and Vietnam (9 %). In Laos, Thailand, Myanmar, and Bangladesh this area is about 3 to 4 %. Less affected are Malaysia (<1 %), Cambodia (1 %), and the southern part of China (2 %).

To slow down further forest encroachment in the tropics and at same time to provide badly needed land for future food production, efforts have been geared to rehabilitate deforested and degraded lands, including the *Imperata* grasslands. It is recognized that if technologies are developed and introduced that permit sustainable and profitable agriculture in the fragile and infertile acid soils of the tropics, there is still a large potential to increase the area under cultivation (von Uexküll and Mutert, 1995).

2.3 Characteristics of *Imperata*

2.3.1 Taxonomy and status

Imperata is a genus of the Poaceae, a grass family (Gabel, 1982; MacDonald, 2004), and is composed of two sub-genera, *Imperata* and *Eriopogon*. The subgenus *Imperata* has only one species, the *Imperata cylindrica* (Garrity et al., 1997). Hubbard et al. (1944) and Santiago (1980) classified *Imperata cylindrica* into five taxonomic varieties – *major, africana, europa, latifolia* and *condensate* (Tjitrosoedirdjo, 1993; Garrity et al., 1997; MacDonald, 2004). *Imperata cylindrica* var. *major* is indigenous throughout Asia and predominant in Southeast Asia, Australia, China, Japan, the Philippines, and East Africa. *Imperata cylindrica* var. *africana* is found in West Africa. *Imperata cylindrica* var. *europa* is found in the Mediterranean and Central Asia. *Imperata cylindrica* var. *latifolia* is found only in north India. Variety *condensate* is found in Chile (Hubbard et al., 1944; Santiago, 1980; Bewick et al., 1997; Shilling et al.1997; Garrity et. al., 1997; MacDonald, 2004). *Imperata cylindrica* varieties *major* and *africana* are considered most serious (Townson, 1991; Terry et al., 1997; Chikoye, 2005). Most research was conducted on these two varieties because they are the most widespread, damaging and variable (Brook, 1989; MacDonald, 2004).

The *Imperata* weed is considered to be of major significance primarily due to *Imperata cylindrica* (Gabel, 1982; MacDonald, 2004). *Imperata cylindrica* (L.) Raeuschel or Beauv (as corrected by Gabel, 1982) is ranked as the seventh most troublesome weed worldwide (Holm et al., 1977; Terry et. al., 1997; MacDonald, 2004).

2.3.2 Biological features

As described by various authors (Hubbard et al., 1944; Holm et al., 1977; Brook, 1989; Shilling et al., 1997; Terry et al., 1997; MacDonald, 2004; Chikoye, 2005), *Imperata* is a warm-season, rhizomatous, perennial C4 grass with a spreading habit and reproduces sexually from seed and vegetatively by rhizomes. It spreads and dominates in areas disturbed by human activities.

The plant is without stems and the leaves grow from the rhizomes and have stomata on both surfaces. A fibrous root system spreads from the rhizomes. The branched rhizomes form a dense mat, which is able to exclude most other vegetation. The sharp apical ends of the rhizomes may grow through the roots of other plants. Rhizome development starts between the third and fourth leaf stage, varying in number from one to four rhizomes. Early rhizome growth is plagiotropic, or vertical, with growth by the fifth leaf stage becoming horizontal and the rhizomes covered by scale leaves (cataphylls). The tips of the rhizomes grow upward (negatively orthogeotropic) between the fifth and sixth leaf stage. The rhizomes can give rise to 350 shoots in 6 weeks and can cover 4 m^2 in 11 weeks. Second generation shoots and rhizomes form simultaneously on strong plants, in which the shoots arise from the apical bud and rhizomes form from sub-apical buds. In weaker plants, the shoot forms first, while buds on the convex side form shoots much later or remain suppressed (Hubbard et al., 1944; Boonitee and Ritdhit, 1984; Eussen and Soerjani, 1975; Eussen, 1980; Ayeni, 1985; Shilling et al., 1997).

Imperata is a prolific seed producer with seedheads that are branched but compacted into a dense, white, fluffy, spike-like panicle, 10-20 cm long (Holm et al., 1977). A single plant may produce as many as 3000 seeds (Sajise, 1972), which are small and are attached to a plume of long hairs that facilitates wind dispersal to a distance of 15 miles or more (Hubbard et al., 1944) and have little or no dormancy period and can remain viable for over a year (Hubbard et al., 1944; Santiago, 1965;

Menz et al., 1998; Chikoye, 2005). However, flowering is rare and generally occurs only, after human disturbance or stress such as drought, burning, overgrazing, and repeated slashing (Sajise, 1972; Chikoye, 2005). Flowers produced in response to stress rarely produce seed (Eussen, 1980).

Imperata has a low shoot to root/rhizome ratio, which contributes to its rapid regrowth after burning or cutting (Sajise, 1976; Chikoye, 2005). The aggressive and invasive nature of *Imperata* is attributed to its rhizomes, which are generally concentrated in upper 15-20 cm of soil where they can remain dormant but viable for a long time (Ivens, 1980; Chikoye, 2005), and can easily regenerate after fire, and the main mechanism for survival and spread (Menz et al., 1998; Chikoye, 2005). The regenerative capacity is also positively correlated with age, weight, length, thickness and number of visible buds (Ayeni and Duke, 1985). Biomass of the rhizomes, which increases with age, is also a necessary component of regenerative capacity, and the roots are necessary for nutrient supply and subsequent accumulation of enzymes and growth substances for regeneration. Young rhizomes are not capable of regenerating the species since roots do not develop in these rhizomes (Ayeni and Duke, 1985).

Physical attacks to the plant (e.g., cutting/slashing) encourages seed production after the shoots regrow from the undisturbed rhizomes which remain dormant but viable. Thus, the plant is characterized as perennial, extensive and prolific. Cultivation stimulates rhizome bud growth, which readily sprout into new shoots after fragmentation by tillage or any other form of disturbance that does not effectively destroy the rhizomes (Menz et al., 1998; Chikoye, 2005). However, the ability of rhizome fragments to regenerate decreases with the reduction in length of the rhizome segment. Longer rhizomes have a better chance of sprouting, because they have more carbohydrate reserves than short fragments (Ivens, 1975; Chikoye, 2005). The plant can produce a large leaf biomass which is highly flammable, especially during the dry season, but the rhizomes are very resistant to heat (either natural or artificial) (Wilcut et al., 1988; Chikoye, 2005).

2.3.3 Ecology

Imperata, reported as native to Southeast Asia (MacDonald, 2004), occupies land as unproductive weed savanna or grasslands (Härdter and Fairhurst, 2003). It is known to be an indicator of poor soils, because it can establish even in poor soil conditions (Eussen and Wirjahardja, 1973). Others observations indicate that *Imperata* can grow on all soil types with a wide range of available nutrients and moisture, as it has a strong ability to extract nutrients and moisture from the soil (Jagoe, 1938; Eussen and Soerjani, 1975; Boonitee and Ritdhit, 1984; Santoso et al., 1997). It occupies both fertile (e.g., Inceptisols and Andisols) and infertile soils (Ultisols and Oxisols) across a wide range of climates and elevations (Garrity et al., 1997). It is found in soils with low pH (4.7) and lack of surface organic matter (Sajise, 1980; Garrity et al., 1997) or in slightly acidic (pH around 6) soils, and also in soils with low to moderate organic C (range 0.6 % -1.7 %), low exchangeable cations (Ca, Mg, K) and P deficient (Chikoye et al., 1999), and generally in low fertility and highly leached soils (Wilcut et al., 1988; Santoso et al., 1997). The low pH could be secondary and due to organic acids converted from sugars and exuded by the rhizomes. The lack of organic matter could be the result of frequent burning and intensive cultivation (Sajise, 1980; Santoso et al., 1997; Chikoye et al., 1999).

Imperata has the ability to impact other crops (Eussen, 1979) and many other plant or grass species have difficulty in competing (Eussen and Wirjahardja, 1973) because of its fast growth rate, and thus suppressing growth of other plants. It causes yellowing of leaves and die-back of crops leading to severe yield reductions (Hubbard et al., 1944; Soerjani, 1970; Menz et al., 1998). It can establish as monotypic stands due to its high competitive ability (Eussen and Soerjani, 1975). The mechanisms of *Imperata* interference are not known but both allelopathy and competition have been reported (Eussen, 1979). Plants that have been found to survive competition with *Imperata* have a deeper root system than that of *Imperata* and/or a taller canopy (Eussen and Wirjahardja, 1973; Menz et al., 1998). *Imperata* is susceptible to cold and herbicides and intolerant to shade (Wilcut et al., 1988; Terry et al., 1997; Macdicken et al., 1997).

Recent observations as cited by Collins (2005) described that *Imperata* is a better competitor for P (Brewer and Cralle, 2003). Soil nutrients (NO_3-N, P, K, Ca, and Mg) decline in *Imperata* invaded patches because of the plants extensive and dense rhizome/root system and rapid accumulation of aboveground biomass. Root exudates into the rhizosphere make the soil more acidic, and a lower nitrate level may also indicate lower ammonium levels. As it lowers nutrient levels, specifically N, *Imperata* may also be able to impede the survival of other species and facilitate its own persistence. The low levels of K in *Imperata* patches could be because of the extensive belowground rhizome network (Daneshgar et al., 2005) as well as to association with mycorrhizae (Brook, 1989), which accounts for the ability to exploit soil K. Potassium is known to affect cell division, formation of carbohydrates, translocation of sugars, some enzyme actions, plant resistant to certain diseases, cell permeability, and several other functions (Plaster, 1992). Thus, decreases in soil K in *Imperata* invaded areas could have serious implications for recruitment and growth of other plant species (Collins, 2005).

Further, the mechanism of decreases in pH has been attributed to increased nitrification, high rates of NH_4^+-uptake and/or changes in litter quality (more acidic, base-poor litter) (Ehrenfeld, 2003). The preferential NH_4^+ ions uptake releases H^+ ions, resulting in a lower pH in the rhizosphere that is immediately surrounding the plant root. In addition to the acidic root exudates, allelochemicals produced by *Imperata* may also make the soil acidic. A decrease in pH may also have implications for other soil extractable nutrient pools in the long term. With low pH, generally the cation exchange capacity is also lower with only the permanent charges of the 2:1 type clays and a small portion of the pH dependent charges on organic colloids, allophane and some 1:1 type clays holding exchangeable ions. Strongly acidic soil holds H^+ and hydroxy aluminum ions (Al^-) tightly on the soil surface. This tight association prevents K and other elements from being closely associated with the colloidal surfaces, which reduces their susceptibility to fixation (Brady and Weil, 2002). Continuous acidic conditions may eventually reduce many soil nutrient pools, greatly reducing the success of other vegetation as well as transforming ecosystem biogeochemical properties. Also, the phenolic compounds present in the foliage, roots, and rhizomes of *Imperata* may be responsible for allelopathic inhibition of germination and seedling development of other species (Inderjit and Dakshini, 1991). Koger and Bryson (2003) suggest that allelopathic substances provide *Imperata* with its extremes invasive and competitive abilities.

2.4 Soil fertility, weed and vegetation management

2.4.1 Soil fertility management

In agricultural production, sustaining soil fertility is an important factor in increasing crop productivity. An adequate supply of essential plant nutrients has a major impact in the yield, and is one crop production factor that can be readily managed through maintenance of soil fertility. Lack of soil fertility decreases yields and offers opportunities for invasive weed species. Many plant diseases are also related to poor soil fertility. Maintaining soil fertility should be directed at maintaining the organic matter content of the soil, through appropriate crop husbandry practices (like organic manure or compost, mulching, green manuring, intercropping, green fallow periods, or agroforestry) and chemical fertilizer application (Vlek et al., 1997).

Commercial fertilizers make up the majority of nutrient inputs for sustaining crop yields, with available organic sources, native soil reserves, and biological N fixation supplying the remainder (Stewart et al., 2005). Legume crops generally serve as alternative or substitute for chemical N fertilizer, especially cropping with N_2-fixing legumes. The commonly cited generalization that at least 30-50 % of crop yield is attributable to commercial fertilizer nutrient appears a reasonable, if not conservative, estimate. However, for the smallholders, fertilizer use is generally a major expense. The low fertilizer use by many smallholder land farmers has been attributed to various factors including the scarcity of resources and the economics of its use (Ibewiro et al., 2000). Fertilizer management techniques have to take into account the economic constraints particularly faced by small farmholders. Fertilizer use practices must increase yield (or profit) without significantly increasing cost or labor on the side of the farmer otherwise this will not be adopted (Christianson and Vlek, 1991).

2.4.2 Weed and vegetation management

Weed management is often the most important crop protection activity undertaken on the farm, and includes prevention, eradication, and control as well as fostering beneficial vegetation (Holt, 2004). Vegetation management is recognized as an essential component in crop production systems. At the same time, the crop and non-crop components of an ecosystem are viewed under the broader theme of vegetation management (Gallagher et al., 1999).

Weed management is part of a general problem in vegetation management where the goal is to minimize weed presence to achieve the desired land-use. Typically, it includes suppressing or removing weeds without injuring the crop or desirable species while at the same time growing or fostering the desired vegetation (FAO, 1986; Gallagher et al., 1999; Holt, 2004). Desirable vegetation includes the introduced crop species, cover crops and green manures, and beneficial or benign plant species. The undesirable vegetation 'interferes' with the growth and development of the desired vegetation and is commonly considered the 'weedy' component of a system (Gallagher et al., 1999). Uncontrolled weed growth, especially in the early stages of crop establishment can greatly decrease crop yields through competition effects between crop and weed populations.

Ensuring the crops´ ability to compete with weeds is an established agronomic objective and is usually a key aspect of integrated weed management. Bàrberi (2005) suggested that fertilizer application can increase the competitive ability against weeds in crops with high growth rates at early stages, although this effect is modulated by the type of weeds prevailing in a field. Mixed cropping or intercropping, crop rotation, and cover cropping are well known techniques promoted against the buildup of troublesome weed populations.

In mixed cropping or intercropping systems, weed communities become more diverse, thus minimizing the predominance of any one weed (Froud-Williams, 1988; Anderson, 1998; Derksen et al., 1995). Such cropping systems provide more control opportunities and disrupt life cycles of weeds that are crop mimics (Patriquin, 1988; Anderson, 1997; Derksen, 2002). Also, the more diverse crop rotations allow cultivators to vary the timing and modes of action of herbicides, thus delaying the evolution of herbicide-resistant biotypes (Jordan and Donaldson, 1996; Derksen, et. al., 2002). Likewise, crop choice and the sequence in which crops are grown have a great impact on weed community composition (Derksen et al., 1996b; Thomas et al., 1996a; Derksen et al., 2002).

Inclusion of cover crops in a rotation in the time frame between or during cropping is considered a good preventive and control method. Especially, legume plants as cover or rotational crops prevent the establishment and/or impact of the parasitic weeds and improve the soil fertility, since they can symbiotically fix N (Mulongoy and

Akobundu, 1990; Lal et al., 1991; Ibewiro et al., 1998; Bàrberi, 2005). The green manure of these crops is known to be an efficient sources of N, and considerable amounts of N can be supplied to the succeeding crop as the legume residues decompose (Heinzmann, 1985; Welty et al., 1988; Badaruddin and Meyer, 1990; Debarba and Amado, 1997; Gallagher et al., 1999), potentially improving the soil physical and biological properties (Hulugalle et al., 1986; Osie-Bonsu and Buckles, 1993; Carsky et al., 1998; Derksen et. al., 2002). At same time it helps control pests and weeds as it acts as smother crop and green manures/mulch thus offsetting the cost of weeding (Akobundu and Poku, 1984; Versteeg and Koudokpon, 1990; Weber et al., 1995; Berne et al., 1996).

2.5 *Imperata* control and management in agroecosystems

Many technologies have been developed to control and manage *Imperata*, which are considered successful, especially when there is sufficient supply of labor and capital. Control methods that require little or no financial means for external inputs are most attractive for the farmers. Measures of control can be preventive or remedial. Many authors indicated that an integrated approach that employs a variety of options and also suits the individual farmer´s agronomic and socio-economic conditions is considered the best since there is no single method can sustainably control *Imperata*. The key objective of any management strategy of controlling *Imperata* should be the destruction of the rhizomes, which are the main organs by which the weed perennates and spreads (Terry et al., 1997; Chikoye et al., 2005). If the ecological niche is not filled with another plant species after control methods have been implemented, *Imperata* will re-invade (Shilling et al., 1997).

Summarized and classified in the following are selected *Imperata* control and management strategies.

2.5.1 Land preparation practices

Crucial to crop production are the land preparation and weeding methods. Perennial weeds like *Imperata* with extensive rhizome system are removed by practices ranging from zero tillage to repeated deep cultivation. In shifting cultivation systems, zero tillage method is the slashing and burning practiced by many farmers. The ´slash and burn´ method is widely used as a means to prepare land preparation and maintain soil fertility. Burning or fire is considered easily available tool for managing weeds. It could result a good harvest especially after burning fallow vegetations since the ashes of leaves contains nutrients in a directly usable form. However, after a few cropping periods there is a significant loss of nutrients from the system through volatilization. Biomass burning exposes the soil, and the nutrient-rich ash is often washed away during rainfall.

Moreover, in the case of *Imperata*, burning the area and /or after slashing leads to rapid regeneration of the shoots/leaves from the underground rhizomes. Also, when burning gets out of control, the associated social costs maybe high. Thus, the practice of burning *Imperata* has long-term (on-farm) environmental and economic impacts on smallholder upland farmers. The declining level of nutrients leads to an increase in the competitive ability of the remaining weeds in the fields that have escaped the fire (Gallagher et al., 1999). Despite the negative impacts, burning is still considered the most profitable method of clearing *Imperata* in shifting cultivation systems under the prevailing biophysical and economic conditions.

Tillage – manual method

Tillage by manual method for *Imperat*a control generally requires a substantial human labor input and reduces the farm size that can be managed by one family (Akobundu, 1991; Gallagher et al., 1999; Chikoye, 2005). Control of *Imperata* by small-scale farmers usually involves slashing and burning of the foliage followed by cultivation or tillage to expose rhizomes to dessication by sunlight (Chikoye, 2003 and 2005). The most widely used weed control methods are tillage by hand weeding and hoeing. Slashing is considered more a means of containment rather than a ‘population-reducing’ practice since it only exhausts the rhizome reserves. It is more labor intensive since it requires repeated application and will not be effective in removing *Imperata*. Also, it needs to be integrated with other options to reduce the amount of labor required.

Tillage (manual, mechanical or animal powered) is practiced to provide a suitable soil tilth for a seed-bed and to control weeds prior to crop establishment. The effect of primary tillage on weeds is mainly related to the type of implement used and to the tillage depth (Bàrberi, 2005). MacDonald et al. (2006) claimed that one of the oldest and considered successful methods for *Imperata* control is deep cultivation/tillage, i.e., deep plowing or disking several times during the dry season to desiccate the rhizomes and exhaust the food reserves. In *Imperata* areas, tillage should be to a depth of about 30-40 cm, since most *Imperata* rhizomes are found above this depth. Shallow tillage is often ineffective in controlling *Imperata*, because it has only limited effect on the rhizomes. Labor investments increase and returns to labor tend to decrease in successive years as weed pressure intensifies and the soil quality declines (Chikoye, 2005).

Chikoye et al. (1999) indicated that manual methods may be well suited to small fields with moderate *Imperata* infestation. Farmers relying on manual cultivation of land invaded with *Imperata* can achieve some success in suppressing *Imperata* infestations for a number of years by using intensive relay and intercropping systems, especially where leguminous cover crops are included in the crop cycle (van Noordwijk et al., 1997).

Chemical application - herbicide use

Chemical application is one of several methods for protecting crops from the effects of competitive weeds. Especially to control invasive weed species, the use of herbicides has become more commonplace in recent years (Frandsen, 1997; Sigg, 1998; Holt, 2004). Farmers who can afford prefer to use herbicides to control *Imperata*. Chikoye et al. (2002) indicated that chemical control may be an alternative *Imperata* management option with high potential in intensive cropping systems where land is scarce and with severe labor shortages (Townson, 1991; Chikoye, 1999). When used rationally, the use of herbicides to control *Imperata* is considered quicker, cost-effective, and with less soil disturbance – a better option in upland agriculture to reduce soil erosion (Townson, 1991; Tjitrosemito et al., 1994; Terry et al., 1997; Chikoye, 1999 and 2005). Zaini and Lamid (1993) reported that herbicides are technically feasible on *Imperata* areas (e.g., Sumatra, Indonesia).

The use of herbicides to control *Imperata* began in the 1940´s, but until today, only a few of the hundreds of herbicides tested are proven effective against *Imperata* (MacDonald et al., 2006). Among the herbicides tested, glyphosate is the most widely used. It is a common active ingredient in several commercial, household herbicidal products (e.g., Round-Up, Touchdown, Kleerawy) and purportedly environmentally safe (e.g., Caffrey, 1996; Baylis, 2000; Smith, 2001). Glyphosate has not only been found to be effective, but also has little or no residual soil activity and no carry-over effects on crops. Crops can be planted immediately subsequent to application. It is non-selective and controls all weeds (or injures all vegetation) and can be applied using weed wipers or carriers with low volume or high volume sprays. The translocation of glyphosate to *Imperata* rhizomes is a major factor behind the success of this herbicide for *Imperata* control (Brook, 1989; Terry et al., 1997; Otsamo, 2001; Chikoye, 2005; MacDonald et al., 2006). Effectiveness is greater if applied to new shoots after slashing or burning. After herbicide spraying, supplementary weeding is still required to control shoots that escape from the initial pre-planting application. The recommended rate of spraying is 5 l of glyphosate per hectare, followed up by a 1 l correction spray (IRRI, NRI and ICRAF, 1996). Since *Imperata* will typically reinvade after 6 to 12 months, various innovations in application technology have been evaluated to increase the efficiency of herbicides (Chikoye, 2005).

When herbicides are readily available, their overuse can lead to negative impacts. The heavy application of traditional (synthetic chemical) herbicides to achieve productivity targets has resulted in both ecological and human health problems (Saxena and Pandey, 2001; Lešnik, 2003). Reduced herbicide use could be possible when controlling moderate weed populations and when the crop has good competitive ability (Mulder and Doll, 1993; Rola et al., 1999, Zhang et al., 2000; Lešnik, 2003). Like for example, if maize crops have a good competitive ability, weed control with lower herbicide doses is suggested, which has less negative ecological and economic effects,. However, with sub-lethal doses of herbicides, weeds may not be completely eliminated. After a relatively short period, they can re-emerge if they are not subsequently suppressed by the main crops (e.g., maize). Some authors suggest that herbicide use can be effective but is not always necessary (Petersen and Hurle, 1998b; Kees, 1990; Heitefuss et al., 1994; Auerswald et al., 2000).

Although tillage and herbicides provide some control and suppression of *Imperata*, it is recognized that long-term eradication is seldom achieved, and thus alternative or improved and integrated farming practices are investigated.

2.5.2 Cultural method or cropping strategy

According to MacDonald (2004), cultural management is the long-term solution to *Imperata* management. Cultural weed control methods in agroecosystems include crop production techniques such as manipulating crop cultivars, sowing time and spatial arrangement, choice of crop genotype, planting of smother or cover crops (when used as living mulches), intercropping and fertilizer application to crops (Ross and Lembi, 1999; Bàrberi, 2005; Holt, 2006) .

Legume cover cropping – mucuna relay

For *Imperata* weed control management, cover cropping especially with legume-based cover crops has become viable due to its competitive ability, contribution to soil fertility through symbiotic N_2 fixation and improved crop performance (von Uexküll, 1984; Smith et al., 1987; Teasdale, 1996; Ibewiro et al., 2000). The current recommendation for the integration of cover crops is relay cropping of the cover crops into the primary crop (Versteeg and Koudokpon, 1990). For example in maize, it is recommended to sow cover crops six weeks after the maize seeding to avoid severe competition (Chikoye et al., 2002). It is reported that delaying cover crop seeding until maize is 15 – 30 cm in height did not reduced grain yield (Scott et al., 1987).

Among the leguminous cover crops, mucuna spp. are widely known and promoted to control *Imperata* and to manage fertility (Versteeg et al., 1998; Udensi et al., 1999; Akobundu et al., 2000, Chikoye, 2002). Mucuna is known to establish easily, grow fast, produce high amounts of biomass, and potentially contribute to soil N through symbiotic N fixation thus increasing the yields of subsequent or associated cereal crops (Sanginga et al., 1996; Houngnandan et al., 2000; Ibewiro et al., 2000; Chikoye, 2005). Studies show that maize yield in fields was higher after mucuna was planted than in fields without mucuna (Versteeg et al., 1998; Chikoye, 2003). This yield improvement was attributed to the large amount of N_2 fixed by the plant (Sanginga et al., 1996; Ibewiro, 1998)**.**

Many reports show that N fixation of mucuna ranges from 43 – 90 % (Sanginga et al., 1996; Becker and Johnson, 1998; Ebewiro et al., 2000; Houngnandan et al., 199 and 2000; Wortmann, et al., 2000; Hauser and Nolte, 2001; Kaizzi, 2002). Hence, according to Smithson and Giller (2002), the proportion of N from N_2-fixation in crops ranges from 0 %, when environmental stresses are severe and prevent nodulation, to 98 % in crops growing in ideal conditions. Also, the N_2 derived from fixation varied depending on whether N fertilized, inoculated or uninoculated (Ebewiro et al., 2000).

In addition to the soil-improving qualities, mucuna has also been shown to effectively smother and suppress *Imperata* growth and can be used to prevent and, in some cases, eradicate *Imperata* (Fujii et. al., 1992: Sanginga et al., 1996; Macdicken et al., 1997; Carsky et al., 1998; Udensi et al., 1999; Ibewiro et al., 2000; Houngnandan et al., 2000; Chikoye et al., 2002). The suppressive effect of mucuna is related to its rapid growth rate and high biomass productivity and the release of toxins such as L-DOPA, that are present in the roots and leaves and that have allelopathic (suppressive) effects on weeds (Fujii et al., 1992). Also, twining young mucuna used the new developed shoots *Imperata* as support until it develops a dense canopy eliminating light for *Imperata* and eventually smothering its growth. In the process, the underground *Imperata* rhizomes become exhausted through the maintenance respiration of the *Imperata* biomass (Koudokpon, 1990).

Use of chemical fertilizers

The FAO (2000) reported that the use of chemical fertilizers steadily increased over the last decades and is expected to continue in the coming years. It has become essential to increase and improve food production and maintain soil fertility. Field experiments initiated in 1843 and in 1855 of the famous Rothamstead Experiment Station north of London, England proved that soil fertility could be maintained for many years with artificial manure or chemical fertilizers. For more permanent cropping systems, it is suggested that inorganic fertilizers are essential to sustain crop yields, although this type of fertilizer inputs are often too expensive for subsistence farmers or may be uneconomical or difficult to obtain. In developing countries in the tropics, crop yields and soil fertility usually go together. The inherently infertile soils coupled with the critical nutrient mining in farmers´ fields implies that external fertilizers have to be applied if optimal crop yields are to be achieved (Vlek, 1990; Foth and Ellis, 1997; Hartemink, 2004).

In tropical Asia where most soils are highly weathered and infertile or characterized as acid soils, the continuous use for annual crops over four to five years resulted in soil degradation (Santoso et al., 1994). As van Noordwijk et al. (1997) indicated the spread of *Imperata* is often linked to such a decline in soil fertility. This process is exacerbated since *Imperata* most effectively competes at lower fertility levels, especially when lack of N reduced the vigor of the main crop. It is also reported that the variation in *Imperata* severity could be explained by the available P, exchangeable Ca and K (Chikoye et al., 1999). The authors further suggested that maintaining an adequate soil nutrient status is one of the key factors for stabilizing crop productivity and preventing *Imperata* infestation. Von Uexküll and Mutert (1995) suggested a one-time heavy application of reactive rock phosphate or its equivalent (TSP or lime) to correct the P and Ca deficiency as a strategy for reclamation of *Imperata* invaded fields. The authors reported the providing the most limiting plant nutrient (P) and ameliorate P adsorption in the soil enhanced the cover crop (mucuna) growth, and thus, had positive effect on the yield of the food crops.

An intensive cropping system based on sufficient fertilizer inputs is considered technically feasible in *Imperata* areas (Zaini and Lamid, 1993). The addition of fertilizer increased the competitiveness of the desired crop over the invasive weeds (Bàrberi, 2005). MacDonald (2004) cited several studies (Stobbs, 1969; Blair et al., 1978; Burnell et al., 2003; Brewer and Cralle, 2003) that addition of fertilizer, particularly N and P, increase the competitiveness of desirable species (primarily legumes) over *Imperata*. The ratio of soil P to N was found to provide an indicator of ecosystem resistance to *Imperata* invasion (Brewer and Cralle, 2003).

2.6 Maize

Among the important cereal crops worldwide, maize ranks third after rice and wheat. In Southeast Asia, maize is the second important staple food and major component of animal feeds. Witt et al. (2006) reported that the total area planted to maize in Southeast Asia is about 8.6 million hectares, with largest areas in Indonesia (41%), the Philippines (29%), Thailand (13%), and Vietnam (12%). But, the growing demand in the region can not be met despite the increase in domestic production and yield of maize in the last 15 years.

CIMMYT (1999) reported that the expansion in maize production that has occurred during the last decade in the region has been concentrated in the hill sides or marginal uplands, where maize cultivation using low level inputs has been shown to collapse because of weed infestation (Sanchez et al., 1987; von Uexküll, 1995). In maize field infested with *Imperata,* the farmers may only have one or two harvests before *Imperata* completely covers the land. A study conducted in Africa show that in fields with uncontrolled *Imperata*, undisturbed rhizomes caused the reduction maize grain yield by 92 % (Akobundu and Ekeleme, 1998). However, after a legume cover crops were planted, maize yield also improved in *Imperata* fields (Sanginga et al., 1996; Ibewiro, 1998; Versteeg et al., 1998; Chikoye, 2003; Hauser and Nolte, 2003).

As cereal crop, maize is considered to be a test plant for identifying the availability of many nutrients, since it very sensitive to nutrient deficiency. It is responsive to fertilizer, especially N, P and K. Maize needs continuous supply of N at all stages of growth until grain formation. Nitrogen influences yield largely because of its role in determining (1) the amount of solar radiation absorbed by crops and (2) the efficiency of its conversion to biomass. Nitrogen deficiency in maize plants, even in the early stages of growth, will reduce the yields substantially. It causes reduction of leaf size thus reduces the crop total leaf area and consequently the ability to absorb radiation. Reduced concentrations of N in the leaves reduce the ability to photosynthesize and cause premature leaf death.

Young maize plants need higher amounts of P in the early stages and absorb P up to near maturity. Phosphorous is essential for the storage and transport of the energy used to drive plant processes and is an important part of biochemical compounds such as DNA that control plant growth and development. It promotes the initial development, bloom and fruit and storage formation. The effects of P on yield are substantial, but less clearly quantifiable than those of N. Phosphorous deficiency symptoms may include smaller leaves, thin stems, and a limited root system (due to reduced sunshine interception by the leaves rather than any direct effect on the roots). A red/purple color is also common in older leaves.

Potassium (K) is the third major nutrient require by maize. Maize has a high K requirement and utilizes large quantities of this nutrient from the knee-high to post flowering stage. Its function within the crop is less clear than that of N and P, but it is nevertheless obvious that significant quantities of K are required for crop growth. It is central to the translocation of photosynthates within plants, and for high yielding crops, and promotes the development of biomass in the shooting phase and increases the steadiness of the maize stands. Potassium deficiency causes a variety of dysfunctions in plant metabolic processes, which result in decreased productivity and quality of crop yield. Poor cob formation and grain fill resulting in low starch levels are consequences of low K content in plant (http://www.pda.org.uk). Potassium deficit causes a variety of defects in the structure of plant tissues and organs: chloroplasts and mitochondria collapse, the development of cuticles is inhibited as is the synthesis of high-molecular carbohydrates (cellulose), which results in the lodging of high-stemmed plants. The increased utilization of N from N mixtures may only be effective if an adequate supply of K is present. In order to achieve maximum efficiency of N fertilizer, there is also a need to increase and maintain K levels (FAR http://www. farmresearch.com).

Hanway (1962) reported that 38 % of the total K uptake by maize for the whole growing season occurred 38-52 days following planting. Any deficiencies in K availability in soil volumes that are exploited by maize roots during the rapid dry matter accumulation phase before pollination can result in inadequate K nutritional status and may result in reduced yields (Heckman and Kamparah, 1992; Vyn and Janovicek, 2001). Jones Jr, (2003) indicated that K deficiency severely reduces grain yield.

Sulfur (S) is a constituent of proteins alongside N. Few experiments have tested the need for S in maize. But, a study conducted in Bangladesh show that S application had a significant influence, especially on maize grain yield. The grain yield increased with increasing level of S fertilizer application (Sinha et al., 1995; Alam et al., 2003). Sulfur deficiency reduce grain yield because affected plants produce fewer, smaller ears with fewer kernels (Jones Jr, 2003).

2.7 Nitrogen recovery

Among the macro nutrients, N is considered the key element limiting crop production. In most situations, it is the nutrient taken up in the greatest quantities by crops, and is almost universally deficient in all but the most extensive agricultural systems (Foth and Ellis, 1997, Smithson and Giller, 2002), especially in maize production systems in the tropics. There is a strong incentive to apply N fertilizer, because most soils cannot supply enough N for maximum productivity. A greater proportion of N from inorganic fertilizer is taken up by the crop than is N from legume residues (Ladd and Atamo, 1986; Bremer and van Kessel, 1992; Harris et al., 1994; Kramer et al., 2002).

Application of fertilizer N to soil or to soil-plant systems often leads to enhanced mineralization and availability of N from soil organic matter. Inorganic fertilizers contribute a large flush of available N upon application (proving to be a significant source of N for the maize early in the growing season), while legume residues show a delayed, sustained release of N (Azam et al., 1985; Groffman et al., 1987; Kramer et al., 2002). This slow N release pattern of organic N sources is attributed to the dependence of organic residues on microbial decomposition and subsequent mineralization of N, a process largely affected by climate and residue quality, such as CN ratio and polyphenolic content (Ladd and Amato, 1986; Palm and Sanchez, 1990; Sisworo et al., 1990). The disparity between crop N-use efficiency of organic and inorganic sources resulting from distinct temporal N availability leads to the question whether yields comparable to those of conventionally grown crops can be achieved by crops solely dependent on organic inputs (Kramer et al., 2002). The combination of organic and inorganic N inputs holds promise for reducing the use of inorganic fertilizers and possible N losses from agroecosystems (Kramer et al., 2002).

Finally, efficient use of N becomes a priority concern for environmentally friendly agricultural production. Nitrogen application in agriculture has been linked to NO_3 contaminations of groundwater (Oberle and Keeney, 1990b; Fergusson et al., 1991; Schepers et al., 1991; Kitchen et al., 1992; Schmidt et al., 2002). Nitrogen application rates in excess of crop requirements contribute to increase the level of NO_3 in the soil profile, and high concentrations of post-harvest soil NO_3 increase the risk of leaching into the groundwater (Roth and Fox, 1990; Schepers et al., 1991; Schmidt et al., 2002). For cropping management, it is deemed necessary to minimize excessive loss of N while maximizing N-use efficiency in meeting crop N requirements.

3 METHODOLOGY

3.1 Study area

This study was carried out within the research area of the project "Stability of Tropical Rainforest Margins" (STORMA) located in Central Sulawesi, Indonesia (Deutsche Forschungsgemeinschaft-DFG, Sonderforschungsbereich- SFB 552). The field research was conducted in the buffer zone of the Lore Lindu National Park (LLNP). This park is situated about 50 km south-east of Palu, the capital of Central Sulawesi, Indonesia (Figure 3.1).

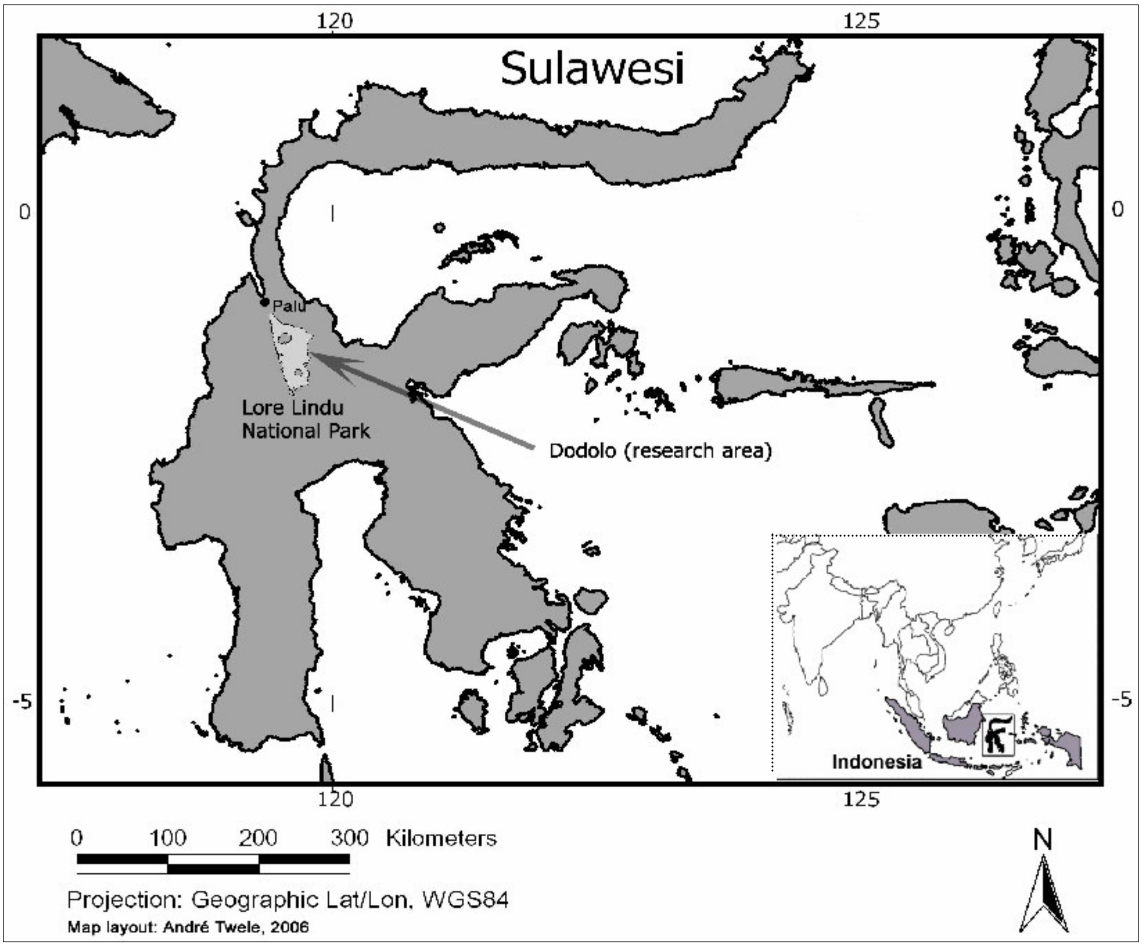

Figure 3.1: Location of the research area in Palu, Central Sulawesi, Indonesia

Central Sulawesi, Indonesia, is characterized by its large rainforests, which have been subjected to intensive and widespread deforestation during last decade. Particularly, the mountains surrounding the national park are still widely forested but the forest margins are currently undergoing rapid conversion into agricultural lands. Most agricultural lands in the area originate from converted natural forests. Only small areas are converted grassland or old forest fallows. The uncontrolled exploitation of the forest resources was not only driven by the local population's precarious economic situation, but also encouraged by the complicated and controversial legal situation in the area (http://www.storma.de). The rainforest margins, especially the margins of the LLNP with more than 100 villages bordering the national park are subjected to intensive clear-cutting by smallholder land farmers, locals and migrants, who utilized the area, initially opened by logging, for agricultural production with the introduction of cash crops.

The initial high fertility of the soils in the area encouraged permanent agriculture (Dechert, 2003). Agricultural cultivation was often established following clearing and burning. The cleared lands are primarily planted with maize as monoculture, while some parts were planted with root crops like cassava after some cropping periods. Farmers do not use fertilizer, and engage in continuous cultivation without fallow period. For unfertilized systems, initially maize yields were relatively high when compared with those reported by Hölscher (1995) for Eastern Amazonia, Brazil, however yield declined after several periods of continuous cultivation (Dechert et al., 2005). The farmers often blamed weed infestation or weather conditions rather than soil fertility for the low yields. After 2-3 years of maize cultivation, farmers often had to switch to cacao-coffee agroforestry.

Forest fallow is mainly found on newly cleared forest sites, which are not immediately cultivated, or on fields that have been long abandoned. Grass fallows were mostly found in areas that had been uncultivated for a long time, but were previously under continuous annual crop cultivation and frequent burning practices, which favor the establishment of grass species dominated by *Imperata cylindrica*. Garrity et al. (1997) estimated that in Central Sulawesi, *Imperata* grasslands already covered an area of about 205,600 hectares. With *Imperata* grassland in the surroundings, cleared forest lands utilized for agriculture are prone to *Imperata* weed infestation which eventually turned into sheets of *Imperata* grass.

3.1.1 Field site

The research site is located in the rainforests margin of the Napu valley, in Dodolo village located at latitude 1° 28' S and longitude 120°18' E with an average elevation of 1,140 m asl (Figure 3.2 and Table 3.1). The cultivated area directly adjacent to a forest and surrounding croplands, with different degrees of *Imperata* infestation (covering the critical range from early infestation to the point of abandonment) were selected for the experiments. Before the conduct of experiment, selected fields were either planted with maize crops or previously under continuous maize cultivation.

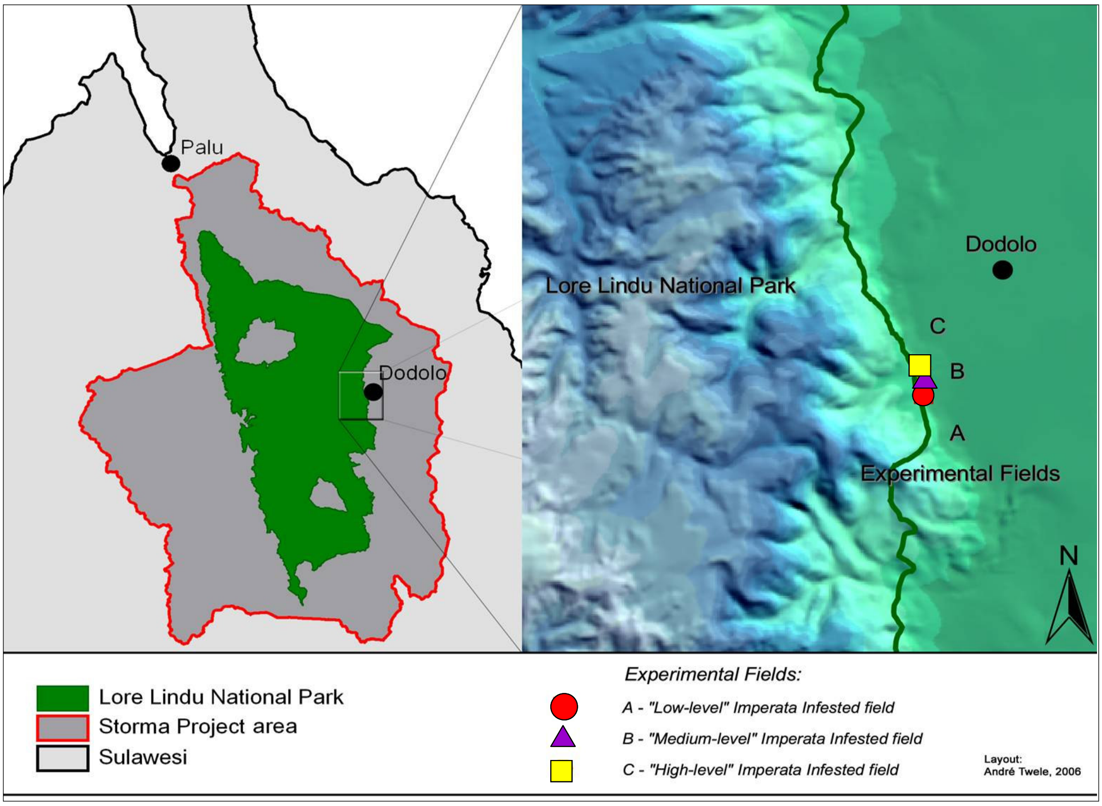

Figure 3.2: Location of the experimental fields at the buffer zone of Lore Lindu National Park

Table 3.1: Location of experimental fields with different levels of *Imperata* infestation categorized as low, medium and high-infested fields

	Field category		
	Low	Medium	High
Latitude	1° 28' 27" 80 S	1° 28' 17" 44 S	1° 28'13" 44 S
Longitude	120°18' 56" 12 E	120°18' 56" 70 E	120°18' 55" 04 E
Altitude (m asl)	1,138 m asl	1,133 m asl	1,136 m asl
Distance between fields	A-B = 320.5 m	B-C = 133.9 m	A-C= 444.9 m

Coordinates were measured at the center of the fields with GPS-handsets.

Population densities in undisturbed natural swards of *Imperata* range from 300 to 500 shoots m^{-2} (IRRI, NRI and ICRAF, 1996). The value 500 shoots m^{-2} was used as reference for full coverage. A pre-sampling counting of *Imperata* shoots was conducted in previously cultivated but long abandoned fields of neighboring villages and with dense *Imperata* cover. The results show that 300-400 shoots m^{-2} is the range for full coverage in the research area (Table 3.2).

Table 3.2: Results of pre-sampling counting of *Imperata* shoots in long abandoned or uncultivated fields in Napu valley side (Wanga and Siliwanga village) conducted in March 2003.

Sample locations	Slope [%]	Replications	No. of shoots m^{-2}
Wanga downhill	5-10	1	315
		2	362
		3	348
		Average =	342
Wanga uphill	70-80	1	239
		2	376
		3	280
		Average =	298
Siliwanga	5-10	1	344
		2	386
		3	392
		Average =	374

The fields were categorized according to the degree of *Imperata* infestation. With 500 shoots m^{-2} as reference, A-field with “low-level” *Imperata* infestation had shoots counts ranging from 1-25 %. The B-field or “medium-level” *Imperata*-infested field had counts ranging from 26-50 %, and the C-field with “high-level” *Imperata*-infested field had 51-75 %. By counting shoots in series of 1-m^2 area, established at random within the 25 m^2 plot, the exact coverage was assessed as summarized in Table 3.3.

Table 3.3: Categorization of selected cultivated area by the initial level of *Imperata* infestation using 500 shoots m^{-2} as full coverage of shoots per m^2

Field	Category with percentage ranges of *Imperata* shoots m^{-2} (500 shoots m^{-2} as reference)		*Imperata* shoots in 1 m^2-quadrat frame [shoots m^{-2}]	Percentage range of *Imperata* infestation in selected fields using 500 shoots m^{-2} as reference
A	Low	[1 % - 25 %]	12-130	2.4 % - 20.6 %
B	Medium	[26 % - 50 %]	131-250	26.2 % - 50.0 %
C	High	[51 % - 75 %]	277-355	55.4 % -71.0 %

Above 75 % is already considered critical level for total abandonment. These conditions are found in areas that were not cultivated for a long period of time. It is considered Imperata fallow. The fields are categorized for reclamation or total rehabilitation.

The low-infested field (A-field) cleared in 2001 from a natural forest, and under continuous maize cultivation for two years until the research experimentation in 2003. The medium-infested field (B-field) cleared in 1996, and was under continuous maize cultivation for four years (with seven maize and one bean cropping period) and subsequently under *Imperata* grass fallow for two years (2001-2002). In 2003, the field was cultivated again but planted with *Cacao* and *Gliricidia*. However, two months before experimentation, the field was burned. The high-infested field (C-field) cleared in 1995, and was under continuous maize cultivation for five years (with seven maize cropping periods until 1999, and one bean cropping in 2000), then left uncultivated for three years with *Imperata* grass fallow until the experiment was initiated (Figure 3.3).

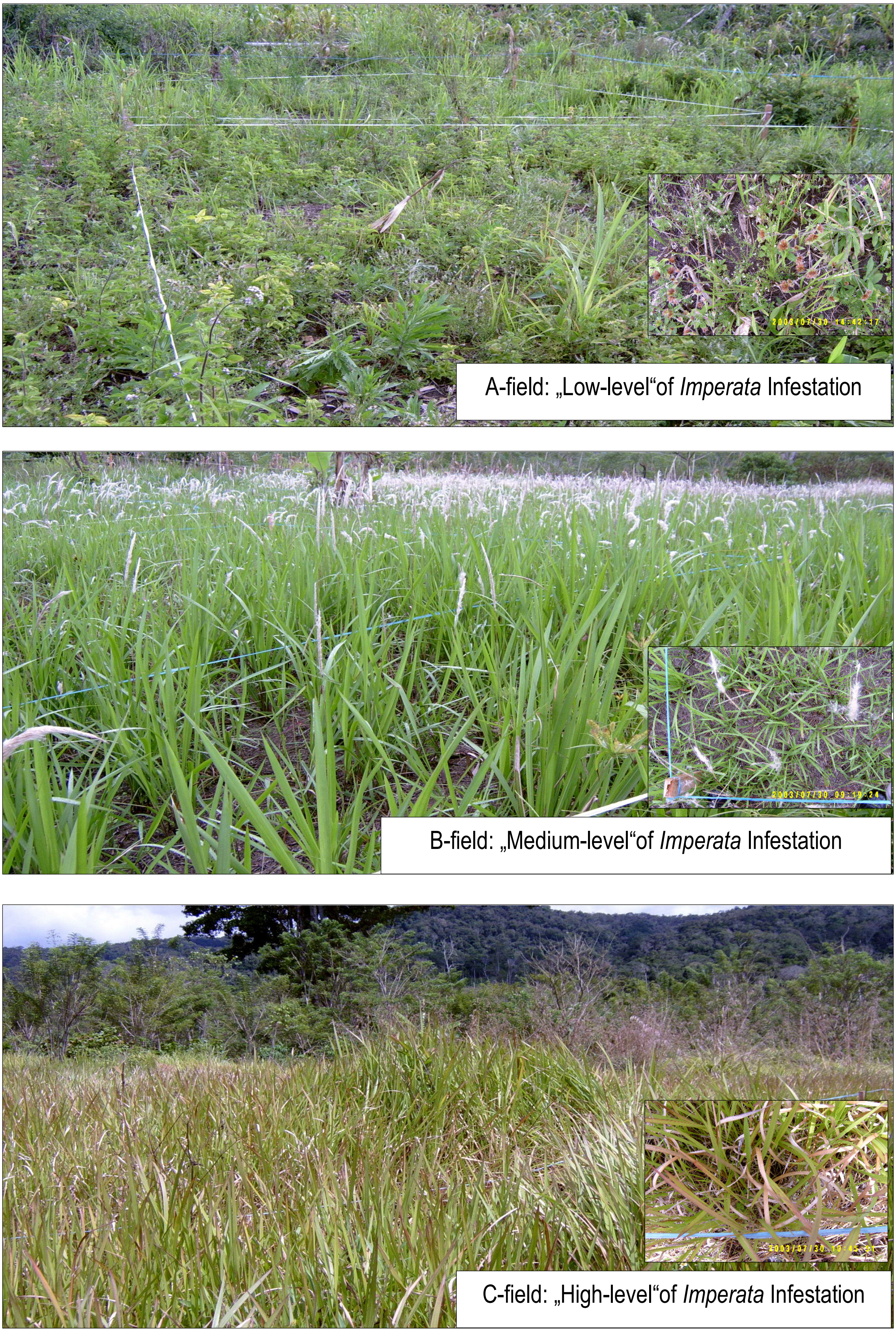

Figure 3.3: Fields with different level of *Imperata* infestation

3.1.2 Soil

The location of the experimental fields is directly adjacent to the area (Latitude: 1° 29.5' S, Longitude: 120°19.4' E, Altitude 1100 m asl) described by Corre et al. (2005) as having Typic Eutropepts soil type and deeply weathered phyllite as parent material.

Soil sampling was conducted before experimentation to characterize the specific soil conditions of the selected fields (Tables 3.4 and 3.5). The CN ratio of around 10 and base saturation of above 90 % suggest that the soils were not degraded. The bulk density of all fields (0.8 – 1.1 g cm^{-3}) was still within the typical ranges for virgin and recently cultivated soils (0.9 – 1.2 g cm^{-3}) rather than for compacted soils (1.1 – 1.4 g cm^{-3}) as described by Taylor et al. (1966) cited in Landon (1991). The soil texture analysis shows that silt percentage ranges from 32-37 %, sand from 34-42 % while clay 22-31 %. The main difference of the three fields was the pH value, which corresponds to the degree of *Imperata* infestation (Table 3.4). The soil of the highly infested field was the most acidic (5.01_{CaCl2} 5.78_{H2O}) followed by the soil of the medium-infested field (5.35_{CaCl2} 6.01_{H2O}) and low-infested field (5.48_{CaCl2} 6.16_{H2O}).

Infestation of *Imperata* was not driven by the lack of P, as the available P was highest in the highly infested field, (i.e., 70 mg g^{-1} and 49 mg g^{-1}) in the first and second set of experiments, respectively. Generally, the decline in soil parameters such as total C (<30 mg g^{-1}), N (<3 mg g^{-1}) and S (<0.3 mg g^{-1}) concentrations and the drop in CEC by about 60 % to 109.4 mmol(+) kg^{-1} with concomitant losses in exchangeable K and Ca cations in the highly infested field suggest that *Imperata* infestation is related to the decline in soil fertility. On the other hand, the low- and medium-infested fields had similar and better soil fertility conditions, (i.e., both had total C (>30 mg g^{-1}), N (±3 mg g^{-1}), and S (±0.3 mg g^{-1}) concentrations, and a CEC (>150 mmol(+) kg^{-1}) with higher exchangeable Ca (>100 mmol(+) kg^{-1}) and Mg (>35 mmol(+) kg^{-1}). Only Mn was significantly higher in the low-infested field (0.94 and 2.25 $mmol^{(+)}kg^{-1}$) than in the medium-infested field (0.69 mmol(+) kg^{-1}). The soil properties of the experimental fields, especially those with high infestations confirm that the presence of *Imperata* indicates soil fertility problems.

Table 3.4: Soil characteristics in the low, medium and high-infested fields of the first set of experiments

Parameters	Unit	Field category Low	Medium	High
Bulk density	$g\ cm^{-3}$	0.89 a	0.92 a	0.99 b
pH				
[1:1 $CaCl_2$]		5.48 c	5.35 b	5.01 a
[1:1 H_2O]		6.16 c	6.01 b	5.78 a
Total organic C[1]	$mg\ g^{-1}$	30.3 b	32.0 b	27.3 a
Total N[1]	$mg\ g^{-1}$	2.9 b	3.1 b	2.6 a
CN ratio		10.5 ns	10.4 ns	10.4 ns
Available P (Bray 1)	$mg\ g^{-1}$	20.2 a	34.3 b	70.0 c
Total S[1]	$mg\ g^{-1}$	0.4 b	0.3 b	0.2 a
CEC [2]	$mmol(+)\ kg^{-1}$	154 b	171 b	106 a
Na^+	$mmol(+)\ kg^{-1}$	0.38 ns	0.91 ns	0.68 ns
K^+	$mmol(+)\ kg^{-1}$	2.48 ns	2.51 ns	1.60 ns
Ca^{++}	$mmol(+)\ kg^{-1}$	114 b	125 b	71 a
Mg^{++}	$mmol(+)\ kg^{-1}$	35.8 ab	41.1 b	32.4 a
Mn	$mmol(+)\ kg^{-1}$	0.94 b	0.69 a	0.61 a
Fe	$mmol(+)\ kg^{-1}$		beyond detection limit	
Al^{+++}	$mmol(+)\ kg^{-1}$	0.00 ns	0.00 ns	0.30 ns
Base saturation	%	99.4 ns	99.6 ns	99.2 ns
Soil texture[3]				
[clay]	%	28.0	29.6	23.2
[silt]	%	33.2	36.3	34.4
[sand]	%	38.8	34.1	42.4

Tukey test ($p<0.05$): Letters a, b, c denote significant difference, ns denotes no significant difference between fields
Mean values of bulk density (n=18); Total organic C, Total N, CN ratio, Total S, Available P, and exchangeable cations/CEC (n=6)
[1] CNS Elemental Analyzer
[2] Percolated with 1 M NH4Cl, analyzed using Flame-Atomic Absorption Spectrometer
[3] Pipette method

Table 3.5: Soil characteristics in the low and high-infested fields of the second set of experiments

Parameters	Unit	Field category Low	Field category High
Bulk density	g cm^{-3}	0.82 a	1.13 b
pH			
[1:1 $CaCl_2$]		6.03 b	4.95 a
[1:1 H_2O]		6.70 b	5.91 a
Total organic C	mg g^{-1}	39.4 b	21.0 a
Total N	mg g^{-1}	3.7 b	1.9 a
CN ratio		10.6 b	11.2 a
Available P (Bray 1)	mg g^{-1}	35.3 ns	49.3 ns
Total S	mg g^{-1}	0.4 b	0.2 a
CEC	mmol(+) kg^{-1}	218 b	113 a
Na^+	mmol(+) kg^{-1}	0.24 b	0.79 a
K^+	mmol(+) kg^{-1}	2.25 b	1.41 a
Ca^{++}	mmol(+) kg^{-1}	165 b	80.7 a
Mg^{++}	mmol(+) kg^{-1}	48.7 b	27.7 a
Mn	mmol(+) kg^{-1}	2.25 b	0.65 a
Fe	mmol(+) kg^{-1}	0.06 ns	0.03 ns
Al^{+++}	mmol(+) kg^{-1}	* 0.00 a	1.48 b
Base saturation	%	98.9 b	98.0 a
Soil texture			
[clay]	%	31.2	22.4
[silt]	%	32.6	37.5
[sand]	%	36.2	40.1

*Least Significance Difference test ($p<0.05$): Letters a, b denotes significant difference, ns denotes no significant difference between fields; Mean values of bulk density, Total organic C, Total N, CN ratio, Total S, Available P, for exchangeable cations/CEC (n=9); * beyond detection*

3.1.3 Climate

The field experiments were conducted under similar climatic conditions. The average annual rainfall in 2002 to 2004 was 1717 mm yr^{-1} and the average daily air temperature was 21 ºC. The experimental period was from the onset of the rainy season in August 2003 to September 2004, when monthly precipitation was mostly >100 mm and the average air temperature was 21 ºC. The first cropping period was from August 2003 to February 2004 with a precipitation of 1167 mm and a monthly average of 167 mm.

During the second cropping period, from March 2004 to September 2004, precipitation was 978 mm with a monthly average of 140 mm (Figure 3.4).

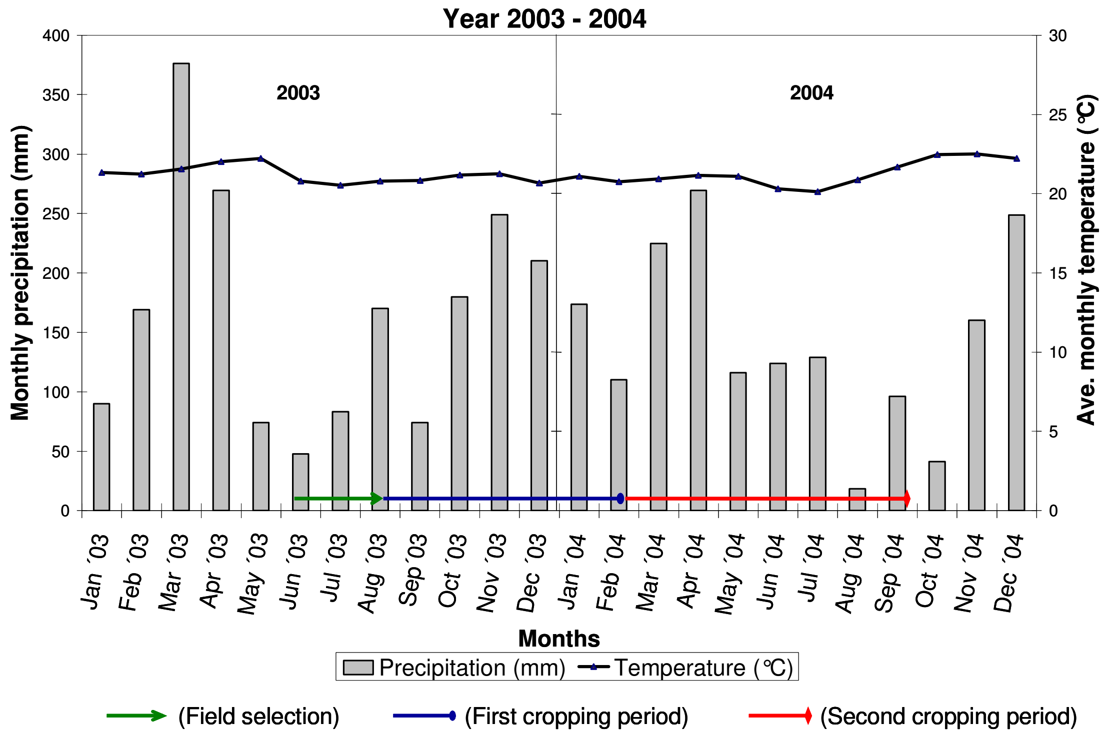

Figure 3.4: Monthly precipitation and temperature in the site during the experimental period (Source: STORMA meteorological data taken in Wanga station)

3.2 Field experiment

The study was carried out in two sets of field experiments.

(1) Two subsequent maize cropping periods were carried out in three selected fields with different levels of *Imperata* infestation, and involved the comparison of two methods of eradicating *Imperata* during land preparation as land management treatments: deep hoeing (soil tillage - manual method) and herbicide application (no-tillage - chemical method). Deep hoeing was conducted to up-turn and destroy the rhizome system and desiccate the *Imperata* rhizomes in the sun, while herbicide application (glyphosate/Round-up) to burned *Imperata* with chemicals during translocation.

(2) A one-maize cropping period in "low-level" and "high- level" *Imperata*-infested fields, which involved shallow hoeing as a method of controlling *Imperata* during land preparation. The method normally practiced by farmers prior to cropping after slashing and burning.

In both field experiments, after land preparation, a crop management strategy (referred here as cropping strategy) for soil fertility enhancement were superimposed, which is the mineral fertilizer application (NPKS fertilizer), mucuna relay (a nitrogen fixing cover crop), and a control (without any superimposed cropping strategies). The purpose of the combined treatments (Table 3.6) was to control and suppress *Imperata* re-growth, and at same time to produce an optimum maize yield.

Table 3.6: Combination of treatments (land preparation and cropping strategy) for *Imperata* control

Land preparation method		Cropping strategy
(1) with two-maize cropping experiment		
Intensive tillage (manual method)		
Ta1 -	Deep hoeing	Fertilizer application
Ta2 -	Deep hoeing	Mucuna relay
Ta3 -	Deep hoeing	No-cropping strategy
No tillage (chemical method)		
Tb1 -	Herbicide application	Fertilizer application
Tb2 -	Herbicide application	Mucuna relay
Tb3 -	Herbicide application	No-cropping strategy
(2) with one -maize cropping experiment		
Minimum tillage (manual method)		
Tc1 -	Shallow hoeing	Fertilizer application
Tc2 -	Shallow hoeing	Mucuna relay
Tc3 -	Shallow hoeing	No-cropping strategy

The second set of experiments was conducted parallel to the second cropping period of the first set of experiments to determine whether a minimum tillage method could be sufficient to control *Imperata* if combined with fertilizer use or mucuna relay as superimposed cropping strategies.

3.2.1 Plot layout and experimental activities

Plot layout

The experiments were carried out in a split-plot design with three replicates in each field category (Figure 3.5). The plot size was 25 m^2 (5m x 5m) with a 1-m wide boundary between plots to prevent cross contamination of treatments. A total of 54 plots (18 plots per field) were established for the first set of experiments with two-maize cropping periods. An additional 18 plots were established for the second set of experiments with one-maize cropping period (9 plots each in low-and high-infested fields).

Figure 3.5 Plot layout of the treatment combinations (land preparation and cropping strategy)

Experimentation

First maize cropping

Before first maize cropping, aboveground *Imperata* was slashed and removed, and the fields were left for 18 days so that *Imperata* could resprout to about 15 cm high before implementing the land preparation treatments. Fields were deep-hoed to a depth of about 15 cm or sprayed with herbicide (Roundup). Before herbicide application, the knapsack sprayer used was calibrated under field conditions to determine the amount of herbicide mixture applied. The recommended spraying rate of Roundup in open *Imperata*- infested fields as indicated in the label (10 l/ha during the rainy season) was adopted. Per plot (25 m^2), 1.6 l herbicide mixtures (25 ml Round-up + 1.575 l of water) were sprayed. Then all fields were left undisturbed for another 18 days for the treatments to take effect prior to maize seeding. The superimposed cropping strategies were employed during maize cropping period, i.e., from seeding to harvest.

The maize variety used was *bisi-2*, released in Indonesia in 1995 and easily available in the region. Maize seeding was done at the onset of the rainy season (2-3 days rainfall) with a spacing of 0.8 m x 0.4 m (2 seeds/hill at approximately 5 cm depth). On plots with fertilizer treatment, chemical fertilizers were applied in 3-split applications. The chemical fertilizers applied were mineral N (Urea), P (Single superphosphate), K (KCl) fertilizers, which were locally available, and S (Gypsum) fertilizer, which was purchased in Jakarta, Indonesia. Mineral N, P, K and S fertilizers were applied since these are the primary nutrients taken up by the crop plants in largest amounts. The rate of application is specified in Table 3.7.

Table 3.7: Inorganic fertilizer application (mineral N, P, K, and S)

Fertilizer			Rate of application (kg ha^{-1})	*Split application of fertilizer (kg ha^{-1})		
				1	2	3
Urea	N	[46 %]	120	30	45	45
SP	P	[31 %]	34	34		
	S	[5 %]	5	5		
KCl	K	[60 %]	50	50		
Gypsum	S	[21 %]	75	35	40	

** Split application: side dressing 15 cm from the hill and at 5 cm depth*
1) During maize seeding, 2) 25 DAS of maize (knee high stage), 3) 40 DAS of maize (boot leaf stage)

For plots with mucuna relay, mucuna (*Mucuna pruriens var cochinchinensis*) was planted 25 days after seeding (DAS) of maize with a spacing of 0.8 m x 0.8 m (2 seeds/hill), planted in between the maize rows/hills. Mucuna seeds were obtained from Jawa Timur, Indonesia. For the control plots, maize was planted as sole crop without fertilizer application and mucuna relay.

Hand weeding was conducted in all plots 60 DAS of maize, which was before maize flowering. Weeded/pulled out grasses were left in the respective plots.

Second maize cropping

Before the second experimental cropping period, all plots were slashed 20 days after maize harvest of the first cropping period. All slashed biomass of mucuna, *Imperata* and other weeds, and maize stover were left in each respective plot. Again, all fields were left undisturbed for 2 weeks, before starting the second maize seeding. For the second land preparation, only shallow hoeing was conducted since there was no significant *Imperata* regrowth. The superimposed cropping strategies were repeated and the methods of the first cropping period were employed.

In the second cropping period, microplots were established in the plots with fertilizer and with mucuna, and labeled 5 atom % ^{15}N Urea was applied. The same mineral fertilizer rate was applied to the "with fertilizer" plots. In the established microplots, of the 120 kg ha^{-1} N fertilizer rate applied, 30 kg ha^{-1} was from labeled ^{15}N Urea granules thus effectively reducing the atom % to 1.25. The labeled ^{15}N Urea was applied in granules.

In the "with mucuna" plots, a 15 kg ha^{-1} dose of labeled ^{15}N Urea was applied on the established microplots, and an equal dose of unlabeled Urea in the macroplots. The labeled ^{15}N Urea was diluted with water and sprayed in the plots. The sprayer was calibrated to field condition to determine the right amount of water sprayed that would cover equally the target area.

The microplots were embedded with aluminum sheets with dimensions as indicated in Table 3.8 to a depth of 40 cm leaving 10 cm above the soil surface to prevent possible contamination during run-off.

Table 3.8: Specification of microplots established in "with fertilizer" and "with mucuna" plots

Field plots	Area (m^2)	Dimensions	Rate of application ($kg\ ha^{-1}$)	Total
"with fertilizer" plots	4.5	2.8 m x 1.6 m x 0.5 m	30	18
"with mucuna" plots	3.2	2.0 m x 1.6 m x 0.5 m	15	18

3.3 Data collection and laboratory analysis

3.3.1 Soil sampling and analysis

Composite soil samples were taken from 0 to 30 cm depth at nine established sampling points per plot using a soil auger. The soil samples were air dried at room temperature for 1 week and passed through a 2 mm sieve. Subsamples were taken and brought to the laboratory[1] for analysis of soil physical and chemical properties. In addition, bulk density was determined using the soil core method following the procedure described by Blake and Hartge (1986). Soil bulk samples in the core sampler per plot were placed in plastic bags and transported to the laboratory. Samples were weighed before and after oven drying at 105 °C for 48 hours to obtain a constant weight.

From air-dried, ground soil samples, total organic C, N and S were measured using a CNS Elemental Analyzer (Vario EL III, Hanau, Germany). The available P (Bray-1) was measured using the method described by Bray and Kurtz (1945) - extraction with dilute acid fluoride, and the P concentration was determined colorimetrically by the Ascorbic Acid Method with an autoanalyzer. The CEC was determined from air-dried, 2-mm sieved samples, percolated with 1 M NH_4Cl, and the percolates were analyzed for element contents sing Flame-Atomic Absorption Spectrometer (Varian, Darmstadt, Germany) (Meiwes et al., 1984). The base saturation was calculated as the percentage base cations (Mg, Ca, K, and Na) of the CEC. Likewise, from 2-mm sieve soil samples, the pH was measured with 1:1 H_2O and 1:1 $CaCl_2$, while the soil texture was determined by the pipette method.

[1] Except for available P, which was analyzed at the Institute of Tropical Agriculture (IAT), soils were analyzed at the Institute of Soil Science and Forest Nutrition (ISSFN). Both institutes belong to University of Göttingen, Germany.

3.3.2 Plant sampling and analysis

Maize

Maize dry matter (leaves[2], grain and stover[3]) was measured by harvesting an area of 6.72 m^2 (2.4 m x 2.8 m) in the center of each plot. For the grain, all maize cobs within the sampling area were harvested and sun dried before shelling, and shelled out grains were again sun-dried, following the general practice of farmers in the area. The weight of the shelled out grains before and after sun drying was measured. However, the weight of shelled grains before sundrying was used as fresh-weight grain yield (FwGs) for grain dry matter yield calculations. Grain subsamples (about 100 g) after sundrying were taken for moisture determination, and the weight of the sub-samples measured again before (FwGss) and after (DwGss) ovendrying to constant weight at 80 °C.

For the stover, 5 maize plants (without the husk and grains) within the sampling area were harvested and weighed to get the fresh weight (FwSs), cut into parts/pieces and subsamples were taken on each part, then oven dried to constant weight at 80 ºC. For the leaves, 25 leaves were collected before the silking/tasseling stage (55 DAS), taking the leaf right below the whorl of the maize stands. All collected leaves were oven dried to constant weight at 80 °C.

Imperata

Imperata shoot counts were conducted before and after the experimentation. The first counting was done as described in section 3.1.1 and the second counting was done using a 0.5 m^2-quadrat frame established within the inner four corners of each plot. Before experimentation, the *Imperata* stands with the rhizomes within the 1 m^2-quadrat frame were excavated down to 30 cm depth for *Imperata* biomass determination. For nutrient analysis, samples were taken within the 0.5 m^2-quadrat frame established. The shoots and rhizomes were separated and oven dried at 80 °C to constant weight. At the end of two sets of experimentation, *Imperata* biomass was collected from the 0.5 m^2-quadrat frame established within the inner four corners in each plot. Since there was no significant *Imperata* regrowth, shoots and rhizomes were not separated, except for the

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[2] Maize leaves sampling (55 DAS)
[3] Maize stover and grain sampling at harvest (130 DAS)

Imperata biomass from the highly infested field of the second set of the experiments. Samples and subsamples were oven dried at 80 °C to constant weight.

Other weeds

Weed[4] samples other than *Imperata* were collected from five selected points in the plot using a 0.5 m^2-quadrat frame, with a total sampling area of 1.25 m^2. Sampling was conducted twice per cropping period, during the weeding maintenance (60 DAS of maize) and after maize harvests (150 DAS). All samples were oven dried at 80 °C to constant weight.

Mucuna

Mucuna[5] samples were collected after the maize harvests and the weed sampling at four established points in each plot using a 0.5 m^2-quadrat frame, with a total sampling area of 1 m^2. All samples were oven dried at 80 °C to constant weight. Both fresh and oven dry weights of all plant samples and subsamples were measured. For nutrient element determination, oven-dried plant samples were milled and passed through a 0.63 mm sieve and a sample taken to the IAT laboratory.

All plant[6] samples were analyzed for total C, N, S, P and K. The total C, N, and S concentrations were measured using the Elemental Analyzer (Vario EL III, Germany), while total P concentration was measured with an Auto Analyzer II (Pulse Instrumentation Ltd., Canada) after color development with the Vanadomolybdate–Yellow-Method. Plant digestion for total P analysis was done with sulfuric acid (H_2SO_4) and hydrogen peroxide (H_2O_2) as described in the Plant Analysis Handbook II (Mills and Benton, 1996). The K-analysis was done after digestion with a Flame-AAS (Analytik Jena Type novAA 315).

[4] First sampling at weeding maintenance (60 DAS of maize), Second sampling after harvest (150 DAS of maize)
[5] Mucuna DM sampling (130 DAP of mucuna)/(155 DAS of maize)
[6] All sample preparations (milling and sieving) were done at STORMA Laboratory in Palu Sulawesi, Indonesia

3.3.3 Microplot sampling and analysis

^{15}N analysis and determination of mucuna N_2 fixation

Plant (maize, mucuna, and other weeds) samples[7] for ^{15}N analysis were collected during the second cropping harvest of the first set of experiments. Sampling was conducted in microplots established in the mucuna relay plots. For maize sampling, four maize hills (8 maize plants) at the center of the microplots occupying an area of 1.28 m^2 (1.6 m x 0.8 m) were harvested. The leaves, stalk/stem, cobs, roots, and grains were separated. For mucuna, the middle two plants occupying an area of 0.64 m^2 (0.8 m x 0.8 m) were harvested. The vines [leaves and stem], pods, and roots were separated. For weeds other than *Imperata*, samples were collected at the center of the microplots occupying an area of 0.25 m^2.

Both fresh and oven-dried weights of plants or plant parts were measured. All samples were oven dried at 70 ºC to constant weight, then milled and sieved through a 0.63 mm wire mesh sieve. Subsamples were taken for analysis to the Institute of Agricultural Chemistry at the University of Bonn. Recovered ^{15}N and total N were determined by mass spectrometer (ANCA-SL coupled to 20-20 stable isotope analyzer IRMS-PDZ Europa). The proportion (%Ndfa) and the amount (Ndfa kg ha^{-1}) of N_2 derived from atmospheric fixation were estimated using the isotope dilution (ID) method following the equation presented by Knowles and Blackburn (1993). The estimate of N_2 fixed by mucuna was calculated using either the associated maize or "other weeds" as reference plants.

^{15}N recovery

Plant (maize and "other weeds") and soil samples for ^{15}N recovery were collected during the second cropping harvest on the first set of experiments. Plant sampling was conducted in microplots established in plots with fertilizer application. For maize, 4 maize hills (8 maize plants) were harvested from the center of the microplots occupying an area of 1.28 m^2 (1.6 m x 0.8 m). The leaves, stalk/stem, cobs, roots, and grains were separated. For the weeds other than *Imperata*, samples were collected at the center of

[7] To avoid contamination, microplot (in "with mucuna relay" plots) plants sampling for ^{15}N analysis for N_2 fixation of mucuna, and for N recovery in microplot (in "with fertilizer" plots), plants and soil sampling were conducted one week later after macroplot plant (maize, other weed, and mucuna sampling).

the microplots occupying an area of 0.25 m^2. Both fresh and oven-dried weights of the maize parts and "other weeds" were measured. All samples were oven dried at 70 ºC to constant weight, then milled and sieved through a 0.63 mm mesh sieve.

For soil, composite samples for ^{15}N analysis were taken within the maize sampling area from three layers at depths of 0-15 cm, 15-30 cm, and 30-60 cm by an augur with 2.5 cm diameter at 5 points for each layer. Also, soil bulk-density samples were taken at each layer using the core method. The upper soil layer within the 1-m^2 area was removed before continuing to another layer. The soil composite samples were air dried at room temperature for one week and passed through a 2 mm sieve. Soil bulk samples were weighed before and after oven drying at 105 °C for 48 hours to constant weight.

Subsamples of the maize plant parts and "other weeds", and soil samples were taken for analysis to the Institute of Agricultural Chemistry at the University of Bonn. Recovered ^{15}N and total N were determined by mass spectrometer (ANCA-SL coupled to 20-20 stable isotope analyzer IRMS-PDZ Europa). The N derived from fertilizer and % recovery of ^{15}N in the plants and soil were estimated following the equation of Hardarson and Danso (1990).

3.4 Calculations

Soil bulk density

$$Bulk\ density\ (g\ cm^{-3}) = \frac{Dw_{(over\text{-}dry\ soil\ bulk)}}{V_{coresampler}}$$

Dry matter yield

1) Grain dry matter: $$GDM_{plot} = \frac{[DwG_{(ss)} / FwG_{(ss)}]\, x\ FwG_{(s)}}{Harvest\ area}\ x\ 10{,}000$$

$DwG_{(ss)}$ = Dry weight of grain subsamples

$FwG_{(ss)}$ = Fresh weight of grain subsamples

$FwG_{(s)}$ = Fresh weight of total grains sampled

2) Stover dry matter: $SDM_{plot} = (DwS_{(s)})/1000/B) \times POP$

$$Population\ density\ (POP) = \frac{nPlant}{Harvest\ area}$$

$(DwS_{(s)}) = [DwS_{(ss)} / FwS_{(ss)}] \times FwS_{(s)}$

$DwS_{(s)}$ = Dry weight of total stover biomass sample

$DwS_{(ss)}$ = Dry weight of stover subsamples

$FwS_{(ss)}$ = Fresh weight of stover subsamples

$FwS_{(s)}$ = Fresh weight of total stover sampled

B = Biomass sample size (e.g. 5 maize stands)

3) Leaves dry matter: $LDM_{plot} = (DwL_{(s)})/1000/B) \times POP$

$$Population\ density\ (POP) = \frac{nleaves/Plant \times nPlant}{Harvest\ area}$$

$DwL_{(s)}$ = Dry weight of total leaf biomass sample

B = Biomass sample size (e.g. 25 leaves)

4) *Imperata* dry matter: $IDM_{plot} = SDM_{plot} + RDM_{plot}$

SDM = shoots dry matter

RDM = rhizomes dry matter

5) "Other weeds" and mucuna dry matter yield were calculated from the oven-dried weight (Dw_{plot}) of the biomass

Harvest index

$$Maize\ harvest\ index:\ HI_{plot} = \frac{Grain\ DM_{plot}}{Total\ DM_{plot}}$$

Total nutrient (N, P, K and S) accumulation

$$UNu\ (kg\ ha^{-1}) = DM \times Nu/100$$

UNu = Nutrient uptake

DM = Dry matter yield of plant or plant parts sampled

Nu = % nutrient concentration (N, P, K and S) in the biomass

N_2 fixation

$$\%\ Ndfa = \left(1 - \frac{^{15}N\ WAE_{\ (mucuna)}}{^{15}N\ WAE_{\ (reference\ plant)}}\right) \times 100$$

$$N_2\ fixed\ (kg\ ha^{-1}) = \frac{\%\ Ndfa \times total\ N_{reference\ plant}\ (kg\ ha^{-1})}{100}$$

$$WAE_{\ (whole\ plant)} = \frac{[AE_{\ (a)} \times N_{total\ (a)} + [AE_{\ (b)} \times N_{total\ (b)}] + \ldots [AE_{\ (n)} \times N_{total\ (n)}]}{N_{total\ (a+b+\ldots n)}}$$

% Ndfa = percent nitrogen derived from air

WAE = weighted ^{15}N atom % excess

AE = ^{15}N atom % excess

a, b, …, n = plant parts

N_{total} = total N in parts

$$^{15}N\ atom\ \%\ excess\ in\ each\ plant\ part = {}^{15}N\ atom\ \%_{\ (plant\ part)} - 0.3663$$

$$N_{total\ (plant\ part)} = \%\ N_{\ (plant\ part)} \times Dw_{\ (plant\ part)}$$

$$Total\ N_{reference\ plant} = \sum_{a-n} (\%\ N_{plant\ parts} \times Dw_{plant\ parts})$$

$$DM_{plant\ yield} = \sum_{a-n} (Dw_{plant\ parts})$$

^{15}N Recovery

In plant system *(maize and weeds)*

$$\% \, Ndff_{(maize\ plant)} = \frac{^{15}N\ wae_{\ (maize\ plant)}}{^{15}Nae_{\ (fertilizer)}} \times 100$$

$$\% \, Ndff_{(weeds)} = \frac{^{15}Nae_{\ (weeds)}}{^{15}Nae_{\ (fertilizer)}} \times 100$$

$$\%^{15}Nae = \% \, ^{15}N\ atom - 0.3663$$

$$^{15}N\ recovered_{\ (kg\ ha^{-1})}\ (fertilizer\ N\ yield) = \frac{\% \, Ndff \times Total\ N_{\ (total\ plant\ yield\ kg\ ha^{-1})}}{100}$$

$$\% \, ^{15}N\ recovery = \frac{Fertilizer\ N\ yield}{Rate\ of\ fertilizer\ (^{15}N\ urea)\ applied} \times 100$$

In soil system *(at 3 depths: 0-15 cm, 15-30 cm, and 30-60 cm)*

$$\% \, Ndfs = \frac{^{15}Nae_{\ (soil)}}{^{15}Nae_{\ (fertilizer)}} \times 100$$

$$^{15}Nae_{\ (soil)} = \% \, ^{15}N\ atom_{\ (soil)} - 0.3663$$

$$^{15}N\ recovered_{\ (kg\ ha^{-1})}\ (soil\ N\ yield) = \frac{\% \, Ndfs \times soil\ N_{\ (kg\ ha^{-1})}}{100}$$

$$Soil\ N_{\ (kg\ ha^{-1})} = \% \, N_{\ (soil)} \times dry\ mass\ weight_{\ (soil\ kg\ ha^{-1})}$$

3.5 Data processing and statistical analysis

Data were analyzed using SPSS 12 software. Each data set variable was tested for normal distribution (Kolmogorov-Smirnov Z-test), and data that did not have normal distribution were transformed with square root or $\log_{10}$. The general linear model (GLM univariate) was used for analysis of variance of multi-observation data. Analysis of variance (ANOVA) of randomized complete block design was used to test the overall effects of the cultivation practices in fields according to degree of *Imperata* infestation, the analysis of variance of the split-plot design was used to test the effects of the superimposed land preparation and cropping strategies by field. The tukey means separation was used to test for comparison of significant effects between the three fields and three cropping strategies, and least significance difference (LSD) for the comparison of two fields and two land preparation practices. Mean value contrasts were set at the 95% confidence level. The T-statistic test was also used to differentiate the identified critical point (as the minimum critical nutrient concentration) to other nutrient concentration in maize biomass.

4 RESULTS AND DISCUSSION

4.1 *Imperata* response

4.1.1 *Imperata* dry matter production

***Imperata* regrowth in low-, medium-, and high-infested fields after intensive land preparation**

The first set of experiments comprised two subsequent maize cropping periods with intensive land preparation methods, either by deep hoeing or herbicide application, conducted before the first maize cropping, and followed by a shallow hoeing land preparation method for the second cropping period. During each maize cropping period, mineral (NPKS) fertilizers were applied or mucuna, which is nitrogen fixing cover crop, was relayed as cropping strategy superimposed to the land preparation to enhance soil fertility and at the same time to suppress *Imperata* and other weeds. Both treatments were compared with a control treatment (without mineral fertilizers applied or mucuna relayed following land preparation).

Before experimentation, the low-infested field had 69 shoots m^{-2} and 1.7 t ha^{-1} biomass, the medium-infested field had 178 shoots m^{-2} and 9.6 t ha^{-1} biomass, and the high-infested field had 312 shoots m^{-2} and 15.0 t ha^{-1} biomass. After two maize cropping periods, *Imperata* shoot counts and biomass drastically reduced in all three fields. In the low-infested field, *Imperata* counts reduced to 10 shoots m^{-2} after the first cropping period, and dropped further to 3 shoots m^{-2} after the second cropping period, while the biomass reduced to 0.1 t ha^{-1}. In the medium-infested field, *Imperata* counts reduced to 18 shoots m^{-2} after the first cropping period and to 4 shoots m^{-2} after the second cropping period, while biomass reduced to 0.2 t ha^{-1}. In the high-infested field, *Imperata* counts reduced to 25 shoots m^{-2} after the first cropping period and to 8 shoots m^{-2} after the second cropping period, while the biomass reduced to 0.1 t ha^{-1} (Table 4.1).

Deep hoeing (DH) and herbicide application (HA) as land preparation method were equally effective in eradicating the initial *Imperata* infestation in all fields (Table 4.2). The effect of mineral fertilizer application and mucuna relay as superimposed cropping strategies suppressed *Imperata* re-infestation after two maize cropping periods of experimentation (Table 4.3). *Imperata* biomass was highest in the control plots, where no cropping strategy was employed.

Table 4.1: *Imperata* density (shoots m^{-2}) and biomass (t ha^{-1}) before experimentation and after two maize cropping periods in fields categorized by the level of initial *Imperata* infestation as the low, medium and high-infested field

Sampling period	Field category Low	 Medium	 High
Before experimentation			
		[shoots m^{-2}]	
Imperata counts	69 a	178 b	312 c
Imperata biomass		[t ha^{-1}]	
Total DM	1.7 a	9.6 b	14.9 c
Shoots	0.6 a	3.8 b	8.2 c
Rhizomes	1.1 a	5.8 b	6.7 b
After two maize cropping periods			
		[shoots m^{-2}]	
Imperata counts after 1^{st} cropping period	10 a	18 ab	25 b
Imperata counts after 2^{nd} cropping period*	3 a	4 ab	8 b
		[t ha-1]	
Imperata biomass after 2^{nd} cropping period	0.1 ns	0.2 ns	0.1 ns

*Tukey test (p<0.05): Letters a, b, c denote significant difference, ns denotes no significant difference between fields; mean values (n=18); * = data transformed (SQT+1)*

Table 4.2: *Imperata* density (shoots m^{-2}) and biomass (t ha^{-1}) after two maize cropping periods in the low, medium and high-infested fields as affected by land preparation methods

Imperata density and biomass	Field category Low		Medium		High	
	DH	HA	DH	HA	DH	HA
			[shoots m^{-2}]			
Imperata counts after first cropping period	11 ns	10 ns	17 ns	20 ns	18 ns	32 ns
Imperata counts after second cropping period	2 ns*	3 ns*	2 ns	6 ns	8 ns	9 ns
			[t ha^{-1}]			
Imperata biomass second cropping period	0.1 ns	0.1 ns	0.2 ns	0.2 ns	0.1 ns	0.1 ns

*Least Significant Difference test (p<0.05): ns denotes no significant difference between land preparation method within field category; mean values (n=3); * = data transformed (SQT+1)*
DH = deep hoeing, HA = herbicide application

Table 4.3: *Imperata* density (shoots m^{-2}) and biomass (t ha^{-1}) after two maize cropping periods in the low, medium and high-infested fields as affected by superimposed cropping strategies

Imperata density and biomass	Field category								
	Low			Medium			High		
	F	M	C	F	M	C	F	M	C
	[shoots m^{-2}]								
Imperata counts after 1st cropping period	7 ns	9 ns	16 ns	19 ns	16 ns	20 ns	37 ns	17 ns	22 ns
Imperata counts after 2nd cropping period [shoots m^{-2}]	1 ns*	1 ns*	6 ns*	5 ns	2 ns	5 ns	12 ns*	7 ns*	6 ns*
	[t ha^{-1}]								
Imperata biomass after 2nd cropping period	0.03 a	0.1 ab	0.2 b	0.1 a	0.1 a	0.4 b	0.1 a	0.1 a	0.2 b

*Tukey test (p<0.05): Letters a, b, c denote significant difference, ns denotes no significant difference between cropping strategies within field category; mean values (n=6); * = data transformed (SQT+1); since there was no significant difference of the two land preparation methods, data were combined*
F = fertilizer, M = mucuna, C = control

Imperata regrowth in low- and high-infested fields after minimum tillage

The second set of experiments was conducted parallel to the second maize cropping period of the first set of experiments to test the effect of minimum tillage by shallow hoeing as a land preparation method. The experiment involved the same superimposed cropping strategies: with mineral fertilizers, with mucuna relay, and without both as control. The experiment was set up within the same two fields categorized as low-level and high-level *Imperata*-infested fields for contrast. The effects were measured after one maize cropping period.

Before experimentation, the low-infested field had 38 shoots m^{-2} and biomass of 3.1 t ha^{-1} while the high-infested field had 286 shoots m^{-2} and biomass of 6.8 t ha^{-1}. After one maize cropping period, *Imperata* significantly ($p<0.05$) decreased in the low-infested field but still remained high in the high-infested field. On average, *Imperata* density reduced by a factor of 4 in the low-infested field and only by a factor of 2 in the high-infested field, while biomass dropped by a factor of 18 and 5, respectively (Table 4.4).

Table 4.4: *Imperata* density (shoots m^{-2}) and biomass (t ha^{-1}) before experimentation and after one maize cropping period in fields categorized by the level of initial *Imperata* infestation as the low and high-infested field

Sampling period	Field category	
	Low	High
Before experimentation		
	[shoots m^{-2}]	
Imperata counts	38 a	286 b
	[t ha^{-1}]	
Imperata biomass		
Total DM	3.1 a	6.8 b
Shoots	1.9 a	2.8 b
Rhizomes	1.2 a	4.0 b
After one cropping period		
	[shoots m^{-2}]	
Imperata counts	9 a	137 b
	[t ha^{-1}]	
Imperata biomass	0.2 a	1.4 b

Least Significant Difference test (p<0.05): Letters a, b denote significant difference between field; mean values (n=9)

Shallow hoeing as a land preparation method was only effective in eradicating *Imperata* in field with low-infestation but not with high-infestation, while the superimposed cropping strategies showed no significant influence after one cropping period in both fields (Table 4.5).

Table 4.5: *Imperata* density (shoots m^{-2}) and biomass (t ha^{-1}) after one maize cropping period in the low and high-infested fields as affected by superimposed cropping strategies

Imperata density and biomass	Field category					
	Low			High		
	F	M	C	F	M	C
	[shoots m^{-2}]					
Imperata counts after one maize cropping period	6 ns	6 ns	15 ns	135 ns	105 ns	172 ns
	[t ha^{-1}]					
Imperata biomass after one maize cropping period	0.1 ns	0.2 ns	0.3 ns	0.9 ns	1.1 ns	2.0 ns

Tukey test (p<0.05): ns denotes no significant difference between cropping strategies within field category; mean vaues (n=3); F = fertilizer, M = mucuna, C = control

4.1.2 Nutrient levels in *Imperata* dry matter

Nutrient content in *Imperata* dry matter in the low-, medium-, and high-infested fields

The uptake of nutrients by *Imperata* was largely determined by the dry matter (DM) yield. Before experimentation, N, P, K and S accumulation of *Imperata* was lower in low-infested field than in the medium- and high-infested fields. *Imperata* N (83.9 kg ha^{-1}) and K (86.6 kg ha^{-1}) accumulation was highest in the medium-infested field, whereas P accumulation (13.1 kg ha^{-1}) was highest in the high-infested field. *Imperata* S accumulation was the same both in the medium-infested and high-infested fields. However, the nutrient concentrations in the *Imperata* biomass were lowest in the high-infested field, except for P, which was not significantly different in the other two fields. *Imperata* N, K and S concentrations were significantly higher both in the low- and medium-infested fields. Particularly, the K concentration (0.92 %) was high in the medium-infested field.

Aboveground (shoots), the nutrient concentrations in the *Imperata* were consistently highest in the medium-infested field, particularly N, K and S, while P concentrations in the three fields were not significantly different. But between in the low- and high-infested fields, N, P and K concentrations in the shoots were higher in the low-infested field than in the high-infested field, while S concentrations were the same in both fields.

Belowground (rhizomes), K concentration (0.68 %) was also highest in the medium-infested field, while N concentration (0.89 %) was highest in the low-infested field. *Imperata* S concentration was higher in the medium-infested field but the same in the low- and high-infested fields. However, P concentrations were not significantly different between the three fields. This suggests that available P utilized by *Imperata* was not significantly different between the three fields. Available K was highest in the medium-infested field but lowest in the high-infested field. Also, N and S levels were lower in the high-infested field but higher both in the low- and medium-infested fields (Table 4.6).

Table 4.6: Content of N, P, K and S in *Imperata* dry matter (shoots and rhizomes) before maize cropping in the low, medium and high-infested fields

Nutrient content	Field category					
	Low	Medium	High	Low	Medium	High
	Uptake [kg ha^{-1}]			Concentration [%]		
Total DM						
N	16.6 a	83.9 c	64.4 b	0.96 b	0.90 b	0.43 a
P	1.5 a	9.3 b	13.1 c	0.09 ns	0.10 ns	0.09 ns
K	11.4 a	86.6 c	55.2 b	0.72 b	0.92 c	0.36 a
S	1.7 a	10.6 b	8.8 b	0.10 b	0.12 b	0.06 a
Shoots DM						
N	6.3 a	46.7 c	35.9 b	1.06 b	1.26 c	0.44 a
P	0.6 a	4.1 b	6.6 c	0.10 b	0.11 b	0.08 a
K	5.7 a	46.7 c	31.5 b	0.98 b	1.26 c	0.38 a
S	0.5 a	5.0 b	5.9 b	0.09 a	0.14 b	0.07 a
Rhizomes DM						
N	10.3 a	37.2 c	28.5 b	0.89 c	0.66 b	0.42 a
P	0.9 a	5.2 b	6.5 b	0.08 ns	0.09 ns	0.09 ns
K	5.7 a	40.0 c	23.7 b	0.55 b	0.68 c	0.34 a
S	1.2 a	5.7 c	2.9 b	0.11 b	0.10 b	0.04 a

Tukey test ($p<0.05$): Letters a, b, c denote significant difference, ns denotes no significant difference between field; mean values (n=18)

The concentrations of nutrients in the *Imperata* biomass were lower when they were limited in the soil. The rhizomes particularly maintain a level of P in the biomass to support the shoots irrespective of the DM production, however the larger the shoots DM the lower the P concentrations in the biomass. The analysis of the soil before experimentation (section 3.1.2.-Table 3.4 and 3.5) show that available P was higher in the high-infested field, which suggests that *Imperata* infestations is not driven by a lack of P. But, the total N and S in the high-infested field was significantly lower compared to the low- and high-infested fields. Although exchangeable K shows no significant differences between fields, the cation exchange capacity (CEC) in the high-infested field was significantly lower.

These accumulated nutrients in the shoot biomass were removed when aboveground *Imperata* biomass was slashed prior to maize cropping. However, the nutrients in the rhizome biomass remained in the fields. After slashing, all fields were left undisturbed to allow *Imperata* to resprout to about 15 cm height before the land preparation treatment.

After two cropping periods, *Imperata* density was significantly higher in the high-infested field, although there was no significant difference in the *Imperata* biomass between the three fields. Likewise, N, P, and S contents in the *Imperata* total DM after the second cropping period were not significantly different in all fields (Table 4.7). However, K (1.9 kg ha^{-1}, 0.85 %) content in *Imperata* in the medium-infested field was significantly higher than in the low- and high-infested fields. This demonstrates that indeed there was higher amount of K supply in the medium-infested field compared to the other two fields since *Imperata* extracted a higher level of K in this field.

Table 4.7: Content of N, P, K and S in total *Imperata* dry matter after two maize cropping periods the low, medium and high-infested fields

Nutrient content	Field category					
	Low	Medium	High	Low	Medium	High
	Uptake [kg ha^{-1}]			Concentration [%]		
N	1.0 ns	2.0 ns	1.2 ns	0.62 ns	0.99 ns	0.98 ns
P	0.1 ns	0.2 ns	0.1 ns	0.08 ns	0.11 ns	0.11 ns
K	0.7 a	1.9 b	0.5 a	0.46 a	0.85 b	0.51 a
S	0.1 ns	0.3 ns	0.1 ns	0.09 ns	0.13 ns	0.09 ns

Tukey test ($p<0.05$): Letters a, b, c denote significant difference, ns denotes no significant difference between fields; mean values (n=18)

Comparing *Imperata* nutrient concentrations before (Table 4.6) and after (Table 4.7) experimentation, extraction of nutrients of *Imperata* in the low-infested field decreased. Thus, the N, K and S supply in the low-infested field reduced after two maize cropping periods. In the medium-infested field, all nutrients in the *Imperata* still remained high, and most particularly K. In the high-infested field, K and S remained low and P was still high, while N increased.

In the control, without fertilizer or mucuna as superimposed cropping strategies, *Imperata* biomass and its nutrient accumulation were highest in all three fields, although the concentrations in the biomass were not significantly different whether with or without any superimposed cropping strategy (Table 4.8).

Table 4.8: Content of N, P, K and S in *Imperata* dry matter after two maize cropping periods in the low, medium and high-infested fields as affected by superimposed cropping strategies

Nutrient content	Cropping strategy					
	F	M	C	F	M	C
	Uptake [kg ha^{-1}]			Concentration [%]		
Low						
N	0.3 ns	0.8 ns	1.9 ns	0.52 ns	0.55 ns	0.80 ns
P	0.04 a	0.1 ab	0.2 b	0.06 ns	0.06 ns	0.12 ns
K	0.3 ns	0.5 ns	1.0 ns	0.35 ns	0.43 ns	0.59 ns
S	0.1 ns	0.1 ns	0.3 ns	0.09 ns	0.07 ns	0.11 ns
Medium						
N	0.9 a	1.0 a	4.1 b	1.06 ns	0.99 ns	0.92 ns
P	0.1 a	0.1 a	0.5 b	0.13 ns	0.09 ns	0.11 ns
K	0.6 a	0.8 a	3.9 b	0.78 ns	0.80 ns	0.96 ns
S	0.1 ns	0.1 ns	0.6 ns	0.16 ns	0.12 ns	0.12 ns
High						
N	0.8 a	0.8 a	1.9 b	1.02 ns	0.93 ns	0.98 ns
P	0.1 a	0.1 a	0.2 b	0.14 ns	0.09 ns	0.11 ns
K	0.5 ab	0.2 a	0.7 b	0.64 ns	0.37 ns	0.52 ns
S	0.1 ns	0.1 ns	0.1 ns	0.12 ns	0.07 ns	0.08 ns

Tukey test ($p<0.05$): Letters a, b, c denote significant difference, ns denotes no significant difference between cropping strategies within field category; mean values (n=6), data of the two land preparation methods were combined since there was no significant difference
F = fertilizer, M = mucuna, C = control

The results confirm the general observations that *Imperata* can establish even at low fertility. *Imperata* with already established rhizomes is highly competitive with strong ability to extract nutrients from poor soils conditions (Jagoe, 1938; Eussen and Soerjani, 1975; Boonitee and Ritdhit, 1984; Santoso et al 1997). *Imperata* effectively utilized available nutrients from the soil to support its growth and biomass production. On the other hand, when the growth of the re-infesting *Imperata* has not established its rhizomes yet, and the growth of primary crop has already take off by the addition of nutrients, *Imperata* may not significantly benefit from the applied mineral fertilizers and from the nutrients contributed by the mulch of the relayed mucuna. Without soil fertility enhancement, the growth of the primary crop was poor (Santoso et. al., 1997; Chikoye et al., 2000). The regrowing *Imperata* can compete out the crop for the nutrients, and thus, re-infestation was high. This was demonstrated by the significantly higher *Imperata* biomass in the control plots of the three fields. The growth and dominance of

Imperata intensified with the stunted growth of maize crop. Maize DM production potential slowed without the enhanced nutrition from the fertilizer inputs, and aggravated by the interference and competition of *Imperata*. As demonstrated, *Imperata* P accumulation in the low-infested field was higher, and likewise N, P, K accumulation both in the medium-and high-infested fields without mineral fertilizers or mucuna relay.

Nutrient content in *Imperata* dry matter in the low- and high-infested fields

The second set of experiments also show that before maize cropping (Table 4.9), the higher *Imperata* total DM in the high-infested field accumulated more P (6.9 kg ha^{-1}) and K (40.6 kg ha^{-1}) than in the low-infested field, while there was no significant differences in N and S accumulation between fields. However, the concentrations of N (0.51 %), K (0.53%) and S (0.10 %) in the high-infested field were lower than in the low-infested field, while P concentrations were the same in both fields. In the high-infested field, P (0.11 %) and K (0.60 %) concentrations in the rhizomes were higher, while N, P, K and S concentrations in the shoots were lower.

Like in the first set of experiments, the aboveground *Imperata* biomass from the two fields were slashed and removed, taking out similar quantities of accumulated N, P, and K but the S removed from the low-infested field (4.2 kg ha^{-1}) was twice as high as that in the high-infested field (2.2 kg ha^{-1}). However, the amount of nutrients stocked in the rhizomes and remained in the soil was much higher in the high-infested field than in the low-infested field.

Shallow hoeing as land preparation method was not effective in eliminating the initial *Imperata* infestation in the high-infested field, and most especially the rhizomes system. After one-maize cropping period, there was massive *Imperata* regrowth in the high-infested field (Table 4.10). Although the total biomass and accumulated nutrients reduced, the nutrient concentrations in the biomass remained high. This was attributed to the nutrient reserved which was stocked in the undestroyed rhizomes.

Further, with fertilizer application, K and S concentrations were significantly higher (Table 4.11). Particularly, the N, K and S concentrations were significantly higher in the shoots, while there was no significant difference of the nutrient concentrations in the rhizomes, irrespective of the cropping strategies (Table 12).

However, effective transfer of nutrients from belowground (rhizomes) to the aboveground (shoots) took place. With fertilizer application, N (1.17 %), K (0.99 %) and S (0.29 %) concentrations in the resprouted shoots were very high.

Table 4.9: Content of N, P, K and S in *Imperata* dry matter (shoots and rhizomes) before maize cropping in the low and high-infested fields

Nutrient content	Field category			
	Low	High	Low	High
	Uptake [kg ha^{-1}]		Concentration [%]	
Total DM				
N	29.5 ns	33.4 ns	0.95 b	0.51 a
P	3.4 a	6.9 b	0.11 ns	0.11 ns
K	25.9 a	40.6 b	0.79 b	0.53 a
S	6.1 ns	6.8 ns	0.19 b	0.10 a
Shoots DM				
N	20.1 ns	17.3 ns	1.08 b	0.65 a
P	2.4 ns	2.7 ns	0.13 b	0.10 a
K	20.6 ns	17 ns	1.03 b	0.65 a
S	4.2 b	2.2 a	0.22 b	0.08 a
Rhizomes DM				
N	9.4 a	16.1 b	0.75 b	0.42 a
P	1.0 a	4.2 b	0.08 a	0.11 b
K	5.3 a	23.6 b	0.42 a	0.60 b
S	1.9 a	4.6 b	0.15 b	0.12 a

Least Significant Difference test (p<0.05): Letters a, b denote significant difference, ns denotes no significant difference between fields; mean values (n=9)

Table 4.10: Content of N, P, K and S in total *Imperata* dry matter after one maize cropping period in the low and high-infested fields

Nutrient content	Field category			
	Low	High	Low	High
	Uptake [kg ha^{-1}]		Concentration [%]	
N	1.8 a	9.8 b	0.91 ns	0.77 ns
P	0.2 a	1.8 b	0.12 ns	0.14 ns
K	1.0 a	9.7 b	0.59 ns	0.71 ns
S	0.2 a	2.4 b	0.08 a	0.19 b

Least Significant Difference test (p<0.05): Letters a, b denote significant difference, ns denotes no significant difference between fields; mean values (n=9)

Table 4.11: Content of N, P, K and S in *Imperata* dry matter after one maize cropping period in the low and high-infested fields as affected by superimposed cropping strategies

Nutrient content	Cropping strategy					
	F	M	C	F	M	C
	Uptake [kg ha^{-1}]			Concentration [%]		
Low						
N	0.7 ns	1.9 ns	2.7 ns	0.72 ns	0.98 ns	1.04 ns
P	0.1 ns	0.3 ns	0.3 ns	0.07 ns	0.15 ns	0.14 ns
K	0.3 a	1.4 b	1.1 ab	0.39 ns	0.88 ns	0.51 ns
S	0.1 ns	0.2 ns	0.2 ns	0.08 ns	0.08 ns	0.09 ns
High						
N	7.1 ns	8.2 ns	14.0 ns	0.88 ns	0.71 ns	0.72 ns
P	1.4 ns	1.6 ns	2.6 ns	0.16 ns	0.13 ns	0.13 ns
K	7.6 ns	7.3 ns	14.0 ns	0.83 b	0.64 a	0.67 ab
S	2.1 ns	2.0 ns	3.2 ns	0.25 b	0.16 a	0.17 a

Tukey test ($p<0.05$): Letters a, b denote significant difference, ns denotes no significant difference between cropping strategies within field category; mean values (n=3); F = fertilizer, M = mucuna, C = control

Table 4.12: Concentration [%] of N, P, K and S in *Imperata* shoots and rhizomes in the high-infested field as affected by superimposed cropping strategies

Nutrient content	Cropping strategy		
	F	M	C
	Concentration [%]		
Shoots			
N	1.17 b	0.84 a	0.82 a
P	0.16 ns	0.12 ns	0.12 ns
K	0.99 b	0.67 a	0.69 a
S	0.29 b	0.16 a	0.17 a
Rhizomes			
N	0.62 ns	0.59 ns	0.64 ns
P	0.16 ns	0.15 ns	0.13 ns
K	0.74 ns	0.61 ns	0.64 ns
S	0.20 ns	0.16 ns	0.16 ns

Tukey test ($p<0.05$): Letters a, b denote significant difference, ns denotes no significant difference between cropping strategies; mean values (n=3); F = fertilizer, M = mucuna, C = control

The *Imperata* response from the two sets of experiments, as measured by density and biomass, show that as land preparation method to control *Imperata*, deep hoeing and herbicide application were equally effective even in field with high-*Imperata* infestation, while shallow hoeing was only effective in field with low-

Imperata infestation. However, even with the effective elimination *Imperata* during land preparation, without fertilizer application or mucuna relay as superimposed cropping strategy during maize cropping, there was high *Imperata* re-infestation in all fields.

The results from the experiments show that the application of mineral fertilizers and relaying of mucuna to the maize crop had indirect suppressive effect to *Imperata* re-infestation after two maize cropping periods, as demonstrated in the first set of experiments. However, the indirect suppressive effect of both cropping strategies may not be achieved when the initial *Imperata* infestation in the fields was not effectively controlled prior to maize cropping.

When initial *Imperata* infestation is not eliminated during land preparation, and when rhizomes are not destroyed, regeneration is high since the shoots regrow from undisturbed rhizomes that remain dormant and viable because of the carbohydrate reserves (Ivens, 1975; Chikoye, 2005). There was also an effective transfer of nutrients from rhizomes to the shoots thus enabling the weed to produce large leaf biomass, which is highly flammable especially during dry season (Macdonald, 2004; Chikoye, 2005).

Generally, nutrient accumulated in *Imperata* was largely determined by its dry matter production. The result demonstrate that a large quantity of *Imperata* biomass in the field also accumulated large amounts of nutrients, but the concentration in the biomass corresponds to measure of availability of such nutrients in the soil, except for P. The non-significant difference of P concentration in the *Imperata* biomass in all fields, indicate that *Imperata* is indeed highly competitive in taking up P from the soil even at early growth and establishment. However, this nutrient had not yet been depleted or P was still stocked in the rhizomes and in soil system, especially in the study fields with high infestation. This suggests that P limitation in the field may not be the prime problem at an early stage of *Imperata* invasion unlike in other studies, where a P deficiency was reported in *Imperata* areas (Chikoye et al., 1999). Von Uexküll and Muter (1995) reported that P was the most limiting nutrient when reclaiming *Imperata* invaded areas for cultivation. In many instances, soils with *Imperata* are low in available P (Santoso et al. 1997).

The newly growing *Imperata* may not benefit from the applied mineral fertilizers and mucuna relay, especially when there is efficient use of the added nutrients by the maize crop. When the maize growth is enhanced, it becomes more competitive thereby suppressing *Imperata* growth. According to Ayeni and Duke (1985) young *Imperata* with newly formed tissue, does not able to produce new shoots. The young rhizomes do not have roots, which are necessary for accumulation nutrients, enzymes and other growth substances. They found that regenerative capacity of *Imperata* increased in older and more mature rhizomes (MacDonald, 2004).

4.2 Response of weeds other than *Imperata*

4.2.1 Other weeds dry matter production

Other weeds growth in low-, medium-, and high-infested fields after intensive land preparation

The elimination of initial *Imperata* infestation in all fields during land preparation did not change the weed pressure but rather paved way for the growth of other weeds. At weeding in the first maize cropping period (60 DAS of maize), the level of other weeds growing in each field followed the ranking of the initial *Imperata* infestation in the fields. The medium- and high-infested fields had high levels of growth of other weeds. At weeding in the second maize cropping period (60 DAS), the condition was reversed. Other weeds growth was more vigorous in the low-infested field than in the medium- and high-infested fields, which in the latter two fields showing no significant difference. However, after harvest in each maize cropping period (150 DAS), the growth of other weeds in all three fields was not significantly different. Overall, the DM of other weeds for two cropping periods suggest that after eradicating *Imperata*, the potential of other weeds growth in the fields even with different levels of initial *Imperata* infestation were the same (Table 4.13).

Table 4.13: Dry matter of weeds other than *Imperata* in fields categorized by the level of initial *Imperata* infestation as low, medium, and high-infested field.

Sampling period	Field category		
	Low	Medium	High
	Other weeds DM [t ha^{-1}]		
1st maize cropping period			
At weeding (60 DAS)	0.7a	1.6 b	1.4 b
After maize harvest (150 DAS)	2.2 ns	2.0 ns	1.5 ns
2nd maize cropping period			
At weeding (60 DAS)	2.2 b	1.7 a	1.4 a
After maize harvest (150 DAS)	1.0 ns	1.0 ns	0.9 ns
Total =	6.1 ns	6.3 ns	5.2 ns

Tukey test (p<0.05): Letters a, b denote significant difference, ns denotes no significant difference between fields; mean values (n=18); DAS = days after seeding of maize

The two methods of land preparation (deep hoeing and herbicide application) showed no difference in affecting other weeds growth in the medium-infested field. However, the direct residual effect of herbicide application resulted in reduced growth of other weeds (60 DAS) in the low-infested field. Deep hoeing resulted in reduced growth of other weeds (after maize first harvest) in the high-infested field during the first maize cropping period. However, the overall DM of other weeds for the two cropping periods suggests that there was no difference between deep hoeing and herbicide application (Table 4.14). The two methods of land preparation to control *Imperata* effected similar response in influencing other weeds growth in all fields after eradicating initial *Imperata* infestation.

Table 4.14: Dry matter of weeds other than *Imperata* in the low, medium, and high-infested fields as affected by the type of land preparation methods

Sampling period	Low		Medium		High	
	DH	HA	DH	HA	DH	HA
	Other weeds DM [t ha^{-1}]					
1st maize cropping period						
At weeding (60 DAS)	0.9 b	0.5 a	1.5 ns	1.7 ns	1.2 ns	1.5 ns
After maize harvest (150 DAS)	2.4 ns	2.0 ns	2.0 ns	2.0 ns	1.2 a	1.8 b
2nd maize cropping period						
At weeding (60 DAS)	2.4 ns	2.1 ns	1.7 ns	1.7 ns	1.6 b	1.2 a
After maize harvest (150 DAS)	1.0 ns	0.9 ns	1.0 ns	1.0 ns	0.7 ns	1.1ns
Total =	6.7 ns	5.5 ns	6.2 ns	6.4 ns	4.7 ns	5.6 ns

Least Significant Difference test ($p<0.05$): Letters a, b denote significant difference, ns denotes no significant difference between land preparation methods within field category; mean values (n=3)
DH = deep hoeing, HA = herbicide application; DAS = days after seeding of maize

At the end of the first maize cropping period, fertilizer application enhanced the growth of other weeds in the low-infested field, mucuna suppressed other weeds growth in the medium-infested field, and both cropping strategies reduced other weeds growth in the high-infested field. At the end of the second cropping period, both cropping strategies were equally effective in suppressing other weeds in all fields compared to the control, which was without fertilizer or mucuna (Table 4.15).

Table 4.15: Dry matter of weeds other than *Imperata* in the low, medium, and high-infested fields as affected the superimposed cropping strategies

Sampling period	Field category								
	Low			Medium			High		
	F	M	C	F	M	C	F	M	C
	Other weeds DM [t ha^{-1}]								
1st maize cropping period									
At weeding (60 DAS)	0.6 ns	0.6 ns	0.8 ns	1.6 ns	1.6 ns	1.7 ns	1.2 ns	1.5 ns	1.4 ns
After maize harvest (150 DAS)	3.5 c	0.9 a	2.2 b	2.3 b	0.7 a	2.9 b	1.4 a	0.9 a	2.2 b
2nd maize cropping period									
At weeding (60 DAS)	2.3 ns	2.1 ns	2.3 ns	1.6 ab	2.1 b	1.3 a	1.6 ns	1.4 ns	1.2 ns
After maize harvest (150 DAS)	0.6 a	0.9 a	1.3 b	0.6 a	0.8 a	1.7 b	0.6 a	0.8 a	1.5 b

Tukey test (p<0.05): Letters a, b, c denote significant difference, ns denotes no significant difference between cropping strategies within field category; mean values (n=6), data of the two land preparation methods were combined since there was no significant difference
F = fertilizer, M = mucuna, C = control; DAS = days after seeding of maize

Other weeds growth in low- and high-infested fields after minimum tillage

Following shallow hoeing and after one-maize cropping period, growth of other weeds in the low-infested field was significantly higher than in the high-infested field. At weeding of the first cropping period (60 DAS of maize), other weeds DM in the low-infested field was 3-fold higher than in the high-infested field. It decreased at the end of the maize cropping period, but was still significantly higher than in the high-infested field (Table 4.16).

Table 4.16: Dry matter of weeds other than *Imperata* in fields categorized by the level of initial *Imperata* infestation as low and high-infested fields

Sampling period	Field category	
	Low	High
	Other weeds DM [t ha^{-1}]	
During one maize cropping period		
At weeding (60 DAS)	1.6 b	0.4 a
After maize harvest (150 DAS)	0.8 b	0.4 a
Total =	2.4 b	0.8 a

Least Significant Difference test (p<0.05): Letters a, b denote significant difference between fields
Mean values (n=9)

With only one cropping period and following shallow hoeing, the effect of fertilizer application and mucuna relay on other weeds growth did not show a significant effect in the low-infested field. However, fertilizer application enhanced other weeds growth in the high-infested field during the early stage of the maize cropping period (60 DAS). But, at the end of the cropping period (150 DAS), other weeds DM with and without any cropping strategy was not significantly different in both fields (Table 4.17). The low growth and DM production of other weeds in the high-infested field could be explained by the competition from the high and dense re-growing *Imperata*, which was not eradicated by shallow hoeing during land preparation.

Table 4.17: Dry matter of weeds other than *Imperata* in the low and high-infested fields as affected the superimposed cropping strategies

Sampling period	Field category					
	Low			High		
	F	M	C	F	M	C
	Other weeds DM [t ha^{-1}]					
During one maize cropping period						
At weeding (60 DAS)	1.2 ns	1.6 ns	2.2 ns	0.6 b	0.3 a	0.4 a
After maize harvest (150 DAS)	0.5 ns	0.8 ns	1.1 ns	0.4 ns	0.3 ns	0.5 ns

Tukey test (p<0.05): Letters a, b, c denote significant difference, ns denotes no significant difference between cropping strategies within field category; mean value (n=3)
F = fertilizer, M = mucuna, C = control; DAS = days after seeding of maize

4.2.2 Nutrient levels in weeds other than *Imperata*

Nutrient content in other weeds dry matter in the low-, medium-, and high-infested fields

Comparing the average nutrient accumulation in weeds other than *Imperata* in the three fields, at weeding in the first maize cropping period (60 DAS), other weeds in the low-infested field with lower DM (0.7 t ha^{-1}), also accumulated a lower amount of nutrients. In the medium- and high-infested fields, accumulated nutrients were higher, especially P and K. In all fields and at early stage in maize cropping period (before 60 DAS), the cropping strategies had no significant effect on other weeds nutrient accumulation (Table 4.18). However, K and S concentrations in the other weeds biomass in all fields were significantly higher with fertilizer application, and particularly in the medium-infested field, even in the control, K (2.49 %) concentration was high

Table 4.18: Content of N, P, K and S in weeds other than *Imperata* at weeding (60 DAS) during first maize cropping period in the low, medium and high-infested fields as affected by the superimposed cropping strategies

Nutrient content	Average nutrient uptake	Cropping strategy					
		F	M	C	F	M	C
	[kg ha^{-1}]	Uptake [kg ha^{-1}]			Concentration [%]		
Nitrogen (N)							
Low	a 20.5	19.4 ns	19.3 ns	22.7 ns	3.45 ns	3.16 ns	2.97 ns
Medium	b 32.3	35.0 ns	30.3 ns	31.7 ns	2.30 ns	1.93 ns	1.95 ns
High	ab 24.3	24.1 ns	24.7 ns	24.1 ns	2.26 b	1.71 a	1.81 a
Phosphorous (P)							
Low	a 1.2	1.1 ns	1.2 ns	1.4 ns	0.19 ns	0.19 ns	0.19 ns
Medium	b 3.4	3.2 ns	3.2 ns	3.6 ns	0.20 ns	0.20 ns	0.20 ns
High	b 2.9	2.8 ns	3.0 ns	3.1 ns	0.23 ns	0.20 ns	0.21 ns
Potassium (K)							
Low	a 16.1	15.5 ns	15.3 ns	17.5 ns	2.74 b	2.50 ab	2.11 a
Medium	b 36.4	37.0 ns	30.5 ns	41.6 ns	2.36 ab	1.97 a	2.49 b
High	b 20.6	21.2 ns	18.0 ns	22.8 ns	1.87 b	1.26 a	1.57 ab
Sulfur (S)							
Low	a 1.6	1.6 ns	1.4 ns	1.6 ns	0.28 b	0.23 ab	0.21 a
Medium	b 2.9	3.6 ns	2.6 ns	2.6 ns	0.22 b	0.17 a	0.17 a
High	ab 2.6	3.4 ns	2.3 ns	2.1 ns	0.29 b	0.16 a	0.15 a

Tukey test ($p<0.05$): Letters a, b, c denote significant difference, ns denotes no significant difference between cropping strategies, mean values (n=6) and between fields, mean values (n=18)
F = fertilizer, M = mucuna, C = control

After harvest (150 DAS) of the first maize cropping period, the average nutrient accumulation (except for S, which was not significantly different in all fields) in other weeds both in the low- and medium-infested fields was significantly higher than in the high-infested field. Nutrient accumulation of other weeds in all fields was significantly higher with fertilizer application, except for N (25.0 kg ha^{-1}) in the high-infested field (Table 4.19). However, with mucuna relay, nutrient accumulation in other weeds was significantly lower in all fields. But, the concentrations in the biomass were significantly higher, especially in the low-infested field.

Table 4.19: Content of N, P, K and S in weeds other than *Imperata* after harvest (150 DAS) in the first maize cropping period in the low, medium and high-infested fields as affected by the superimposed cropping strategies

Nutrient content	Average nutrient uptake	Cropping strategy					
		F	M	C	F	M	C
	[kg ha^{-1}]	Uptake [kg ha^{-1}]			Concentration [%]		
Nitrogen (N)							
Low	b 40.8	58.4 b	25.0 a	39.2 a	1.65 a	2.87 b	1.79 a
Medium	ab 37.9	46.9 b	17.9 a	49.0 b	2.03 ab	2.40 b	1.78 a
High	a 25.6	25.0 a	16.1 a	35.7 b	1.92 ns	1.94 ns	1.63 ns
Phosphorous (P)							
Low	ab 4.6	6.6 b	2.3 a	4.8 b	0.19 a	0.26 b	0.22 a
Medium	b 4.8	5.8 b	2.1 a	6.4 b	0.25 ns	0.28 ns	0.23 ns
High	a 3.0	3.4 b	1.8 a	3.9 b	0.27 ns	0.22 ns	0.18 ns
Potassium (K)							
Low	b 43.6	63.6 b	30.0 a	37.3 a	1.79 a	3.24 b	1.56 a
Medium	b 38.7	42.9 b	19.4 a	53.8 b	1.84 a	2.61 b	1.96 a
High	a 19.7	21.9 b	12.3 a	25.1 b	1.70 ns	1.46 ns	1.17 ns
Sulfur (S)							
Low	ns 5.4	8.4 c	2.6 a	5.3 b	0.24 a	0.28 b	0.24 a
Medium	ns 5.2	7.1 b	1.8 a	6.6 b	0.31 ns	0.25 ns	0.24 ns
High	ns 3.7	4.4 b	1.7 a	4.8 b	0.33 b	0.20 a	0.22 a

Tukey test ($p<0.05$): Letters a, b, c denote significant difference, ns denotes no significant difference between cropping strategies, mean values (n=6) and between fields, mean values (n=18)
F = fertilizer, M = mucuna, C = control

At weeding (60 DAS) in the second maize cropping period, average nutrient accumulation in other weeds in the low-infested field still remained significantly higher. But, lower both in the medium- and high-infested fields, except K (45.4 kg ha^{-1}) accumulation in the medium-infested field, which was also significantly higher. There was no significant effect of the cropping strategies on other weeds nutrient accumulation in the low-infested field, although N (3.12 %) and S (0.26 %) concentrations were significantly higher with fertilizer application. In the medium-infested field, N (43.3 kg ha^{-1}, 2.67 %) and S (4.0 kg ha^{-1}, 0.25 %) content in the biomass were significantly higher with fertilizer application, while N (44.2 kg ha^{-1}) and K (55.6 kg ha^{-1}) accumulation with mucuna relay was also higher but with low nutrient concentrations. In the high-infested field, nutrient contents in other weeds biomass were significantly higher with fertilizer application, and only N accumulation was significantly higher with mucuna relay (Table 4.20).

Table 4.20: Content of N, P, K and S in weeds other than *Imperata* at weeding (60 DAS) during second maize cropping period in the low, medium and high-infested fields as affected by the superimposed cropping strategies

Nutrient content	Average nutrient uptake	Cropping strategy					
		F	M	C	F	M	C
	[kg ha^{-1}]	Uptake [kg ha^{-1}]			Concentration [%]		
Nitrogen (N)							
Low	b 59.5	72.0 ns	54.3 ns	52.2 ns	3.12 c	2.59 b	2.20 a
Medium	a 36.8	43.3 b	44.2 b	23.0 a	2.67 b	2.06 a	1.60 a
High	a 29.1	40.2 c	28.0 b	19.1 a	2.59 b	2.02 a	1.66 a
Phosphorous (P)							
Low	b 5.1	5.4 ns	4.8 ns	5.2 ns	0.23 ns	0.23 ns	0.23 ns
Medium	a 3.6	3.6 ns	4.2 ns	3.0 ns	0.23 ab	0.20 a	0.24 b
High	a 3.0	3.8 b	3.0 ab	2.3 a	0.23 ns	0.22 ns	0.21 ns
Potassium (K)							
Low	c 58.5	64.6 ns	59.8 ns	51.2 ns	2.82 ns	2.82 ns	2.35 ns
Medium	b 45.4	44.7 a	55.6 b	35.8 a	2.79 ns	2.66 ns	2.89 ns
High	a 29.8	44.8 b	25.3 a	19.4 a	2.77 b	1.82 a	1.76 a
Sulfur (S)							
Low	b 4.8	6.0 ns	4.2 ns	4.3 ns	0.26 b	0.20 a	0.19 a
Medium	a 2.9	4.0 b	3.0 ab	1.7 a	0.25 b	0.14 a	0.13 a
High	a 3.4	6.4 b	2.1 a	1.8 a	0.41 b	0.15 a	0.15 a

Tukey test ($p<0.05$): Letters a, b, c denote significant difference, ns denotes no significant difference between cropping strategies, mean values (n=6) and between fields, mean values (n=18)
F = fertilizer, M = mucuna, C = control

After harvest (150 DAS) during the second maize cropping period, average nutrient accumulation in other weeds was not significantly different between fields, except that K accumulation (23.2 kg ha^{-1}) was significantly higher in the medium-infested field. Nutrient accumulation was already low in all fields even with fertilizer or mucuna relay, except for K accumulation (18.6 kg ha^{-1}) with mucuna relay in the medium-infested field. In fact, nutrient accumulation was significantly higher without cropping strategies (control), particularly in the low- and medium-infested fields. In the high-infested field, there was no significant difference of nutrient accumulation either with or without cropping strategies, except for N accumulation (25.5 kg ha^{-1}), which was significantly higher without cropping strategies. However, nutrient concentrations in the biomass were significantly increased with the cropping strategies, particularly with fertilizer application (Table 4.21).

Table 4.21: Content of N, P, K and S in weeds other than *Imperata* after harvest (150 DAS) in the second maize cropping period in the low, medium and high-infested fields as affected by the superimposed cropping strategies

Nutrient content	Average nutrient uptake	Cropping strategy					
		F	M	C	F	M	C
	[kg ha^{-1}]	Uptake [kg ha^{-1}]			Concentration [%]		
Nitrogen (N)							
Low	ns 21.3	17.1 a	20.4 ab	26.4 b	2.76 b	2.41 b	1.95 a
Medium	ns 18.9	13.7 a	16.4 a	26.7 b	2.40 b	2.19 b	1.63 a
High	ns 17.9	12.4 a	15.8 a	25.5 b	2.25 ns	2.21 ns	1.86 ns
Phosphorous (P)							
Low	ns 1.9	1.4 a	1.7 a	2.7 b	0.22 ns	0.20 ns	0.19 ns
Medium	ns 1.8	1.3 a	1.4 a	2.8 b	0.22 b	0.19 ab	0.17 a
High	ns 1.6	1.1 ns	1.4 ns	2.2 ns	0.21 b	0.19 ab	0.15 a
Potassium (K)							
Low	ab 20.3	14.0 a	20.0 ab	27.3 b	2.17 ns	2.30 ns	1.94 ns
Medium	b 23.2	12.3 a	18.6 b	38.8 c	2.17 ns	2.47 ns	2.37 ns
High	a 13.0	8.8 ns	10.2 ns	19.8 ns	1.57 ns	1.39 ns	1.26 ns
Sulfur (S)							
Low	ns 1.8	1.6 ns	1.7 ns	2.2 ns	0.25 b	0.18 a	0.17 a
Medium	ns 2.0	1.9 ab	1.4 a	2.5 b	0.34 b	0.19 a	0.15 a
High	ns 2.1	2.4 ns	1.3 ns	2.5 ns	0.42 b	0.18 a	0.18 a

Tukey test ($p<0.05$): Letters a, b, c denote significant difference, ns denotes no significant difference between cropping strategies, mean values (n=6) and between fields, mean values (n=18)
F = fertilizer, M = mucuna, C = control

Nutrient content in other weeds dry matter in the low- and high-infested fields

In the second set of experiments with shallow hoeing, the average nutrient accumulation of other weeds in the low-infested field was higher than in the high-infested field. The higher DM of other weeds in the low-infested field also accumulated higher amount of nutrients, except S (2.1 kg ha^{-1}) at first harvest, which was not significantly different to the S accumulation of other weeds in the high-infested field.

In the low-infested field, the cropping strategies did not influence other weeds DM production and nutrient accumulation, except S concentration (0.32 %), which was significantly higher in other weeds biomass after harvest with fertilizer application

(Table 4.22). In the high-infested field, where growth of weeds was lower (0.4 t ha^{-1}), N (15.5 kg ha^{-1}), K (15.8 kg ha^{-1}), and S (3.8 kg ha^{-1}) accumulations as well as N and S concentrations at early stage in the maize cropping period (60 DAS) and S concentration after harvest (150 DAS), were significantly higher with fertilizer application.

Table 4.22: Content of N, P, K and S in weeds other than *Imperata* at weeding (60 DAS) and after harvest (150 DAS) for one maize cropping period in the low and high-infested fields as affected by affected by the superimposed cropping strategies

Nutrient content	Average nutrient uptake	Cropping strategy					
		F	M	C	F	M	C
	[kg ha^{-1}]	Uptake [kg ha^{-1}]			Concentration [%]		
At weeding (60 DAS)							
Nitrogen (N)							
Low	b 39.0	34.0 ns	36.3 ns	46.7 ns	3.03 b	2.28 a	2.15 a
High	a 9.3	15.5 b	5.7 a	6.8 a	2.49 b	1.69 a	1.81 ab
Phosphorous (P)							
Low	b 5.2	3.1 ns	5.7 ns	6.7 ns	0.27 ns	0.35 ns	0.30 ns
High	a 1.2	1.4 ns	1.0 ns	1.3 ns	0.23 ns	0.30 ns	0.34 ns
Potassium (K)							
Low	b 45.0	32.5 ns	47.7 ns	54.8 ns	2.82 ns	2.94 ns	2.44 ns
High	a 10.3	15.8 b	6.9 a	8.2 a	2.52 ns	2.03 ns	2.18 ns
Sulfur (S)							
Low	b 4.2	3.2 ns	3.6 ns	5.9 ns	0.27 ns	0.23 ns	0.28 ns
High	a 1.9	3.8 b	0.8 a	1.1 a	0.59 b	0.24 a	0.27 a
After harvest (150 DAS)							
Nitrogen (N)							
Low	b 17.8	13.4 ns	16.7 ns	23.1 ns	2.82 ns	2.19 ns	2.28 ns
High	a 7.0	7.8 ns	4.2 ns	8.8 ns	1.85 ns	1.68 ns	1.62 ns
Phosphorous (P)							
Low	b 2.3	1.4 ns	2.5 ns	3.2 ns	0.28 ns	0.29 ns	0.29 ns
High	a 1.2	1.3 ns	0.8 ns	1.5 ns	0.30 ns	0.31 ns	0.27 ns
Potassium (K)							
Low	b 15.2	8.9 ns	17.0 ns	19.7 ns	1.81 ns	2.05 ns	1.87 ns
High	a 7.5	7.7 ns	5.0 ns	9.7 ns	1.85 ns	1.97 ns	1.78 ns
Sulfur (S)							
Low	ns 2.1	1.6 ns	2.0 ns	2.8 ns	0.32 b	0.26 a	0.27 a
High	ns 1.3	2.0 ns	0.5 ns	1.5 ns	0.46 b	0.21 a	0.26 a

Tukey test (p<0.05): Letters a, b denote significant difference, ns denotes no significant difference between cropping strategies, mean values (n=6); Least Significance Difference test (p<0.05): between fields; mean values (n=18)

The two sets of experiments demonstrated that effective elimination of *Imperata* during intensive land preparation paved way for other weeds growth. These are annual weeds species, which seed bank lie dormant in the soil. The condition becomes favorable for these seeds to germinate when they are brought up to the surface during land preparation and free from *Imperata* suppressive competition (Udensi et al., 1999; Chikoye et al., 2001; Chikoye, 2003; Chikoye et al., 2005).

The two methods of intensive land preparation (deep hoeing and herbicide application) had no differentiating effect in influencing other weeds growth in all three fields since both effectively eradicated the initial *Imperata* infestation. On the hand, since the minimum tillage by shallow hoeing affected less the *Imperata* infestation in the high-infested field, growth of other weeds in this field was lower. There was still high interference of re-growing *Imperata*, which competed and suppressed the seed germination and growth of other weeds. Whereas in the low-infested field, shallow hoeing was effective in controlling the *Imperata*, so there was no competition and suppression to the germination and growth of other weeds species.

The suppressive effect of the fertilizer application as cropping strategy was also secondary which means the resulting effect was only after two maize cropping periods. Other weeds likely benefited from fertilizer application, especially when there was no more competition from *Imperata* and low competition from the maize crop at early stage. This was not the case with mucuna relay as cropping strategy. Even at early stage, the mucuna as a relay crop already competed and smothered other weeds because of its twining and creeping growth habit. Without fertilizer application and mucuna relay as superimposed cropping strategy after eliminating *Imperata*, other weeds growth was significantly higher.

Low DM yield of other weeds also accumulated low levels of nutrients in the biomass. Fertilizer inputs (either from mineral fertilizer or mucuna mulch) could potentially contributed to a better nutrient supply for its growth and production, most especially when there was no competition yet from the main (maize) crop. When fertilizer inputs significantly enhanced maize growth as demonstrated by the high stover DM production, it also suppressed other weeds DM production and competed strongly for the nutrients, and thus reducing the availability to the other weeds.

4.3 Maize response

4.3.1 Maize dry matter production

Maize yield in fields with intensive land preparation

This section presents the maize yield in three fields, initially with different levels of *Imperata* infestation reflecting the soil fertility conditions. Intensive land preparation (deep hoeing and herbicide application) was employed for eradicating *Imperata* infestation. Fertilizer application or mucuna relay were superimposed cropping strategies, which were compared with a control (no fertilizer or mucuna).

The average maize response by field to the cultivation practices employed show that total DM yield of maize in the first cropping period was significantly higher in the medium-infested field (11.0 t ha^{-1}) and lowest in the high-infested field (7.1 t ha^{-1}). The DM yield in the low-infested field (9.4 t ha^{-1}) was not significantly different to that of the medium- and high-infested fields. In the subsequent cropping period, total DM production was not significantly different between fields (Table 4.23). However, DM production in the high-infested field was not translated into grain yield as shown by a very low harvest index, which was only 0.1 for the two cropping periods. In comparison, the harvest index in the medium-infested field averaged 0.4 and in the low-infested field 0.3.

Table 4.23: Average maize dry matter yield and harvest index in the low, medium and high-infested fields for two cropping periods in response to the cultivation management practices

Sampling period	Field category		
	Low	Medium	High
1st cropping period			
Total DM [t ha^{-1}]	9.4 ab	11.0 b	7.1 a
Harvest index	0.3 b	0.5 c	0.1a
2nd cropping period			
Total DM [t ha^{-1}]	12.3 ns	10.5 ns	9.2 ns
Harvest index	0.3 b	0.4 b	0.1 a

Tukey test ($p<0.05$): Letters a, b, c denote significant difference, ns denotes no significant difference between fields; mean values (n=18)

In the first cropping period, total DM of maize in the deep-hoed plots was about 2 t ha^{-1} higher than in the herbicide-sprayed plots (Table 4.24). However, the significant differences in maize total DM in the first cropping period were not reflected in the grain yield, except in the high-infested field where grain yield was significantly higher in deep-hoed plots than in plots sprayed with herbicide. The grain yield in the high-infested field was very low that the significant differences between the two methods are hardly relevant. In the second cropping period, there were no longer significant differences. The two land preparation methods employed prior to the first maize cropping period had no residual effects in the second maize cropping period.

Table 4.24: Maize dry matter yield in the low, medium, and high-infested fields for two cropping periods as affected by the type of land preparation employed to control *Imperata*

Sampling period	Field category					
	Low		Medium		High	
	DH	HA	DH	HA	DH	HA
	Maize yield [t ha^{-1}]					
1st cropping period						
Total DM	10.5 b	8.3 a	11.8 b	10.1 a	8.3 b	5.8 a
Stover	6.6 b	5.4 a	5.9 ns	5.2 ns	6.2 b	5.3 a
Grain	3.8 ns	3.0 ns	5.9 ns	4.9 ns	2.1 b	0.5 a
2nd cropping period						
Total DM	12.8 ns	11.9 ns	11.3 ns	9.8 ns	10.3 ns	8.0 ns
Stover	8.0 ns	7.7 ns	6.6 ns	5.3 ns	7.9 ns	7.0 ns
Grain	4.8 ns	4.2 ns	4.7 ns	4.5 ns	2.4 ns	1.0 ns

Least Significant Difference test ($p<0.05$): Letters a, b, denote significant difference, ns denotes no significant difference between land preparation methods within field category; mean values (n=3)
Grain yield data in the high-infested field (transformed with SQT+1)
DH = deep hoeing, HA = herbicide application

On average by field, the stover yields in all three fields for the two cropping periods were not significantly different. However, at first harvest, grain yield was significantly higher in the medium-infested field then in the low-infested field and lowest in the high-infested field. At the second harvest, grain yield were the same in the low- and medium-infested fields but lower in the high-infested field (Table 4.25).

Table 4.25: Maize dry matter yield in the low, medium, and high-infested fields for two cropping periods as affected by the superimposed cropping strategy

Maize DM	Cropping strategy							
	F	M	C	Avg.	F	M	C	Avg.
	1st cropping period DM yield [t ha^{-1}]				2nd cropping period DM yield [t ha^{-1}]			
Stover								
Low	ns 8.3 b	ns 5.2 a	ns 4.5 a	ns 6.0	ab 11.7 c	b 8.0 b	ns 3.7 a	ns 7.8
Medium	ns 7.3 b	ns 4.9 a	ns 4.4 a	ns 5.5	a 10.4 c	a 4.8 b	ns 2.5 a	ns 5.9
High	ns 7.9 b	ns 4.9 a	ns 4.5 a	ns 5.8	b 13.8 b	ab 5.6 a	ns 3.1 a	ns 7.5
Grain								
Low	a 4.8 b	b 2.6 a	b 2.8 a	b 3.4	ab 7.8 b	b 3.6 a	b 2.1 a	b 4.5
Medium	b 8.8 c	b 3.2 a	b 4.3 b	c 5.4	b 8.8 c	b 3.2 b	b 1.7 a	b 4.6
High	a 3.6 b	a 0.1 a	a 0.1 a	a 1.3	a 4.3 b	a 0.6 a	a 0.2 a	a 1.7
Harvest index								
Low	ab 0.4 ns	b 0.3 a	b 0.4 ns	b 0.4	b 0.4 ns	b 0.3 ns	b 0.4 ns	b 0.4
Medium	b 0.5 b	b 0.4 a	b 0.5 b	b 0.5	b 0.5 ns	b 0.4 ns	b 0.4 ns	b 0.4
High	a 0.3 b	a 0.03 a	a 0.03 a	a 0.1	a 0.2 b	a 0.07 a	a 0.05 a	a 0.1

Tukey test ($p<0.05$): Letters a, b, c denote significant difference, ns denotes no significant difference
Between cropping strategies within field (column), mean values (n=3)
Between fields by cropping strategy (rows), mean values (n=6), combined data of the two land preparation methods; F = fertilizer, M = mucuna, C = control

Fertilizer application significantly enhanced maize DM production in the three fields. The effect was even more pronounced in the second cropping period, especially in enhancing stover production. Also, the grain yield in all fields significantly improved with fertilizer application. However, the averaged grain yield for the two cropping periods in the high-infested field (4.0 t ha^{-1}) was lowest, while in the medium-infested field (8.8 t ha^{-1}) was the highest, and then in the low-infested field (6.3 t ha^{-1}). In the high-infested field, grain yield was relatively low considering that the stover yield for two cropping periods (10.9 t ha^{-1}) was higher than in the low-infested (10.0 t ha^{-1}) and medium-infested (8.9 t ha^{-1}) fields. Most particularly during the second cropping, stover production was significantly higher in the high-infested field (13.8 t ha^{-1}) than in the medium-infested field (10.4 t ha^{-1}). However, for two cropping periods, the grain yield in the high-infested field was only 4.3 t ha^{-1}, while in the medium-infested field was 8.8 t ha^{-1}. The results suggest a nutrient disorder, which is responsible for the low potential grain yield in the high-infested field.

With mucuna relay, during the first cropping period, stover production in all fields shows no significant difference to the control. In the subsequent maize cropping, stover production significantly improved in the low-infested field (from 5.2 t ha^{-1} to 8.0 t ha^{-1}) as well as in the high-infested field (4.9 t ha^{-1} to 5.6 t ha^{-1}) and remained basically the same in the medium-infested field (4.8 t ha^{-1}). Particularly in the high-infested field, stover production also increased during the second cropping period, but grain yield was still low, which was not different to the control, and likewise still very low compared to the other two fields. In the medium-infested field, the grain yield at first harvest with mucuna relay was significantly lower compared to the control. But at the second harvest, grain yield with mucuna relay was already higher than in the control, where the grain yield was severely reduced (from 4.3 ha^{-1} to 1.7 ha^{-1}). In the low- and high-infested fields, grain yield with mucuna relay for the two cropping periods show no significant difference to the control.

After eliminating *Imperata* during land preparation and even without any superimposed cropping strategy, maize crop can still grow in all fields regardless of the initial degree of *Imperata* infestation, but with very low DM production potential. Although stover production was not significantly different in all fields, only the low-infested and medium-infested fields produced corresponding grain yield. Grain yields in the low- (average for two cropping periods 2.4 t ha^{-1}) and medium-infested (3.0 t ha^{-1}) fields were not significantly different. In the high-infested field (0.1 t ha^{-1}), practically no grain was produced during the two maize cropping periods.

Compared with mucuna relay and in the control, the mineral fertilizers improved the harvest index in the high-infested field. But compared to other two fields, this harvest index was still low. The low crop yield, which is the inability to produce grain yield is the major reason why farmers abandon *Imperata*-infested fields at a certain degree of infestation. Although many reports state that farmers abandon the field when they can no longer cope with the *Imperata* as the cropping period proceeds, it may well be that it is the low grain yield that is discouraging farmers to continue the cultivation of such fields.

Maize yields in fields with minimum tillage

In the second set of experiments with only minimum tillage employed as land preparation prior to maize cropping, the pooled average maize yield results by field show that maize total DM yield and harvest index was significantly higher in the low-infested field than in the high-infested field (Table 4.26). Although the average maize total DM yield in the low-infested in this experiment is higher, harvest index was the same to the first set of experiments in the same low-infested field. But in the high-infested field, the second set of the experiment had lower maize DM and much lower harvest index compared to the same high-infested field in the first set of experiments.

Table 4.26: Maize dry matter yield and harvest index in the low, medium and high-infested fields for one cropping period in response to the cultivation management practices

Sampling period	Field category	
	Low	High
One cropping period		
Total DM [t ha^{-1}]	17.0 b	6.1 a
Harvest index	0.3 b	0.05 a

Least Significance Difference test ($p<0.05$): Letters a, b denote significant difference between fields
Mean values (n=9)

In both fields, there was a clear maize yield response to fertilizer application, whereas there was no significant effect of mucuna relay (Table 4.27). Maize yield in the low-infested field with shallow hoeing was comparable to that in the low- and medium-infested fields in the first set of experiments with deep hoeing. Fertilizer application following shallow hoeing was beneficial in the low-infested fields, but not likely in the high-infested field. Although fertilizer application enhanced the stover yield (10.3 t ha^{-1}) in the high-infested field, it did not improve the grain yield (0.9 t ha^{-1}). In this set of experiments, the grain yield was much lower than the grain yield in the high-infested field in the first set of experiments with intensive land preparation. Also, the mucuna relay as cropping strategy after a shallow hoeing land did show a significant beneficial effect on maize stover and grain production in both fields after one cropping.

Table 4.27: Maize dry matter yield in the low and high-infested fields for one cropping period as affected by the superimposed cropping strategy

Maize DM	Cropping strategy			
	F	M	C	Average
	DM yield [t ha^{-1}]			
Stover				
Low	b 17.2 b	b 9.4 a	b 10.2 a	b 12.3
High	a 10.3 b	a 3.8 a	a 3.8 a	a 5.8
Grain				
Low	b 7.3 b	b 3.3 a	b 3.6 a	b 4.7
High	a 0.9 b	a 0.0 a	a 0.3 a	a 0.4

Tukey test (p<0.05): Letters a, b, c denote significant difference between cropping strategies within field (column); mean values (n=3); between fields by cropping strategy (rows), mean values (n=3)
DH = deep hoeing, HA = herbicide application

The two set of experiments demonstrate that effective elimination of initial *Imperata* infestation in the field opens up the opportunity to enhance the nutrient supply needed by maize for its growth and DM production, and to overcome the nutrient constraint by fertilizer application, though not fully. This was demonstrated particularly in the high-infested fields, where fertilizer was effective in enhancing stover production and even improving the grain yield. However, the harvest index still remained unusually low, which were: 0.3 following deep hoeing, 0.1 following herbicide application, and 0.1 following shallow hoeing. Further, removing *Imperata* without destroying the rhizomes negates the positive effect of fertilizer application to maize growth and DM production. Due to interference and strong competition of the regrowing *Imperata*, which was not effectively eliminated prior to cropping, the enhanced stover production of maize developed a cob, however the cob tissue was mostly empty or without kernels. Other similar studies also reported a maize yield reduction as high as 70% or even a complete crop failure (Udensi et al.,1999; Chikoye et al., 2002; Chikoye et al, 2005), attributed to *Imperata* interference, especially when *Imperata* rhizomes underground are not destroyed prior to maize cropping. In this study, the grain production was impeded by nutritional constraints aggravated by competition from *Imperata*, and particularly in field, initially with high-*Imperata* infestation.

4.3.2 Nutrient levels in maize

In the first set of experiments where competition from initial *Imperata* infestation was removed by employing intensive land preparation, the low grain yield particularly in the high-infested field is assumed due to nutrient deficiency. In the second set of experiments, the problem of nutrient deficiency was aggravated by *Imperata* competition, which was not completely removed by shallow hoeing.

Since N, P_2O_5, K_2O and S mineral fertilizers were applied, the N, P, K and S level of maize was examined. The relationship between DM production and nutrient accumulation was used to determine which of the four nutrients applied was limiting, and possibly the underlying cause of limited grain development in the high-infested field. Uptake of nutrients and DM production of the maize leaves taken at mid-cropping (55 DAS) and maize stover at harvest (130 DAS) were plotted as shown in the graphs (Figures 4.1 to 4.4, 4.7 to 4.8). The lines define the critical nutrient content in maize at the given stage of growth, assuming that Liebig's Law of the Minimum applies, which states that yield is proportional to the amount of the most limiting nutrient, whichever nutrient it may be.

In this study, this critical concentration is considered the minimum quantity of respective nutrient necessary to produce the given amount of DM biomass. Any points to the right of this line were assumed to indicate a 'luxury consumption' that could have been utilized for additional biomass production. The highest point within the line was used as a point reference of the minimum concentrations, and set as the critical minimum nutrient concentration[8].

Nutrient content in maize dry matter in the low-, medium-, and high-infested fields

Leaves

As a first indicator of the nutrient availability, the N, P, K and S levels in the maize leaves in the mid-cropping period (55 DAS) were examined. For the first cropping period, the critical nutrient concentrations in the leaves tissue of maize were 2.22 % for N, 0.18 % for P, 1.58 % for K, and 0.15 % for S (Table 4.28 and Figure 4.1).

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[8] T-statistic test ($p>0.05$) was used to differentiate the critical nutrient concentration to other points (representing nutrient concentrations) in the graph.

Table 4.28: Maize leaves (55 DAS) nutrient concentrations [%] in the low, medium and high-infested fields during first cropping period as affected by the superimposed cropping strategies

Nutrient content	Cropping strategy		
	F	M	C
	Concentration [%]		
Nitrogen (N)			
Low	(+) 3.80	(+) 3.30	(+) 3.33
Medium	(+) 3.23	(-) 2.36	(*) 2.22
High	(+) 3.15	(-) 2.37	(-) 2.32
Phosphorous (P)			
Low	(+) 0.22	(+) 0.20	(+) 0.21
Medium	(+) 0.20	(-) 0.19	(*) 0.18
High	(+) 0.23	(+) 0.26	(+) 0.24
Potassium (K)			
Low	(+) 2.12	(+) 2.09	(+) 2.14
Medium	(+) 1.84	(+) 1.81	(+) 2.02
High	(+) 1.78	(*) 1.58	(-) 1.63
Sulfur (S)			
Low	(+) 0.25	(+) 0.22	(+) 0.22
Medium	(+) 0.22	(-) 0.16	(*) 0.15
High	(+) 0.22	(-) 0.16	(-) 0.16

T-statistic test (p>0.05): (*) denotes the critical nutrient concentration; (+) higher than the critical concentration, (-) not significantly different from the critical concentration, mean values (n=6)
F = fertilizer, M = mucuna, C = control

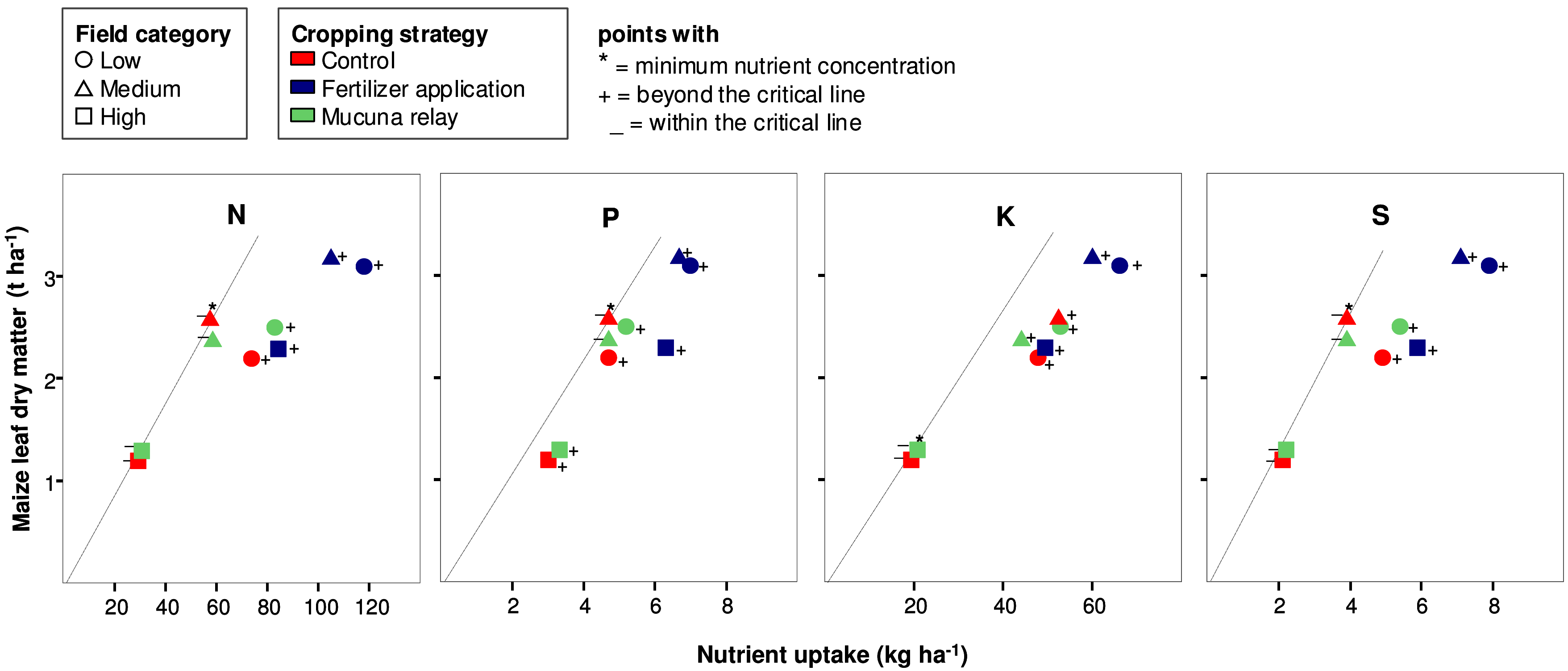

Figure 4.1: Content of N, P, K and S in maize leaf dry matter (55 DAS) in the first cropping period (points represent the mean, n=6)

In the low-infested field, whether with fertilizer or with mucuna relay or without both (control), N, P, K and S concentrations in the maize leaves (55 DAS) were higher than the critical concentrations. Fertilizer application significantly increased the level of N to 3.80 % and S to 0.25 % concentrations in maize leaves, but for P and K made no significant difference. Even with mucuna relay, N, P, K and S concentrations were still above the critical level, suggesting that mucuna did not significantly compete with maize.

In the medium-infested field, concentrations of N, P and S in the maize leaves in the control were at critical levels, while K was higher than the critical concentration. Fertilizer application significantly increased the concentration level of the four nutrients to higher than critical concentration, increasing significantly the N to 3.23 % and S to 0.22 %. With mucuna relay, only K concentration was higher than the critical concentration. The level of N, P and S were at critical concentrations, suggesting the mucuna competed for the nutrients.

In the high-infested field, concentrations of N, K and S in the maize leaves in the control were at a critical level, while P (0.24 %) was higher than the critical concentration. Fertilizer application significantly increased the concentration level of the four nutrients to higher than critical concentration, increasing significantly the N to 3.15 % and S to 0.22 %. With mucuna relay, the level of N, K and S were at critical levels, suggesting the mucuna competed for the nutrients. The P supply was sufficient for the maize at this stage of growth (55 DAS) in this field. Of the four nutrients and comparing between fields, even without any superimposed cropping strategy, N, K and S concentrations were higher in the low-infested field, K concentration was higher in medium-infested field, and P concentration was higher in the high-infested field (Appendix 1).

For the second cropping period, the critical concentrations in the maize leaves at mid-cropping (55 DAS) were 1.78 % for N, 0.15 % for P, 1.24 % for K, and 0.15 % for S (Table 4.29 and Figure 4.2).

Table 4.29: Maize leaves (55 DAS) nutrient concentrations [%] in the low, medium and high-infested fields during second cropping period as affected by the superimposed cropping strategies

Nutrient content	Cropping strategy		
	F	M	C
	Concentration [%]		
Nitrogen (N)			
Low	(+) 3.47	(+) 2.32	(-) 1.91
Medium	(+) 3.07	(*) 1.78	(-) 1.59
High	(+) 3.05	(-) 1.95	(-) 1.74
Phosphorous (P)			
Low	(+) 0.23	(+) 0.19	(-) 0.16
Medium	(+) 0.20	(*) 0.15	(-) 0.16
High	(+) 0.23	(+) 0.19	(+) 0.20
Potassium (K)			
Low	(+) 1.80	(+) 1.67	(*) 1.24
Medium	(+) 1.69	(+) 1.54	(+) 1.77
High	(+) 1.76	(-) 1.38	(-) 1.48
Sulfur (S)			
Low	(+) 0.41	(+) 0.31	(+) 0.26
Medium	(+) 0.24	(*) 0.15	(+) 0.23
High	(+) 0.27	(-) 0.17	(-) 0.16

T-statistic test (p>0.05): (*) denotes the critical nutrient concentration; (+) higher than the critical concentration; (-) not significantly different from the critical concentration, mean values (n=6)
F = fertilizer, M = mucuna, C = control

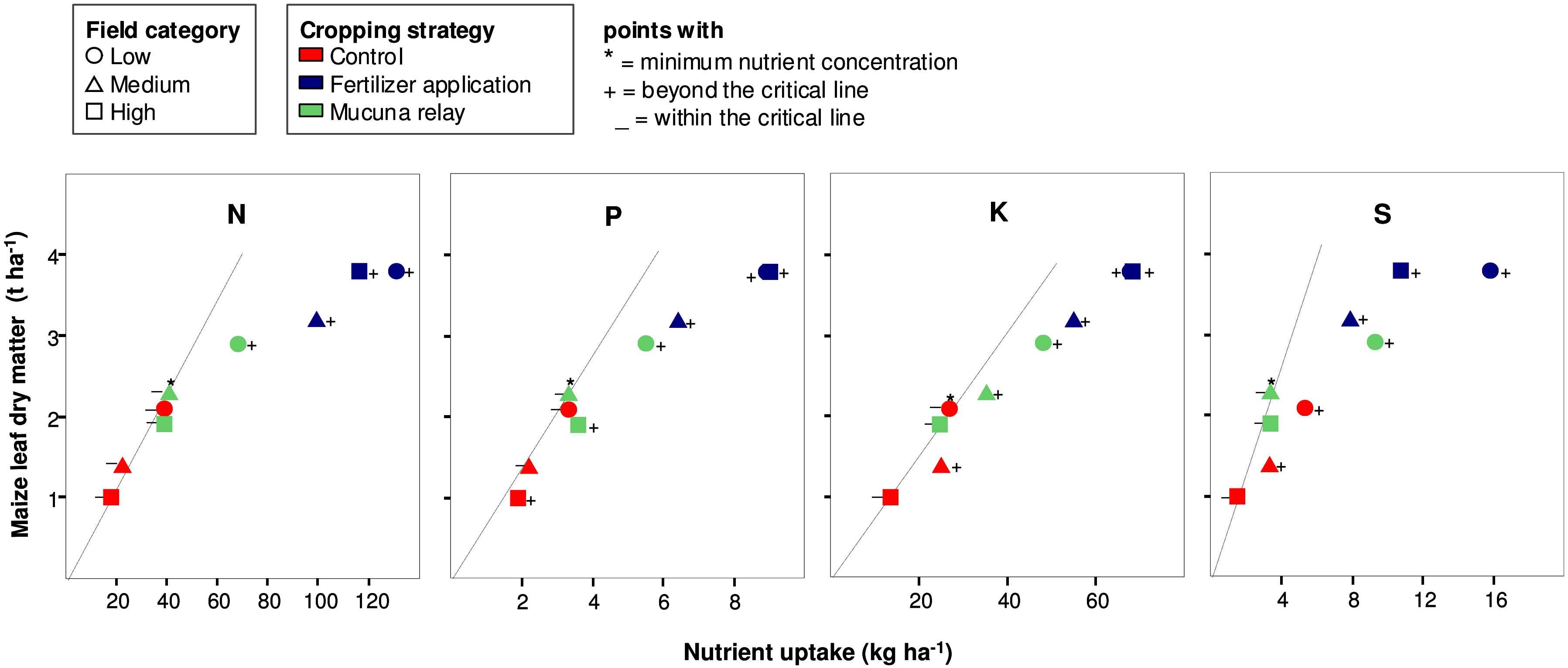

Figure 4.2: Content of N, P, K and S in maize leaf dry matter (55 DAS) in the second cropping period (points represent the mean, n=6)

In the low-infested field, concentrations of N, P and K in maize leaves (55 DAS) in the control were at critical level, while S was higher than the critical concentration. Continued fertilizer application enhanced the level of the four nutrients, significantly increasing N to 3.47 %, P to 0.23 % and S to 0.41 % although not so significant for K. With mucuna relay, the four nutrients in the leaves were also higher than the critical concentration. Further, the level of N, P and S concentrations in the maize leaves with mucuna relay as cropping strategy were significantly higher than in the control, while the K concentration was not significantly different whether with fertilizer, with mucuna, and in the control (Appendix 1). This suggests that with mucuna relay, some nutrients from the mulch were returned to the soil and utilized in the second cropping period.

In the medium-infested field, concentrations of N and P in the control during the second cropping period were still at a critical level, whereas K and S were above the critical level. Continued fertilizer application enhanced the level of the four nutrients, but only significantly increasing the N to 3.07 %. With mucuna relay, N, P and S were all at critical concentrations, while K (1.54 %) was still above the critical level, and adequate even with the competition from mucuna.

In the high-infested field, concentrations of N, K and S in the control were at critical level, while P (0.20 %) was above the critical level. Continued fertilizer application enhanced the level of the four nutrient concentrations. But with mucuna relay, only P concentration was above the level. Comparing between fields without any cropping strategies (Appendix 1), N concentration was higher in the low-infested field, while P concentration was higher in the high-infested field.

Stover

The analysis of the leaves was complemented with an analysis of the maize stover taken at harvest in order to determine the maize nutrient levels of the entire cropping period. In the maize stover during the first cropping period, the critical concentrations were 0.70 % for N, 0.07 % for P, 0.44 % for K, and 0.10 % for S (Table 4.30 and Figure 4.3).

Table 4.30: Maize stover nutrient concentrations [%] at harvest (130 DAS) in the low, medium and high-infested fields during first cropping period as affected by the superimposed cropping strategies

Nutrient content	Cropping strategy		
	F	M	C
	Concentration [%]		
Nitrogen (N)			
Low	(+) 0.91	(+) 0.89	(+) 0.91
Medium	(+) 0.79	(*) 0.70	(-) 0.70
High	(+) 0.84	(+) 0.96	(+) 1.03
Phosphorous (P)			
Low	(-) 0.08	(-) 0.10	(-) 0.10
Medium	(*) 0.07	(-) 0.08	(-) 0.09
High	(+) 0.12	(+) 0.13	(+) 0.13
Potassium (K)			
Low	(+) 0.75	(+) 0.69	(+) 0.63
Medium	(+) 0.75	(+) 0.78	(+) 1.00
High	(+) 0.69	(*) 0.44	(-) 0.37
Sulfur (S)			
Low	(+) 0.13	(-) 0.11	(*) 0.10
Medium	(+) 0.14	(-) 0.12	(-) 0.11
High	(+) 0.20	(+) 0.18	(+) 0.22

T-test (p>0.05): (*) denotes the critical nutrient concentration; (+) higher than the critical concentration; (-) not significantly different from the critical concentration, mean values (n=6)
F = fertilizer, M = mucuna, C = control

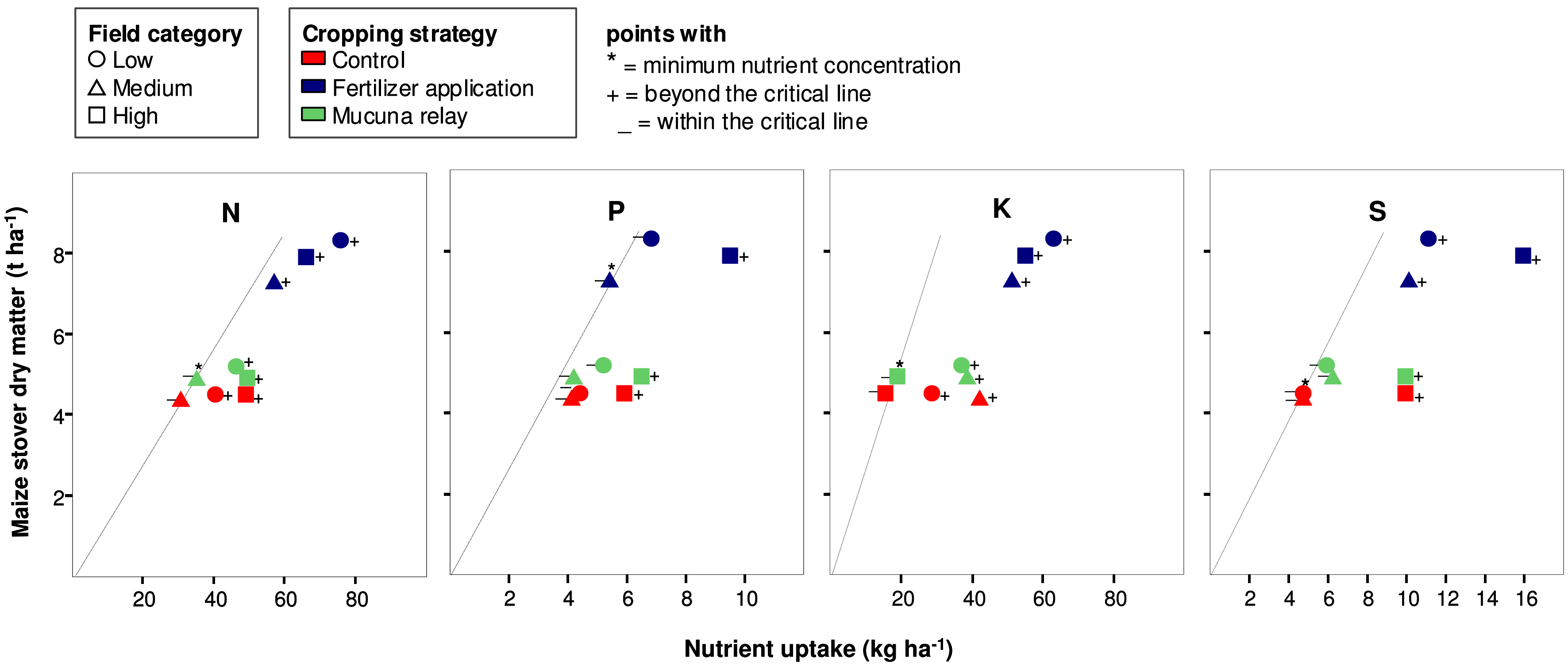

Figure 4.3: Content of N, P, K and S in maize stover dry matter at harvest (130 DAS) in the first cropping period (points represent the mean, n=6)

During the first cropping period, in the control of the low-infested field, concentrations of N and K in the stover at harvest (130 DAS) were significantly above the critical level, while P and S were at the critical level eventhough S showed sufficiency at the early stage of maize growth (55 DAS). Fertilizer application enhanced the stover production with N, K and S concentrations above the critical level, but not the P concentration, which was already at critical level. The supply of N and K was adequate for stover production even with mucuna relay, while P and S were at a critical level.

In the medium-infested field, concentrations of N, P and S in the stover remained at critical level in the control. Wth fertilizer application, N, K and S concentration increased, but not P, which remained at a critical level. Particularly, the K concentration in the stover was high and above the critical level, even in the control (1.0 %), with mucuna relay (0.78 %), and with fertilizer application (0.75%). This suggests that K was not a problem in this field.

In the high-infested field in the control, K was particularly the nutrient at the critical level in the stover, while N, P and S concentrations were higher than the critical concentrations. The constraints in supply of N and S in maize at early stage of growth were overtaken by the limiting K after 55 DAS to maturity. With fertilizer application, all four nutrients were above critical concentrations. Particularly, the K concentration increased significant from 0.37% to 0.69 %, which strongly indicate that K was the deficient element in this field

Further, comparing nutrient concentrations in the control between three fields, the results show that N and K was higher in the low-infested field, and K was also higher in medium-infested field, while N, P and S were higher in the high-infested field (Appendix 2).

During the second cropping period, the critical concentrations in the stover were 0.57 % for N, 0.06 % for P, 0.40 % for K, and 0.09 % for S (Table 4.31 and Figure 4.4). The critical concentration level is more dependent on the cropping period, particularly for N which is lower compared to the first cropping period.

Table 4.31: Maize stover nutrient concentrations [%] at harvest (130DAS) in the low, medium and high-infested fields during second cropping period as affected by the superimposed cropping strategies

Nutrient content	Cropping strategy		
	F	M	C
	Concentration [%]		
Nitrogen (N)			
Low	(-) 0.64	(-) 0.72	(-) 0.67
Medium	(*) 0.57	(-) 0.65	(-) 0.51
High	(+) 0.77	(+) 1.10	(+) 1.25
Phosphorous (P)			
Low	(-) 0.06	(-) 0.08	(-) 0.08
Medium	(*) 0.06	(-) 0.08	(-) 0.10
High	(+) 0.12	(+) 0.17	(+) 0.19
Potassium (K)			
Low	(+) 0.69	(+) 0.74	(-) 0.54
Medium	(+) 0.78	(+) 0.86	(+) 1.27
High	(+) 0.61	(*) 0.40	(-) 0.37
Sulfur (S)			
Low	(+) 0.11	(-) 0.19	(-) 0.10
Medium	(-) 0.07	(-) 0.07	(-) 0.06
High	(*) 0.09	(-) 0.09	(-) 0.08

T-test (p>0.05): (*) denotes the critical nutrient concentration; (+) higher than the critical concentration; (-) not significantly different from the critical concentration, mean values (n=6)
F = fertilizer, M = mucuna, C = control

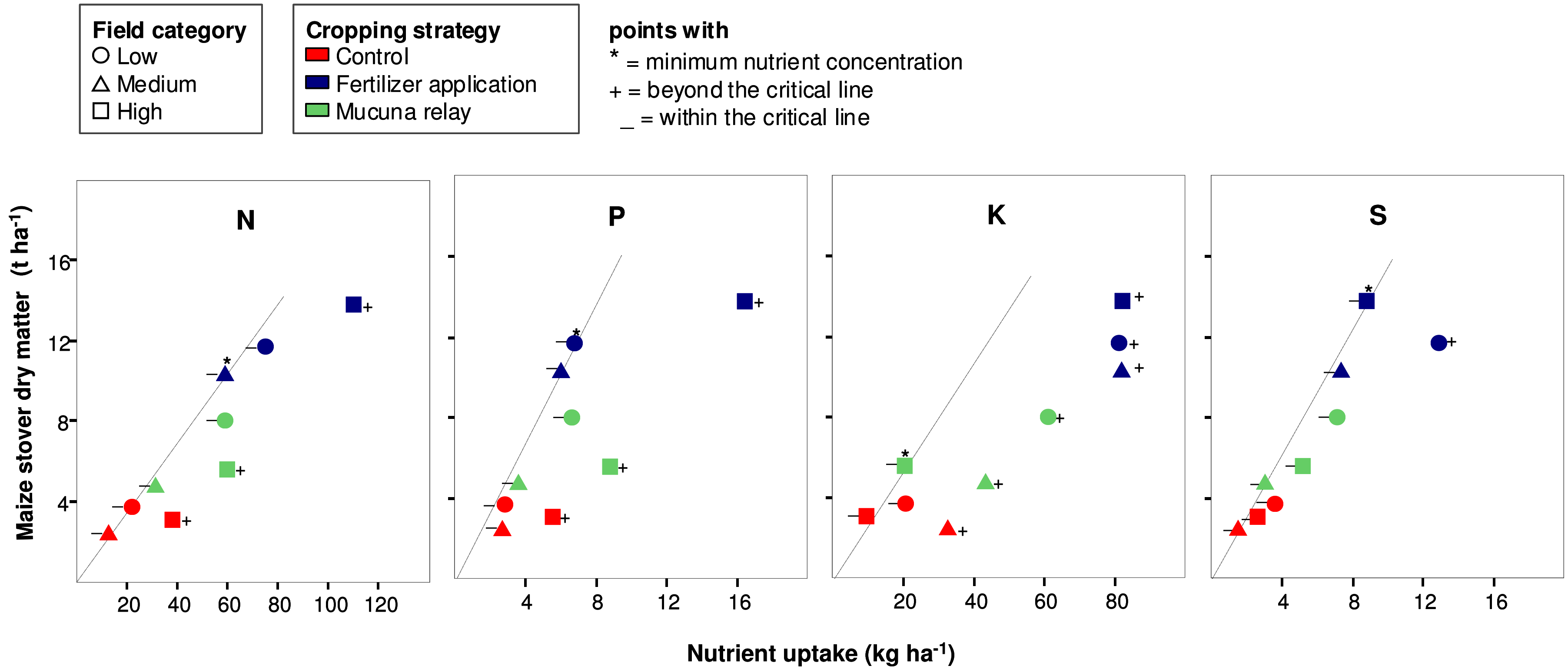

Figure 4.4: Content of N, P, K and S in maize stover dry matter at harvest (130 DAS) in the second cropping period (points represent the mean, n=6)

In the low-infested field, stover N and P concentrations in the control, with mucuna relay, and even with fertilizer application were at critical levels. The same was true for S, except with fertilizer application where the S level increased above the critical level. In the control, K concentration in the stover was also at a critical level, but above the critical level with mucuna relay (0.69 %) and with fertilizer application (0.74 %). Also, in the medium infested field, stover N, P and S concentrations were at critical levels, while the K concentration was always above the critical level for entire maize growth until maturity. In the high-infested field, N and P concentrations were above the critical levels even in the control and with mucuna relay, while K and S concentrations were at critical levels. Fertilizer application increased the K (0.61 %) concentration to an adequate level. Comparing the nutrient concentrations in the control of the three fields show that N and P in the stover were significantly higher in the high-infested field (Appendix 2).

Grain

In contrast to the stover, the grain yield and nutrient uptake show a linear relationship with high regression coefficient. The concentration of nutrients in maize grain was independent to the yield (Table 4.32). For the first (Figures 4.5) and second (Figures 4.6) cropping periods, the slope and regression values were 0.08 (r^2=0.99) and 0.09 (r^2=0.99) for N, 0.59 (r^2=0.99) and 0.81 (r^2=0.97) for P, 0.24 (r^2=0.99) and 0.23 (r^2=1) for K, and 0.81 (r^2=0.98) and 0.80 (r^2=0.99) for S, respectively.

Comparing nutrient concentrations in the grain between fields (Appendix 3), at first harvest, the grain in the low-infested field had higher N and P concentrations in the biomass, especially with mineral fertilizer. Grain DM in the medium-infested field had higher P concentration, while in the high-infested field had higher N even without mineral fertilizer. At second cropping harvest, grain DM in the medium- infested fields had high P concentration even with mineral fertilizer, while in high-infested field, N concentration with mucuna relay as well P and K were higher with fertilizer application.

Table 4.32: Maize grain nutrient concentrations [%] at harvest (130DAS) in the low, medium and high-infested fields for the two cropping periods as affected by the superimposed cropping strategies

	Cropping strategy					
	F	M	C	F	M	C
Nutrient content	1st cropping period			2nd cropping period		
	Concentration [%]					
Nitrogen (N)						
Low	1.49	1.48	1.46	1.22	1.37	1.34
Medium	1.22	1.32	1.29	1.13	1.37	1.40
High	1.36	1.87	1.91	1.45	1.71	1.15
Phosphorous (P)						
Low	0.17	0.17	0.17	0.11	0.13	0.14
Medium	0.17	0.17	0.19	0.13	0.15	0.16
High	0.14	0.12	0.13	0.15	0.15	0.12
Potassium (K)						
Low	0.41	0.41	0.40	0.44	0.46	0.50
Medium	0.42	0.43	0.45	0.44	0.46	0.49
High	0.49	0.42	0.44	0.50	0.46	0.47
Sulfur (S)						
Low	0.13	0.12	0.13	0.13	0.12	0.13
Medium	0.16	0.14	0.13	0.14	0.13	0.14
High	0.14	0.14	0.15	0.13	0.14	0.12

Mean values (n=6); F = fertilizer, M = mucuna, C = control

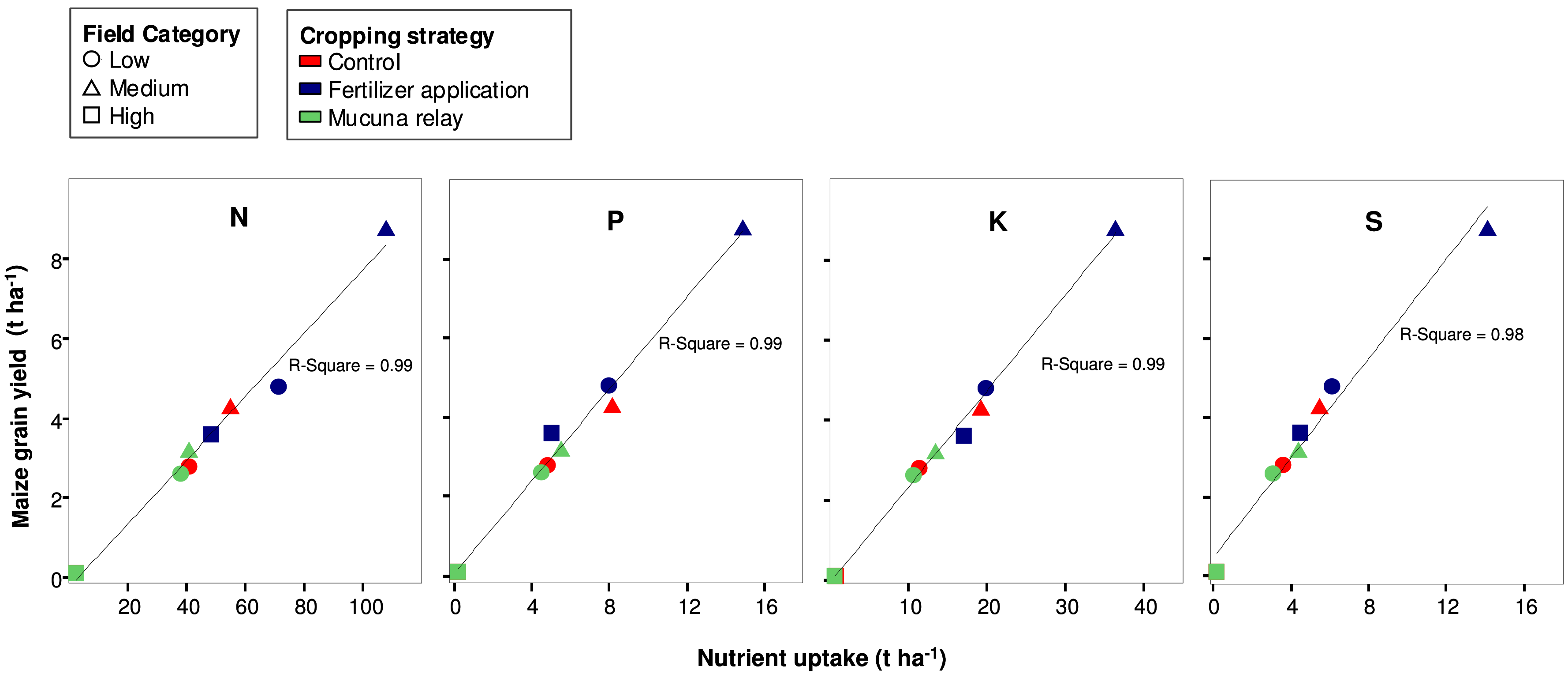

Figure 4.5: Content of N, P, K and S in maize grain dry matter at harvest (130 DAS) in the first cropping period (points represent the mean, n=6)

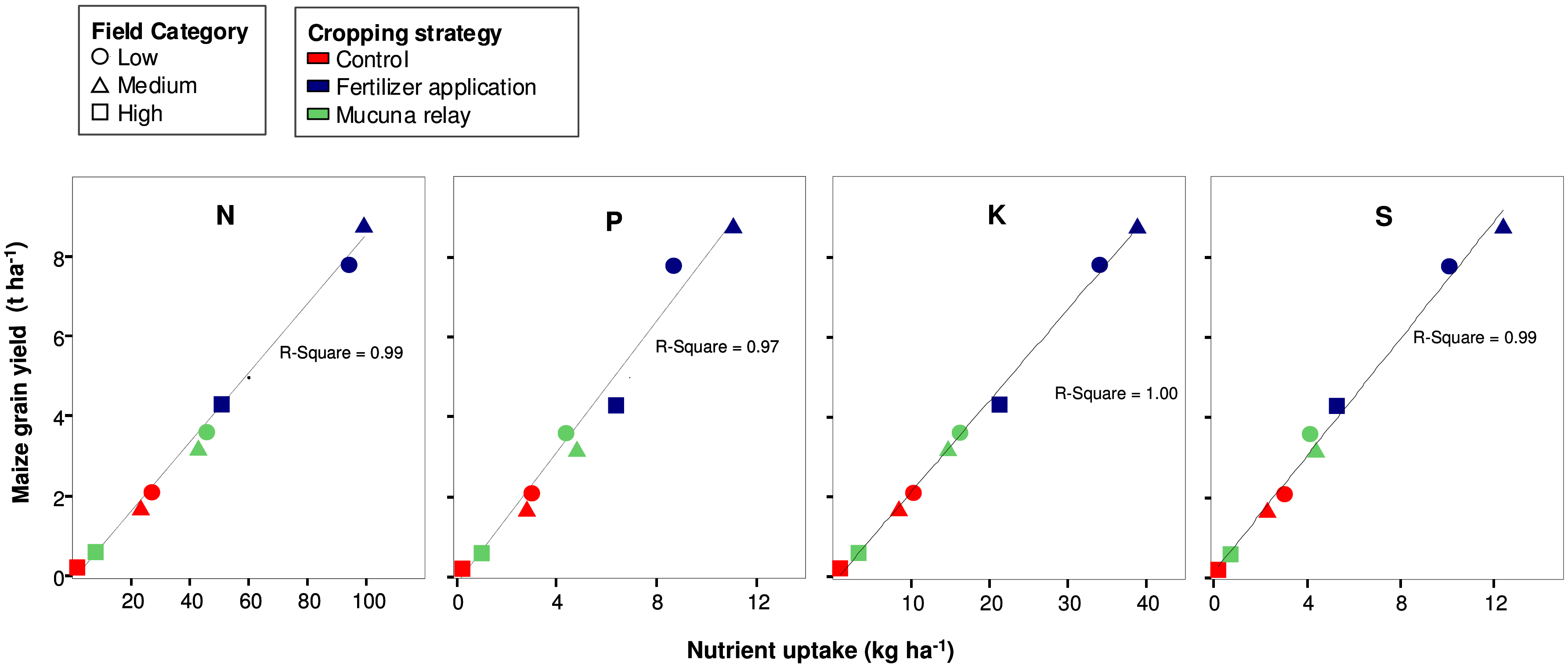

Figure 4.6: Content of N, P, K and S in maize grain dry matter at harvest (130 DAS) in the second cropping period (points represent the mean, n=6)

In the first maize cropping period all the four nutrients were still sufficient in the low-infested field at the early stage of maize growth (55 DAS), although P was lower compared to other two fields. However, P and S were limiting at later stages of maize growth (>55DAS) to maturity, whereas N and K were still adequate for the entire maize growing period. Thus, grain yield was slightly affected by the nutrient P and S deficiency at later stage (>55DAS). In the medium-infested field, without fertilizers and with mucuna relay crop competing for such nutrients, N, P and S were at critical supply, but K was sufficient for the entire maize growing period. Although P was clearly deficient, when N and S constraints was corrected by fertilizer application, DM matter production was enhanced and resulting to high grain production. In the high-infested field, although P was adequate, N, K and S were limiting even at early stage. The addition of mineral fertilizers enhanced maize DM production that resulted to a higher stover yield but grain produced was lower to its potential.

In the second cropping period in the low-infested field, S was still adequate, while N, P and K was already limiting for subsequent maize crop. However, at later stage all the four nutrients becomes limiting when there is no soil fertility enhancement as cropping strategy. The K and S fertilizer application and the residual effect of mucuna relayed at first cropping significantly enhanced stover production. With improved K level in the stover, grain yield also improved. Without a cropping strategy or fertility enhancement employed in this field during cropping, there is clear signal of soil degradation due to continued cropping, and eventually giving *Imperata* a chance to firmly establish in the field.

In the medium-infested field, K and S were adequate for subsequent maize at early stage of growth. However N, P and S supply also becomes critical to support DM production until maturity. The supply of S as well as N and P were inadequate with the presence of mucuna. Especially, N and S supply becomes more limiting without mineral fertilizer inputs. Fertilizer application significantly increased the supply. Although N, P and S supply were barely able to sustained maize growth until maturity, K supply was adequate and even show sufficiency for two cropping periods in the stover, and thus resulting to a higher grain yield.

In the high-infested field, P was showing sufficiency for the entire maize cropping cycle for two cropping periods, which can be attributed to the *Imperata* residues with high P content that becomes available during the maize growing period. However, N, K and S were clearly deficient and especially with mucuna competing the nutrients. Although N was already marginal for maize at early stage of growth, still the supply was able to support DM production until maturity. Fertilizer application was able to sustain the K and S supply during the early growth of maize to maturity. However, the potential of the high stover yield to produce grain was low.

Overall, for the two maize cropping periods, the results of the nutrient analysis demonstrate that K was the nutrient determining the difference in DM production among the three fields. The first cropping maize nutrient analysis suggests that among the fields and of the four nutrients, K is adequate both in the low- and medium-infested fields, but deficient in the high-infested field. The second cropping maize nutrient analysis similarly shows that K was the most limiting nutrient in the high-infested field, ample in the medium-infested field, and potentially limiting in the low-infested field.

The concentration of nutrients in the maize grain for the two cropping periods, indicate that the grain draws its nutrients from the stover in accordance with its needs. The nutrient that was least available from the source, which is the stover (weak source strengths), determined the amount of grain produced. The stover in the high-infested field demonstrated a weak source of nutrients for the grain sink. Among the four nutrients, K was identified as the most limiting nutrient in the high-infested field. Thus, it is viewed that this K nutrient limitation was the primary cause for the poor grain development in this field.

Nutrient content in maize dry matter in the low- and high-infested fields

Leaves

The critical nutrient concentrations in maize leaves in the second experiment were similar to those in the first experiment, especially in the second cropping period. The critical concentrations in the maize leaves (55 DAS) were 1.77 % for N, 0.19 % for P, 1.55 % for K, and 0.23 % for S (Table 4.33 and Figure 4.7).

Table 4.33: Maize leaves (55 DAS) nutrient concentrations [%] in the low and high-infested fields at one cropping period as affected by the superimposed cropping strategies

Nutrient content	Cropping strategy		
	F	M	C
	Concentration [%]		
Nitrogen (N)			
Low	(+) 3.31	(*) 1.77	(-) 1.97
High	(+) 2.94	(-) 1.52	(-) 1.44
Phosphorous (P)			
Low	(+) 0.24	(-) 0.19	(*) 0.19
High	(-) 0.19	(+) 0.24	(+) 0.24
Potassium (K)			
Low	(+) 1.85	(-) 1.58	(*) 1.55
High	(+) 1.82	(+) 2.27	(+) 2.18
Sulfur (S)			
Low	(+) 0.32	(-) 0.24	(*) 0.23
High	(+) 0.35	(-) 0.23	(-) 0.22

T-test (p>0.05): (*) denotes the critical nutrient concentration; (+) higher than the critical concentration; (-) not significantly different from the critical concentration, mean values (n=3)
F = fertilizer, M = mucuna, C = control

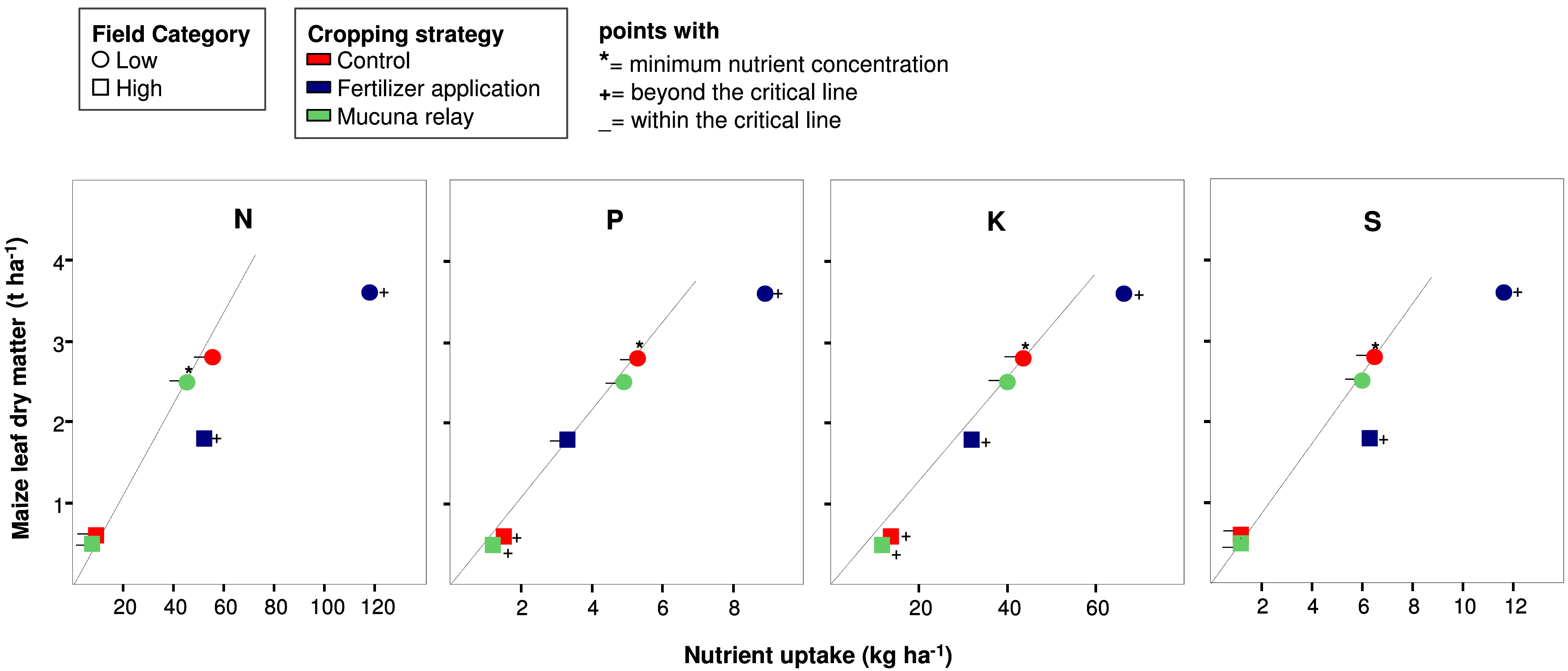

Figure 4.7: Content of N, P, K and S in maize leaf dry matter (55 DAS) in fields of the second set of experiments (points represent the mean, n=3)

In the low-infested field, without the cropping strategies (control) and with competition from mucuna relay, N, P, K and S concentrations in the maize leaves were at a critical level. Fertilizer application increased significantly the concentrations of N to 3.31 % and S to 0.32%. But, whether with fertilizer or with mucuna relay or in the control, P and K concentrations in the leaves were not significantly different (Appendix 4), suggesting that the P and K supply was adequate to support maize growth at early stage (55 DAS).

In the high-infested field with massive *Imperata* regrowth, without the cropping strategies (control) and with competition from mucuna relay, N, P and S were at a critical level, while K concentrations (2.18% and 2.27 %, respectively) are seemed to be very high. But actually, these were luxury consumption for a stunted maize growth considering that in this field the leaves DM (55 DAS) was only 0.6 t ha^{-1} (in the control) and 0.5 t ha^{-1} (with mucuna relay) (Appendix 4) compared to 1.8 t ha^{-1} (with fertilizer application). Fertilizer application enhanced significantly the concentrations of N to 2.94 % and S to 0.35 %, while it affected neither P (0.19 %), which was even lower, nor K (1.82 %) although the latter was still above the critical level. This non-significant different effect of fertilizer application to P and K concentration level in the maize leaves was due to the competition by *Imperata* as indicated in section 4.1.2.2 (Tables 4.11 and 4.12). There was high accumulation of *Imperata* for such nutrients. As the P and K concentrations in the leaves without the cropping strategies were higher than the critical concentrations and showed no significant difference to the P and K concentrations with fertilizer and mucuna (Appendix 5), these nutrients were not limiting during the early stage of maize growth (55 DAS).

Stover

Critical nutrient concentrations in the stover were 0.54 % for N, 0.05 % for P, 0.58 % for K, and 0.07 % for S (Table 4.34 and Figure 4.8).

Table 4.34: Maize stover nutrient concentrations [%] at harvest (130DAS) in the low and high-infested fields at one cropping period as affected by the superimposed cropping strategies

Nutrient content	Cropping strategy F	M	C
	Concentration [%]		
Nitrogen (N)			
Low	(+) 0.67	(*) 0.54	(-) 0.58
High	(+) 0.75	(+) 0.95	(+) 0.99
Phosphorous (P)			
Low	(*) 0.05	(+) 0.10	(+) 0.10
High	(+) 0.12	(+) 0.21	(+) 0.23
Potassium (K)			
Low	(+) 0.61	(+) 1.05	(+) 0.70
High	(*) 0.58	(-) 0.64	(-) 0.67
Sulfur (S)			
Low	(+) 0.12	(-) 0.11	(-) 0.08
High	(-) 0.07	(*) 0.11	(-) 0.08

T-test (p>0.05): (*) denotes the critical nutrient concentration; (+) higher than the critical concentration; (-) not significantly different from the critical concentration, mean values (n=3)
F = fertilizer, M = mucuna, C = control

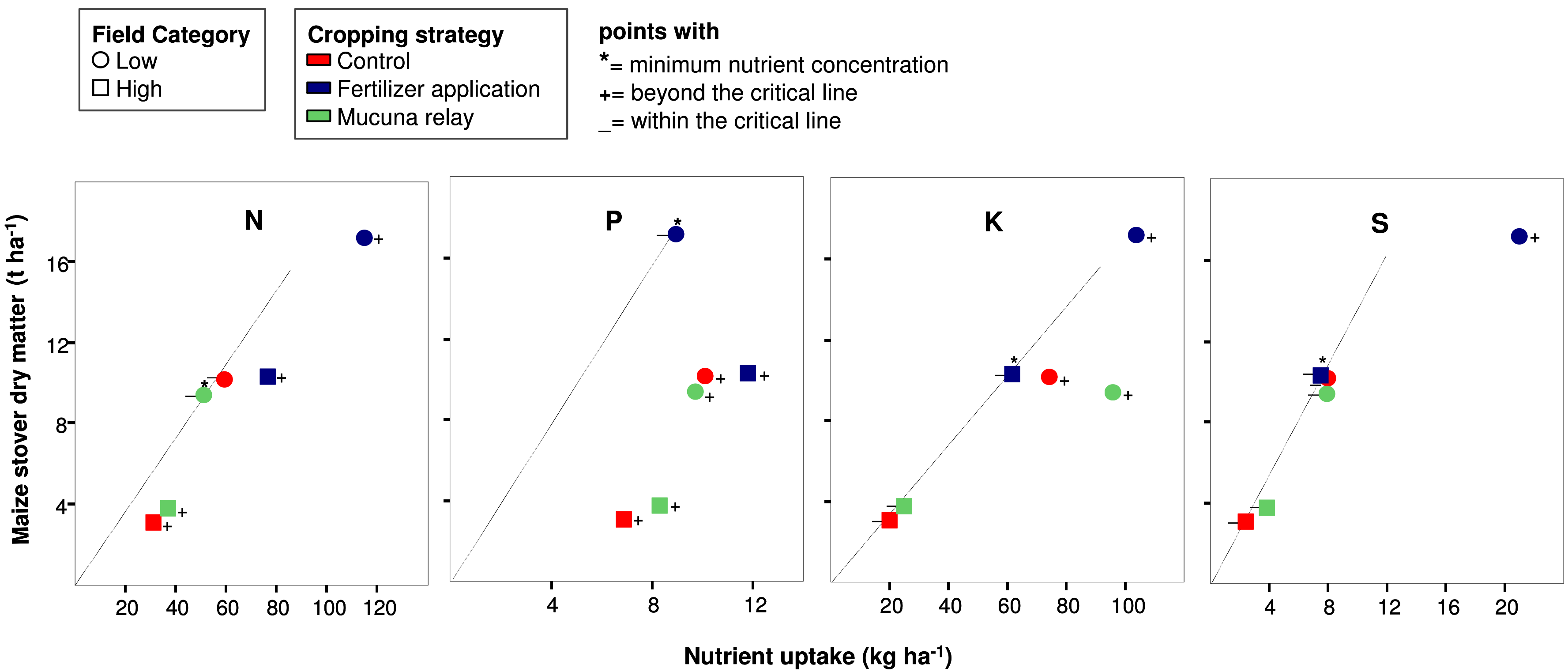

Figure 4.8: Content of N, P, K and S in maize stover dry matter at harvest (130 DAS) in fields of the second set of experiments (points represent the mean, n=3)

Examining the nutrient concentration in the stover, in the low-infested field without the cropping strategies (control) and with competition from mucuna relay, N and S concentrations were at a critical level, but not P and K. Fertilizer application enhanced the nutrient levels leading to even higher DM production with concomitant high stover N accumulation (115.0 kg ha^{-1}) although the P concentration in the DM was at critical level. The high K concentration (1.05 %) even with mucuna competition suggests that available K in the field was still adequate to support maize growth until maturity. The high stover yield (average: 12.3 kg ha^{-1}) may have stressed the nutrient pools of N, P and S, but likely not of K. Even with mucuna competing for K, the concentration was still high.

In the high-infested field, without the cropping strategies (control) and with competition from mucuna relay, and even with fertilizer application, K and S were at critical levels, whereas N and P were above the critical levels. But, the high N and P concentrations in the maize stover in the control and with mucuna relay reflected a luxury consumptions of these nutrients considering that the stover DM in plots with mucuna relay (3.8 kg ha^{-1}) and in the control (3.1 kg ha^{-1}) were low. The stunted maize stands continued to take up the remaining available nutrients in the soil. Fertilizer application enhanced maize DM production, thus K (61.5 kg ha^{-1}) and S (7.5 kg ha^{-1}) nutrients accumulated in the biomass were high (Appendix 5). However, because of the strong competition from *Imperata*, applied fertilizer made no difference on the nutrient concentrations in the biomass. Fertilizer application supplies the nutrients for maize growth until maturity, but apparently barely enough for the stover production.

Grain

Like in the first set of experiments, grain yield and nutrient uptake show a linear relationship with high regression coefficient with similar slope for all four nutrients and consistent R^2 –values of ≥ 0.97. Also, the concentration of nutrients in grain show that it is independent of the DM yield (Table 4.35 and Figure 4.9)

The grain in the low-infested field had higher N (89.1 kg ha^{-1}) and K (32.3 kg ha^{-1}) suggests that both N and K, especially with fertilizer application (Appendix 4). On the other hand, nutrient accumulations in the high-infested field were not significantly different irrespective with or without cropping strategies (Appendix 5). The nutrient concentrations were even lower with fertilizer application, suggesting that there was no effective transfer of nutrients to the grain from the stover. Further, the higher nutrient concentrations in the grain in the control and with mucuna relay suggest that there was high supply from stover, which had luxury consumption of the nutrients.

Table 4.35: Maize grain nutrient concentrations [%] at harvest (130DAS) in the low and high-infested fields for one cropping period as affected by the superimposed cropping strategies

Nutrient content	Cropping strategy		
	F	M	C
	Concentration [%]		
Nitrogen (N)			
Low	1.23	1.20	1.21
High	1.15	1.90	1.55
Phosphorous (P)			
Low	0.11	0.14	0.13
High	0.12	0.14	0.15
Potassium (K)			
Low	0.44	0.49	0.48
High	0.42	0.47	0.52
Sulfur (S)			
Low	0.15	0.13	0.10
High	0.13	0.16	0.14

Mean values (n=3); F = fertilizer, M = mucuna, C = control

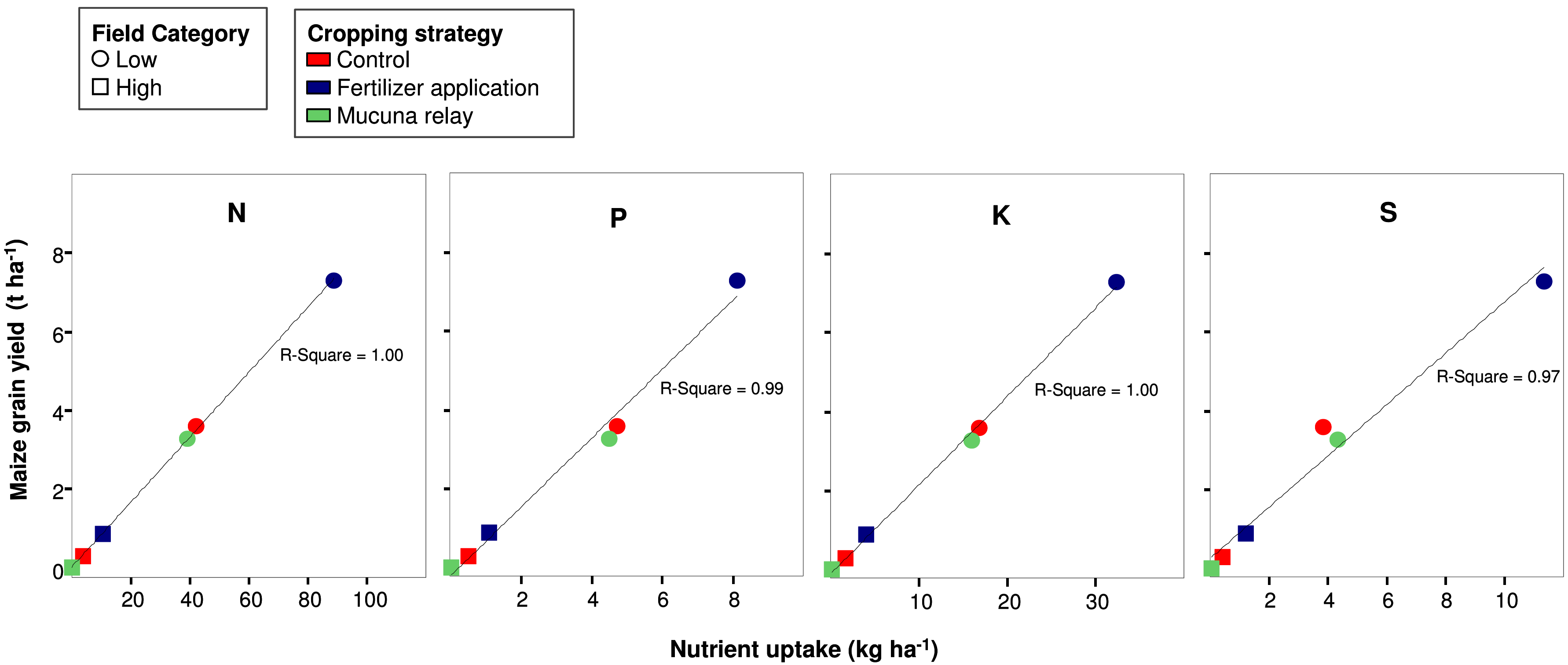

Figure 4.9: Content of N, P, K and S in maize grain dry matter at harvest (130 DAS) in fields of the second set of experiments (points represent the mean, n=3)

The result of second set of experiments that suggests that in the low-infested field, all four nutrients were marginal at early stage of maize growth. But, P and K supply were adequate to support DM production until maturity, especially when mineral fertilizers were applied. Although P fertilizer added was not sufficient enough for DM production until maturity, stover yield was significantly higher with corresponding high grain yield.

In the high-infested field, due to high competition from massive *Imperata* regrowth and the stunted maize growth except maize with mineral fertilizers, all four nutrients were assumed limiting. With fertilizer application, N, K and S were enhanced and able to support maize growth at early stage. However, because of the strong competition from massive *Imperata* regrowth, P was not sufficient even with fertilizer application, while N, K and S fertilizers were able to support and enhance maize growth and DM production at early stage. However, P, K and S supply were already limiting until maturity, thus affecting stover production. Although, stover yield was higher with fertilizer application, it failed to produce grain. In this field, not only K, but also P and S deficiencies were causing grain production impediments. The nutrient constrains was aggravated by the high competition of massive *Imperata* regrowth.

The two sets of experiments as demonstrated by the DM production and nutrient content in the maize biomass show that that maize yield response was higher when initial *Imperata* infestation was effectively controlled prior to cropping. Among the land preparation methods, the immediate positive effect of deep hoeing on maize growth was much stronger as exhibited by maize total DM production during the first cropping period. The maize yield in the respective fields, as affected by the land preparation methods, show that deep hoeing had a better effect on maize growth than herbicide application, as indicated by the stover production in all fields. However, the effect of land preparation methods had no far-reaching influence on grain yield. Also, neither land preparation method had a residual effect on the subsequent maize cropping period.

Alternatively, herbicide application also had positive effect on maize DM production in all three fields. In contrast, the shallow hoeing method only had a positive effect on maize in the low-infested field. Further, shallow hoeing in the high-infested fields combined with fertilizer application was only to some extent able to enhance maize stover production.

Fertilizer application was effective in enhancing maize growth in all fields. Mucuna relay was a better alternative than maize cropping without fertilizer, as it had a residual effect on maize in the subsequent crop. In the first maize cropping period, mucuna relay did not have a significant effect on maize yield, but did not also affect negatively maize DM production. Maize stover growth was enhanced but with little effect on grain yield. In the control (without fertilizer or mucuna), maize DM (stover and grain) decreased in the subsequent cropping period. Particularly, in the high-infested field, fertilizer application was effective in raising grain yields, but the harvest index remained unusually low, which were: 0.3 following deep hoeing, 0.1 following herbicide application, and 0.1 following shallow hoeing.

Effective elimination of initial *Imperata* infestation opens up the opportunity to overcome the nutrient constraint by fertilizer application, though not fully. Further, removing *Imperata* without destroying the rhizomes largely negates the positive response to fertilizer application, as demonstrated in the high-infested field by the high stover production. The stover developed a cob, but the cob tissue was mostly empty or without kernels. In this field, grain production was impeded by nutritional constraints aggravated by competition from *Imperata*. Thus, it appears shallow hoeing as land preparation to control high *Imperata* infestation in the field, is not adequate even when combined with fertilizer application or mucuna relay.

On the other hand, since fertilizer application was able to enhance maize growth and stover production in the high-infested field, the poor grain or no grain production could be attributed to insufficiency of supply of mineral fertilizers added or the failure to correct the limiting nutrients, which was aggravated by the massive regrowth of *Imperata* competing for the nutrients.

Therefore, an effective control of *Imperata* infestation prior to maize cropping is necessary for the growth of maize. Also, in order to free the maize crop from the strong competition from *Imperata* for the already limiting nutrients as well as for an efficient use of the added nutrients through mineral fertilizer application and contribution from mucuna relay.

Among the four nutrients, K was identified as the determining factor for the grain production in the three fields. With the fertilizer inputs, the K nutrient level was alleviated in all fields. The proportion of nutrients in the mix of fertilizers should be sufficient to alleviate and correct the specific nutrient limitations in all fields in order to supply the right amount needed by the crop.

Even with high maize growth at early stage and with high stover production, but with no grain produced would certainly discourage farmers to continuously cultivate the field for maize production. The condition especially becomes worst for the farmers when the fields are totally covered by *Imperata*.

4.4 Mucuna response as relay crop to maize

4.4.1 Mucuna dry matter production

Mucuna DM yield in fields with intensive land preparation

The intensive land preparation method (deep hoeing or herbicide application) eliminates *Imperata* and thus its competition with mucuna. The results show that the average DM yields of the mucuna relay for the two maize cropping periods were not significantly different in the three fields (Table 4.36).

Table 4.36: Mucuna dry matter (t ha^{-1}) after two cropping periods in the low, medium and high-infested fields with intensive land preparation

Sampling period	Field category		
	Low	Medium	High
	Mucuna DM [t ha^{-1}]		
After 1st harvest (130 DAP)	5.3 ns	4.4 ns	5.5 ns
After 2nd harvest (130 DAP)	1.7 ns	1.2 ns	2.1 ns

Tukey test (p<0.05): ns denotes no significant difference between fields, mean values (n=6)
DAP = days after planting mucuna

Even with only shallow hoeing conducted prior to the second cropping period, there was an effective residual effect of the *Imperata* eradication to the subsequent mucuna. The lack of competitive pressure from *Imperata* remained even during subsequent cropping. However, there was a three-fold reduction of the mucuna DM yield during the second cropping harvest in all three fields, which was probably due to the competition by other weeds, aggressively growing during the second cropping period (section 4.2.1.1- Table 4.15). Also, the enhanced subsequent maize growth with high stover production that benefit from the nutrient inputs of the previous mucuna relayed may have had a suppressive effect on mucuna (section 4.3.1.1-Table 4.25).

Comparing the residual effect of deep hoeing and herbicide application in affecting mucuna DM production, the results show that there were no significant differences of the two methods (Table 4.37).

Table 4.37: Mucuna dry matter (t ha^{-1}) after two cropping periods in the low, medium and high-infested fields with intensive land preparation as affected by the land preparation methods

Sampling period	Field category					
	Low		Medium		High	
	DH	HA	DH	HA	DH	HA
	Mucuna DM [t ha^{-1}]					
After 1st harvest (130 DAP)	5.2 ns	5.4 ns	3.4 ns	5.3 ns	5.9 ns	5.0 ns
After 2nd harvest (130 DAP)	1.8 ns	1.7 ns	1.4 ns	1.2 ns	2.1 ns	2.1 ns

Least Significant Difference test ($p<0.05$): ns denotes no significant difference between the two land preparation methods within field category, mean values (n=3)
DH = deep hoeing, HA = herbicide application; DAP = days after planting mucuna

Mucuna DM yield in fields with minimum tillage

In the high-infested field, where *Imperata* still remained highly competitive, mucuna growth was substantially suppressed, producing less than 50 % (4.5 t ha $^{-1}$) of the mucuna DM in the low-infested field (9.6 t ha^{-1}) (Table 4.38). However, mucuna DM production in the high-infested field was, however, comparable to that of the three fields in the first set of experiments.

Table 4.38: Mucuna dry matter (t ha^{-1}) after one cropping period in the low and high-infested fields with minimum tillage

Sampling period	Field category	
	Low	High
	Mucuna DM [t ha^{-1}]	
After 1st harvest (130 DAP)	9.6	4.5

Least Significant Difference test ($p<0.05$): ns denotes no significant difference between field, mean values (n=3); DAP = days after planting mucuna

4.4.2 Nutrient levels in mucuna dry matter

Nutrient content in mucuna dry matter in the low-, medium-, and high-infested fields

Nutrient accumulation in mucuna was concomitant with DM production. During the first cropping period, there was no significant difference in DM yield and nutrient accumulation in the mucuna biomass in all fields (Table 4.39). However, the concentrations in the mucuna biomass show that mucuna in the medium-infested field had significantly higher N and K concentrations, but lower in the high-infested field. Again, indicating that N and K were limiting in the high-infested field.

In the second cropping period, DM yield of mucuna as well as the nutrient accumulated in the biomass decreased in all fields. Also, there was no significant difference in N, K, and S accumulation in mucuna in the three fields. The P content was significantly higher in the high-infested field, which again demonstrates that P supply was high in this field. The N concentration in mucuna was higher in the medium-infested field, while S concentration was highest in the low-infested field, and K concentrations were not significantly different between fields.

Table 4.39: Content of N, P, K and S in mucuna dry matter for two cropping periods in the low, medium and high-infested fields with intensive land preparation

Nutrient content	Field category					
	Low	Medium	High	Low	Medium	High
	Mucuna DM					
	Uptake [kg ha^{-1}]			Concentration [%]		
1st harvest (130 DAP)						
N	170.4 ns	159.3 ns	149.2 ns	3.18 ab	3.23 b	2.74 a
P	11.0 ns	8.9 ns	10.5 ns	0.21 ns	0.18 ns	0.19 ns
K	59.6 ns	61.7 ns	47.2 ns	0.13 ab	1.25 b	0.83 a
S	16.9 ns	16.4 ns	17.0 ns	0.32 ns	0.33 ns	0.31 ns
2nd harvest (130 DAP)						
N	48.0 ns	40.9 ns	64.2 ns	2.79 a	3.05 b	2.99 ab
P	2.9 ab	2.0 a	4.3 b	0.17 ab	0.15 a	0.20 b
K	13.8 ns	10.6 ns	15.9 ns	0.78 ns	0.79 ns	0.69 ns
S	5.3 ns	3.2 ns	4.2 ns	0.31 c	0.24 b	0.19 a

Tukey test ($p<0.05$): Letters a, b, c denote significant difference, ns denotes no significant difference between fields; mean values (n=6); DAP = day after planting mucuna

Nutrient content in mucuna dry matter in the low- and high-infested fields

With shallow hoeing, mucuna N accumulation in the low-infested field was significantly higher than in the high-infested field (Table 4.40). Accumulation of P, K and S were not significantly different. However, the P and K concentrations in the mucuna were significantly higher in the high-infested field than in the low-infested field. This indicates that in the high-infested field and among the four nutrients, P and K were highly available for mucuna growth than N and S.

Table 4.40: Content of N, P, K and S in mucuna dry matter for one cropping period in the low and high-infested fields with minimum tillage

Nutrient content	Field category			
	Low	High	Low	High
	Mucuna DM			
	Uptake [kg ha^{-1}]		Concentration [%]	
At harvest (130 DAP)				
N	295.8 b	122.4 a	3.08 ns	2.73 ns
P	18.3 ns	11.7 ns	0.19 a	0.26 b
K	62.7 ns	50.1 ns	0.65 a	1.12 b
S	17.8 ns	10.6 ns	0.19 ns	0.21 ns

Least Significant Difference test (p<0.05): Letters a, b denote significant difference, ns denotes no significant difference between fields, mean values (n=3); DAP = day after planting mucuna

The two sets of experiments demonstrate that mucuna can grow irrespective of the different levels of initial *Imperata* infestation and soil fertility conditions in the field. However, the potential high mucuna DM production is restricted when there was strong competition from the *Imperata* and other weeds, and when nutrients were limited for its growth and DM production.

Many authors indicated that poor establishment of in the field could be due to lack of nodulation and effective N_2 fixation (Sanginga et al., 2996), which are limited by N, P and micronutrients (Craswell et al., 1987; Giller and Wilson, 1991); the poor symbiotic effectiveness of mucuna and/or its poor nutrition because of mineral deficiencies in the soil (Houngnandan et al., 2001).

4.4.3 Mucuna biological nitrogen fixation in fields with intensive land preparation

Nitrogen derived from atmospheric N_2 (Ndfa) of mucuna was not significantly different between fields. This also demonstrates that the initial degree of *Imperata* infestation and respective soil conditions of the fields had no differentiating effect on the potential of mucuna for N fixation. The percentages of N fixed (Table 4.41) were higher than those reported in similar studies, suggesting that all three fields still provided good conditions for N fixation.

Table 4.41: Nitrogen fixation of mucuna in the low, medium and high-infested fields determined at the end of the two-maize cropping period experiment (September 2004) using maize and weeds as reference

Mucuna N_2 fixation	Field category		
	Low	Medium	High
Maize as reference			
Mucuna Ndfa [%]	86 ns	86 ns	87 ns
Ndfa [kg ha^{-1}]	41.1	35.1	56.0
Weeds as reference			
Mucuna Ndfa [%]	93 ns	94 ns	92 ns
Ndfa [kg ha^{-1}]	44.6	38.6	58.9

Tukey test ($p<0.05$): ns denotes no significant difference between fields, mean values (n=6)

Reports of many studies have shown that N_2-fixation of mucuna ranges from 43 – 90 % (Sanginga et al., 1996; Becker and Johnson, 1998; Ebewiro et al., 2000; Houngnandan et al., 199 and 2000; Wortmann, et al., 2000; Hauser and Nolte, 2001; Kaizzi, 2002). Also, the proportion of N from N_2-fixation in crops ranges from 0 %, when environmental stresses are severe and prevent nodulation, to 98 % in crops growing in ideal conditions (Smithson and Giller, 2002).

In this study, however, the amount of N fixed by mucuna in all fields, ranging from 35 - 60 kg ha^{-1}, was very low due to the low biomass production during the second cropping period (ranging from 1.2 - 2.1 t ha^{-1} with total N yield of 48 – 64 kg ha^{-1}). Assuming that this fixation rate for the biomass production (4.4 – 5.5 t ha^{-1}) and N yield (149- 170 kg ha^{-1}) of the first harvest was the same, the N fixed by the mucuna should ranged from 130 – 158 kg ha^{-1} N, which was about the amount of mineral N fertilizer added to the plots with fertilizer application. This can explain the increased or stable maize yield in all fields in the second cropping period when a mucuna relay was incorporated into cropping system.

Further, the results confirmed the beneficial of mucuna as relay crop to maize crop. Primarily as a contributor of N and other nutrients from its residues to the maize crop in the subsequent cropping period, as a smother crop suppressing other weeds growth replacing *Imperata* after it has been effectively eliminated prior to cropping, and as a strategy for suppressing an eventual *Imperata* re-infestations in the field. On the other hand, the reduction of growth rate due to strong competition and soil degradation also reduce the effectiveness of mucuna as a smother crop in suppressing *Imperata* as well as other weeds. Further, as a source of N, the BNF potential is constrained by the prevailing and eventual soil conditions. The lack of nutrients restricts the development and the population of free-living rhizobia in the rhizosphere, thus limiting the growth of mucuna and restricting the nodulation, and impairing nodule function (Giller and Wilson, 1991; Houngnandan et al., 2001).

4.5 ^{15}N recovery in fields with intensive land preparation

Of the 30 kg ha^{-1} of applied ^{15}N labeled urea, on average 98% was recovered. There was no significant difference of ^{15}N recovery in the plant-soil system between fields (Table 4.42). The plant system took up only 37 % (~11 kg ha^{-1}); 10.8 kg ha^{-1} by the maize and 0.39 kg ha^{-1} by weeds, while 61 % (~18 kg ha^{-1}) remained in the soil system. About 41 % (12 kg ha^{-1}) was recovered on the upper soil layer (0-15 cm depth), ~12 % in the 15-30 cm and ~ 8 % in the 30-60 cm soil layers.

Table 4.42: Recovery of ^{15}N-labeled urea in plant-soil system at the end of the two-maize cropping period experiment (September 2004) in the low, medium and high-infested fields

Plant-soil system ^{15}N recovery	Field category		
	Low	Medium	High
Total (plant-soil system)			
^{15}N recovered [%]	99.4 ns	95.6 ns	98.7 ns
^{15}N recovered [kg ha^{-1}]	29.8 ns	28.6 ns	29.7 ns
Plant system			
^{15}N recovered		[%]	
maize	38.1 ns	33.6 ns	35.9 ns
weeds	1.2 ns	1.6 ns	1.2 ns
^{15}N recovered		[kg ha^{-1}]	
maize	11.4 ns	10.1 ns	10.8 ns
weeds	0.4 ns	0.4 ns	0.4 ns
Soil system			
^{15}N recovered		[%]	
0-15 cm depth	b 39.3 ns	b 41.6 ns	b 43.3 ns
15-30 cm depth	a 11.7 ns	a 11.3 ns	a 10.4 ns
30-60 cm depth	a 9.1 ns	a 7.5 ns	a 7.9 ns
^{15}N recovered		[kg ha^{-1}]	
0-15 cm depth	b 11.8 ns	b 12.5 ns	b 13.0 ns
15-30 cm depth	a 3.5 ns	a 3.4 ns	a 3.1 ns
30-60 cm depth	a 2.7 ns	a 2.2 ns	a 2.4 ns

Tukey test ($p<0.05$): ns denotes no significant difference between fields, mean values (n=6)
Letters a, b denote significant difference between soil depths (by rows) mean values (n=6)

This suggests that higher N immobilization occurred in the upper soil layer, which was with the plant roots. A considerable amount of N was also observed in the 15 to 30 cm depth in all fields, suggesting that the amount of added N leached below 60 cm depth was not significant. The intensive land preparations prior to cropping were equally effective in eradicating *Imperata* in all fields and thus freeing the growth of maize from competition. The ^{15}N recovered in the maize in all fields is in line with the positive response of maize in all fields to mineral N fertilizer application. The application of fertilizer N to the soil-plant system enhanced mineralization and plant availability of N. This was demonstrated by the enhanced maize growth with maize total DM yields equally high in all fields. This was true even with the competition through the presence of *Imperata*, as demonstrated in high-infested field under shallow hoeing, where the response of maize to fertilizer also suppressed the growth of other weeds. Further, it suggests that even with intensive land preparation, an excessive loss of N through erosion and leaching could be minimized while maximizing N-use efficiency in the maize crop.

5 GENERAL DISCUSSION

Forests lands conversion continued and is increasingly utilized for food production (FAO, 2005). In Asia, this conversion is equally divided between permanent agriculture and shifting cultivation. It is reported that the acid soils in the tropics represent the last and largest reserve for agricultural land (von Uexküll and Mutert, 1995). But these soils are vulnerable to degradation when cleared of forest cover and utilized for agriculture using low-inputs techniques since they easily lose their inherent fertility. Low N, P, K and Al toxicity are reportedly the major problems of these soils.

In Southeast Asia, the greatest potential for extending agriculture production lies in the 64% of the total land area classified as "upland" or rainfed land or the acid upland soils (Dierolf et al. 2001). In earlier times, when pressure on land was still low, shifting cultivation practiced by the farmers was sustainable. However, the need to increase food production to meet the demand of the increasing human population, and unavailability of additional land has caused a reduction in the fallow period or led to permanent cultivation, but often without or limited fertilizer inputs. Further, the demand for maize in Southeast Asia is rapidly outpacing the supply (CIMMYT, 1999). Since suitable land for intensive lowland agriculture is no longer available, farmers are growing more maize in the uplands. However, the upland cultivation is at risk of *Imperata* weed infestation (Sanchez et al., 1987; Santoso et al. 1994; von Uexküll, 1995; van Noordwijk et al., 1997).

Imperata cylindrica is a noxious and pandemic weed in tropical Asia. The traditional slash-and-burn practice during field preparation and the declining soil fertility as a result of continuous cultivation without fertilizer inputs has aggravated the spread of *Imperata*. *Imperata* strongly competes with crops leading to declining yield or complete crop loss (Koch et al., 1990; Udensi, 1994; Chikoye et al., 1999). When crop production is low, the farmer has little incentive to weed infested fields, and thus *Imperata* becomes firmly established. Forest lands utilized for annual crop production once infested with *Imperata* are fallowed or totally abandoned.

Soil tillage by deep hoeing/plowing or disking several times during dry season, desiccating the rhizomes is one of the oldest methods of *Imperata* control (MacDonald, 2004). Shallow tillage is considered ineffective since *Imperata* rhizomes are hardly affected (Chikoye, 2005). Many studies have indicated that most manual *Imperata* control measures have limited success (Ivens, 1975; Anoka et al., 1991; Akobundu and Ekeleme, 2000) compared to chemical control (Chikoye et al. 2000 and 2002), while integrated control approaches are suggested (Menz et al., 1998; MacDonald, 2004; Chikoye, 2005).

Intensive cropping with sufficient fertilizer inputs and herbicide use was found feasible (Zaini and Lamid, 1993; van Noordwijk et al., 1997). Likewise, intercropping of cover crops with food crops is widely recommended (von Uexküll and Mutert, 1995; Versteeg and Koudokpon, 1990; van Noordwijk et al., 1997; Carsky et al., 1998; Akobundu et al, 2000; Houngnandan et al., 2000 and 2001; Giller, 2003). Generally, the use of inorganic fertilizer is to improve soil fertility, while a green manure cover crop is recognized as an alternative since not all farmers can afford the chemical fertilizers. Mucuna (*Mucuna pruriens*) is among the well-known leguminous cover crops which were initially introduced to restore soil fertility. Recently, the use of mucuna is primarily related to the control of weeds (Versteeg and Koudokpon, 1990; Buckles, 1995; Triomphe, 1996; Buckles et al., 1998; Manyong et al., 1999).

This study investigated various combinations of *Imperata* control during land preparation with crop management practices to determine whether such combinations are feasible either to eradicate or to prevent maize cultivated fields in the rainforest margins, which are at various stages of *Imperata*-infestation, from turning into sheets of *Imperata*. Maize is considered a good test plant, since it is widely planted in the uplands, and very sensitive to nutrient deficiency. Further, maize yield and quality are strongly influenced by nutritional factors, which reflect the soil nutrient status of the fields.

5.1 Effect of land preparation and cropping strategy as weed control cultivation practices

It is generally recognized that the objective of any *Imperata* control management strategy should be the destruction of rhizome system, the plant part by which the weed persists and spreads. The results of this study confirmed that deep hoeing (hoe tillage) or herbicide (glyphosate) application during land preparation prior to maize cropping were equally effective methods of *Imperata* control even in fields with high infestations.

Shallow hoeing was only effective in fields with low infestation. This was also observed by a similar study conducted in West Africa by Chikoye et al., (2005). However, in their study, glyphosate application was found more effective in reducing *Imperata* shoot biomass than hoe tillage. Further, these authors indicated that for tillage to be effective, tillage should be to about 30 to 40 cm depth since most rhizomes are found above this depth.

In this study, the effects of both deep hoeing and glyphosate application in reducing *Imperata* density and biomass in all fields were not significant different. Initially, *Imperata* rhizomes in the fields were observed up to 30 cm soil depth. But, hoeing conducted only to about 15 cm soil depth was still effective in up-turning and destroying the *Imperata* rhizomes through desiccation. This result confirmed the report of Ivens (1975) that 2-3-nodes length rhizomes could not sprout when at the depth of >7.5 cm. Even longer rhizomes at 20 cm depth will just rot. When *Imperata* has just newly established and rhizomes are shallow, minimum tillage is still feasible. This was demonstrated in the second set of experiments where shallow hoeing was still effective in fields with low *Imperata* infestations. In a highly *Imperata* infested fields, where rhizomes are deeply established, shallow hoeing only destroyed the foliage and the surface rhizomes. The in-tact rhizomes below that depth were still viable so the *Imperata* regenerated rapidly. Ivens (1975) indicated that the longer the rhizomes underground, the better the chances of sprouting because of the carbohydrates reserves. The failure of totally destroying the rhizomes appears the prime reason for manual *Imperata* control to meet with limited success (van Noordwijk et al., 1997; Akobundu and Ekeleme, 2000; Chikoye et al. 2000 and 2002).

On the other hand, the chemical application with systemic herbicides (e.g. glyphosate) was very effective in combating the *Imperata*. This was because of the effective translocation of chemicals to the rhizomes. Furthermore, this type of *Imperata* suppression is much easier and quicker to conduct. It is also reported to be cost effective and associated with less soil disturbance, which is important especially where erosion may be of concern (Townson, 1991; Chikoye, 2005). Chikoye et al., (2000 and 2002) reported that herbicide application provided larger benefits than manual control. However, for smallholder farmers without the resources to purchased herbicides but with farm labor readily available, manual hoeing seems preferable.

An effective elimination of *Imperata* prior to cropping does not mean that maize growth is free from weeds interference. During maize cropping, other weeds grow abundantly in all fields, previously dominated by *Imperata*. The change of weed composition in fields after *Imperata* control was also reported by similar studies conducted in West Africa (Anoka et al., 1991; Udensi et al., 1999; Chikoye et al., 2005). They observed that annual weeds increased after effective control of *Imperata* with glyphosate application, except when a cover crop was combined with the chemical control. Chikoye et al., (2005) reported that effective *Imperata* control resulted in increased dominance of sedges and annual broadleaved weeds. Apparently, the conditions become favorable for the seeds of other weeds species to germinate when the strong competition from *Imperata* is eliminated. Also, the seeds of other weeds that lie dormant in the soil are brought up to the surface during tillage (Udensi et al., 1999; Chikoye et al., 2001; Chikoye, 2003).

The results demonstrate that after effective *Imperata* control during land preparation, a superimposed crop management strategy during maize cropping is vital to smother infestations by other weeds and suppress *Imperata* growth and possible re-infestation. As superimposed cropping strategy, fertilizer application and mucuna relay both had a suppressive effect on growth by other weeds and *Imperata* re-infestation. Although in this study, the significant suppressive effect was observed only after second maize cropping period.

The application of mineral fertilizers also contributed to a better nutrient supply for other weeds, especially when there was no more competition from *Imperata* and no strong competition yet from the young maize crop at an early growth stage. However, once the growth of the maize accelerated due to the efficient utilization of fertilizer, the maize crop became highly competitive, thereby suppressing *Imperata* growths and that of other weeds thus reducing their competition for nutrients.

The newly grown *Imperata*, which has not yet fully established its root/rhizomes system did not significantly benefit from the nutrient inputs. The roots do not develop easily in the young rhizome so it is not capable of rapid regeneration (Ayeni and Duke, 1985) and therefore it is not very competitive for nutrients. Rather, fertilizer application increases the maize crop competitive ability against weeds due to the high growth rate (Bàrberi, 2005); particularly, the addition of fertilizer N and P increases the competitiveness of a desirable crop species over *Imperata* (Stobbs, 1969; Blair et al., 1978; Burnell et al., 2003; Brewer and Cralle, 2003; Macdonald, 2004). The enhanced maize growth, as demonstrated by high stover DM had a shading effect. Barnes et al. (1990) also reported this and linked the increase in competitive ability of crop cultivars to plant height and canopy leaf area index (LAI), which increased with narrow rows for maize crop spacing (Chikoye et al., 2005).

Mucuna relay consistently had a suppressive effect on the growth of weeds other than *Imperata*, attributed to its growth habit which is twining and creeping. The physical effect of mucuna as live mulch is largely a shading effect rather than a nutrient-mediated effect (Teasdale and Mohler, 2000; Bàrberi, 2005). Shading reduces the carbohydrate content and growth vigor of the weed (Moossavi-nia and Dore, 1979; Chikoye and Ekeleme, 2001; Chikoye et al., 2005). Bàrberi (2005) indicated that interference from cover crops and their residues is related to their occupation of ecological niches otherwise occupied by the weeds. But in this study, other weeds with mucuna relay also managed to accumulate high content of nutrients (Tables 4.18 to 4.22), which suggests that other weeds are potentially competitive and can take advantage of available nutrients.

Thus, the effective elimination of the initial *Imperata* during land preparation alone created opportunities for infestation by other weeds which constituted a major constraint to maize crop production. Superimposing mineral fertilizer application or mucuna relay as cropping strategy was needed to prevent this. Further, *Imperata* re-infestation was potentially high when the fields are continually cropped without any soil fertility inputs. A stunted and unhealthy maize plant has no chance to compete for the remaining available nutrients in the soil. As indicated by many authors, and as observed in this study, when *Imperata* has already established its root-rhizomes system, it has a strong ability to extract nutrients even in fields with poor soils or low soil fertility status.

5.2 Maize yield response to land preparation and cropping strategy

The elimination of the initial *Imperata* infestation prior to cropping positively affects maize growth, as indicated by the maize total DM production. Chikoye et al. (2005) also reported that hoe tillage and use of herbicide (glyphosate) increased maize grain yield by 21 %. However, in this study land preparation by itself to control initial *Imperata* infestation in the field had no great influence on maize grain production. However, it was observed that the residual effect of deep hoeing was much better than herbicide application, as demonstrated by the higher maize total DM in all fields. This can be attributed to the mulching effect of the high biomass of dug-up rhizomes after deep hoeing. As Akobundu and Ekeleme (2000) indicated, the mulch of dug-up rhizomes can provide nutrients or may affect soil temperature, thus benefiting the maize crop. Scopel et al. (2001) indicated that soil tillage can also affect water availability to the crop as mulching increases soil water storage.

Maize yield response in all fields was influenced more by the superimposed cropping strategies. Fertilizer application and mucuna relay are soil fertility enhancing inputs that nourish the maize crop more than weed control. The efficient use of nutrient inputs from mineral fertilizers and from N fixed by mucuna explained the enhanced the growth of maize in fields with fertilizer application as well with mucuna relay. However, it is still essential that effective control of initial *Imperata* infestation should be undertaken prior to cropping in order for the maize crop to be able to efficiently utilize the nutrients added, free from strong competition. As demonstrated by the ^{15}N recovery, once there was no strong competition from newly grown *Imperata* and other weeds, maize took up 10.8 kg ha^{-1}N, and only about 0.39 kg ha^{-1} N was in the weeds.

When *Imperata* infestation is eliminated prior to cropping and then measures are taken to improve the fertility status of the field, maize growth is enhanced and thus became an effective competitor for nutrients. As indicated in the previous section, the enhanced maize growth had a shading effect, thereby suppressing *Imperata* re-infestation and other weeds (annual weeds) that replace *Imperata*. Often, fertilizer application increased the harvest index. However in the high-infested field in particular, mineral fertilizer was able to enhanced stover production, but the grain produced did not commensurate with the potential of the stover.

Mucuna relay as cropping strategy had no immediate positive effect on maize yield. However, it did have a residual positive effect on the subsequent maize crop which was attributed to the N_2 fixed and other nutrients added from the mulch of the mucuna relayed during the previous cropping period. With this added nutrient, maize stover production was slightly enhanced with a concomitant effect on the grain yield.

Without fertilizer or mucuna relay as cropping strategy, maize growth and DM production decreased in the subsequent cropping period, especially in the high-infested field where maize cropping was a complete failure. This is the main reason why farmers fallow or totally abandoned *Imperata* infested areas.

The eradication of *Imperata* opens up the opportunity for maize to become highly competitive in utilizing the added nutrients and to enhance its growth and DM production. The mineral fertilizers applied in this experiment did not fully alleviate the nutrient deficiency for the maize crop to substantially increase grain yield in the high-infested field, in particular. It seemed that the amount of minerals fertilizer added failed to fully correct the nutrient constraining the grain development in the high-infested field. In line with the ´Law of the Minimum` by von Liebig, the analysis of nutrient levels in maize DM suggested that among the four nutrients tested, K was the most limiting in the field with the highest *Imperata* infestation. Even though fertilizer enhanced the maize DM, the K levels in the stover tissue were still very low. This low stover source strength of K apparently was unable to meet the sink demand for grain production. Thus, it impeded the development of grains. In the high-infested field where initial *Imperata* infestation was not fully eradicated, the condition was aggravated by the strong competition from the remaining and re-growing *Imperata* for K as well for other nutrients.

Similar studies in West Africa reported a maize yield reduction as high as 70% and a complete crop failure (Udensi et al., 1999; Chikoye et al., 2002; Chikoye et al, 2005), attributed to *Imperata* interference, especially when *Imperata* rhizomes are not destroyed prior to maize cropping. Chikoye et al. (2005) reported a low maize grain yield also on fields with cover crop but they attributed the low grain yield to cover crop competition. Hairiah et al. (1997) also reported a low maize grain yield (0.4 t ha^{-1}) in *Imperata* invaded areas in Northern Lampung, Indonesia. In their study, the authors attributed the low grain yield to low P-availability in the soil even though fertilizer P was added. On the other hand, Hauser and Nolte (2001) reported that total P uptake of maize had only a slight effect on grain yield, and considerably less than N which was the overriding factor for maize response on the soils of their study area. In many instances, it is indicated that soils of *Imperata* areas are low in available P and effective N supply (von Uexküll and Mutert, 1995; Santoso et al., 1997; Chikoye et al., 1999).

But contrary, the fields in this study with high-*Imperata* infestation had the highest available P. The large biomass accumulated high P and the other nutrients accumulated correspond to the availability in the soil.

In this study, K was identified as the key constraining nutrient in fields highly-infested with *Imperata*. This result confirmed the recent investigations by Collins (2005), who indicated that *Imperata* areas have low levels of K. The extensive belowground rhizome network (Daneshgar et al., 2005) as well as the association with mycorrhizae (Brook, 1989) accounts for the ability of *Imperata* to exploit soil K. Further, the author indicated that decreases in soil K have serious implication for recruitment and growth of other plant species since K is known to affect cell division, formation of carbohydrates, translocation of sugars, and several other functions (Plaster, 1992). Potassium is also associated with the regulation of water within the plant and with the control of water loss from the leaves. The symptoms exhibited in the high-infested fields are classic examples of K deficiencies. According to Jones Jr. (2003), K deficiency severely reduces yield in maize. The poor cob formation and grain fill in maize resulting in low starch level are consequences of low K. As indicated by Beringer (1980), better K nutrition improved grain setting in the ear, i.e. stimulated the storage capacity for assimilates, which could be seen from the remarkable increase in single grain weight and number of grains/ear. It was also reported by Mussgnug et al. (2005) that K was the most yield-limiting macronutrient in the Red River valley in Vietnam, and regular K applications were required to make investments in the application of other mineral nutrients profitable.

5.3 Effect of land preparation as an *Imperata* control method to the DM production and BNF potential of mucuna as relay cover crop to maize

The results demonstrate that once the strong competition of *Imperata* is eliminated, the N fixation potential of mucuna relayed with maize is also high, irrespective of the initial *Imperata* infestation. The exceptionally high dependence on N_2 fixation of mucuna reflects the poor N status of the soil in this study. Apparently, the other nutrients in the soil, particularly P, were adequate to support N_2 fixation. Nitrogen fixing crops have a high P requirement for nodule development and optimum plant growth. This further indicates that P limitation is not the main problem in this *Imperata*-infested field.

Houngnandan et al. (2001) reported that mucuna established and fixed N_2 effectively in fields where P is not deficient.

The positive effect of mucuna is certainly related to its ability to fix N, but the immediate effects are non N-related, e.g., smothering of weeds (Hamadina et al., 1996; Carsky et al, 1998; Hauser and Nolte, 2001; Chikoye et al., 2005). Indeed, in this study, the beneficial effect of the mucuna relay is primarily in its nutrient contribution for the subsequent maize crop. As a strategy to control weeds, the mucuna relay is more effective in suppressing the annuals weeds replacing *Imperata*. Mucuna as relay crop to maize is not effective as a stand-alone against *Imperata*. If not managed properly, it has its drawbacks because it can also potentially smother the maize crop. Also, as an added plant species during cropping it competes for nutrients. Chikoye and Ekeleme (2003) indicated that cover crops do not eliminate *Imperata* in the system. But as a superimposed alternative to fertilizer following an effective land preparation method to control *Imperata*, mucuna relay is a better option than sole maize cropping. As with mineral fertilizers, the subsequent positive effects of the mucuna relayed on the maize are in the secondary suppressive effect on the newly grown or re-infesting *Imperata*

6 CONCLUSIONS AND RECOMMENDATIONS

The experiments conducted in the montane rainforest margins in Central Sulawesi, Indonesia, in maize-based cultivated fields with different degrees of *Imperata* infestation show that *Imperata* can be combated and suppressed by appropriate combination of land preparation and cropping management practices.

When *Imperata* infestation in the field is above a critical thresholds with >100 shoots m^{-2}, total DM >5.0 t ha^{-1}, shoot DM >2.0 t ha^{-1}, rhizome DM >2.0 t ha^{-1} or when rhizomes are deeply established at depth >15 cm, intensive land preparation such as deep hoeing or herbicide use is the only effective option. However, when *Imperata* has just newly established in the field or as long as the infestation is still below the critical level, shallow hoeing is sufficient to eliminate the competition by *Imperata* on maize. After eradicating the initial *Imperata* infestation, cropping strategies enhancing soil fertility management (fertilizer application and mucuna relay) have a suppressive and smothering effect on *Imperata*.

In *Imperata*-infested fields, fertilizer application was the best cropping strategy following intensive land preparation, since it effectively enhanced maize growth and increased crop competitiveness, thus suppressing *Imperata* re-infestation. As an alternative, mucuna as a relay crop in maize can be a viable cropping strategy provided the mucuna is prevented from smothering the maize, and the nutrient stocked in the soil allows vigorous growth and DM production of maize crop as well as for mucuna growth.

Infestation and eventual *Imperata* invasion of a field can be avoided by improving soil fertility status from the onset of cropping to avoid the depletion of soil nutrients to levels limiting for crop productivity. When maize growth is healthy, it can compete better for light and nutrients, and thereby suppressing the re-infestation of *Imperata*. Thus, the key concept lies in correcting the limiting nutrients in the infested fields with the right kinds and balance amounts of fertilizer, so that the primary crop is given a chance to compete with the weeds and most importantly, provide a reasonable yield.

The field experiments provide evidence that maize grain production in fields highly infested with *Imperata* was impeded by K limitations. However, conclusive findings regarding K as the nutrient limiting maize yield should be based on a factorial experimentation with N, P, K, and S fertilizer application. Thus, additional studies are recommended to verify this result. Also, in order to design an optimum soil fertility enhancement strategy suited for the area, especially prone to *Imperata* infestation, and likewise, to determine the best economic rates of mineral fertilizer application for the region, especially for K fertilizers.

Further, it is recommended to conduct studies in fields with the early stage of *Imperata* infestation. Here it seems promising to assess the potential for effective use of less intensive land preparation methods combined with fertilizer application as a means of keeping *Imperata* at bay. Furthermore, since adequate amounts of essential nutrients are required to achieve a desired crop yield and quality, it is necessary to assess further the potential substitution of N fertilizer application by mucuna or other N-fixing cover crops as relay crop with maize. The results from the short-term experimentation reported here are encouraging in this regard.

This study emphasize that the key target of any soil fertility or cropping strategies is not only to maintain and improve the soil fertility status of *Imperata*-infested cultivated fields, but to correct the limiting nutrients for crop production to achieve optimum yield. Ultimately, if no economic return can be derived from cultivating the fields, farmers would eventually abandon the land or seek other potential cultivation areas in the forest areas and leaving the fields more vulnerable to *Imperata* invasion.

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8 APPENDICES

Appendix 1: Maize leaves (55 DAS) nutrient concentration [%] for two cropping periods in low, medium and high-infested fields as affected by the superimposed cropping strategies

Nutrient content	Field category					
	Low	Medium	High	Low	Medium	High
	1st cropping period			2nd cropping period		
	Concentration [%]					
Nitrogen (N)						
F	b 3.80 b	b 3.23 a	b 3.15 a	c 3.47 b	c 3.07 a	b 3.05 a
M	a 3.30 b	a 2.36 a	a 2.37 a	b 2.32 b	b 1.78 a	a 1.95 a
C	a 3.33 b	a 2.22 a	a 2.32 a	a 1.91 b	a 1.59 a	a1.74 ab
Phosphorous (P)						
F	ns 0.22 ns	ns 0.20 ns	ns 0.23 ns	c 0.23 b	b 0.20 a	b 0.23 b
M	ns 0.20 a	ns 0.19 a	ns 0.26 b	b 0.19 b	a 0.15 a	a 0.19 b
C	ns 0.21 a	ns 0.18 a	ns 0.24 b	a 0.16 a	a 0.16 a	ab 0.20 b
Potassium (K)						
F	ns 2.12 ns	ab 1.84 ns	ns 1.78 ns	ns 1.80 ns	ns 1.69 ns	b 1.76 ns
M	ns 2.09 b	a 1.81 ab	ns 1.58 a	ns 1.67 ns	ns 1.54 ns	a 1.38 ns
C	ns 2.14 b	b 2.02 b	ns 1.63 a	ns 1.24 ns	ns 1.77 ns	ab 1.48 ns
Sulfur (S)						
F	b 0.25b	b 0.22 a	b 0.22 a	c 0.41 b	ns 0.24 a	b 0.27 ab
M	a 0.22 b	a 0.16 a	a 0.16 a	b 0.31 b	ns 0.15 a	a 0.17 a
C	a 0.22 b	a 0.15 a	a 0.16 a	a 0.26 ns	ns 0.23 ns	a 0.16 ns

Tukey test ($p<0.05$): Letters a, b denote significant difference, ns denotes not significantly different between fields (column), and between cropping strategies (rows), mean values (n=6)
DAS = days after seeding of maize; F = fertilizer, M = mucuna, C= control

Appendix 2: Maize stover nutrient concentration [%] at harvest (130 DAS) for two cropping periods in low, medium and high-infested fields as affected by the superimposed cropping strategies

Nutrient content	Field category					
	Low	Medium	High	Low	Medium	High
	1st cropping period			2nd cropping period		
	Concentration [%]					
Nitrogen (N)						
F	ns 0.91 ns	ns 0.79 ns	a 0.84 ns	ns 0.64 ns	ns 0.57 ns	a 0.77 ns
M	ns 0.89 b	ns 0.70 a	ab 0.96 b	ns 0.72 a	ns 0.65 a	ab 1.10 b
C	ns 0.91 b	ns 0.70 a	b 1.03 b	ns 0.67 a	ns 0.51 a	b 1.25 b
Phosphorous (P)						
F	ns 0.08 a	ns 0.07 a	ns 0.12 b	ns 0.06 a	a 0.06 a	a 0.12 b
M	ns 0.10 a	ns 0.08 a	ns 0.13 b	ns 0.08 a	ab 0.08 a	ab 0.17 b
C	ns 0.10 a	ns 0.09 a	ns 0.13 b	ns 0.08 a	b 0.10 a	b 0.19 b
Potassium (K)						
F	ns 0.75 ns	ns 0.70 ns	ns 0.69 ns	ns 0.69 ns	a 0.78 ns	ns 0.61ns
M	ns 0.69 ab	ns 0.78 b	ns 0.44 a	ns 0.74 ab	a 0.86 b	ns 0.40 a
C	ns 0.63 ab	ns 1.00 b	ns 0.37 a	ns 0.54 a	b 1.27 b	ns 0.37 a
Sulfur (S)						
F	ns 0.13 ns	ns 0.14 ns	ns 0.20 ns	ns 0.11ns	ns 0.07 ns	ns 0.09 ns
M	ns 0.11 ns	ns 0.12 ns	ns 0.18 ns	ns 0.09 ns	ns 0.07 ns	ns 0.09 ns
C	ns 0.10 a	ns 0.11 a	ns 0.22 b	ns 0.10 ns	ns 0.06 ns	ns 0.08 ns

Tukey test ($p<0.05$): Letters a, b denote significant difference, ns denotes not significantly different between fields (column), and between cropping strategies (rows), mean values (n=6)
DAS = days after seeding of maize; F = fertilizer, M = mucuna, C= control

Appendix 3: Maize grain nutrient concentration [%] at harvest (130 DAS) for two cropping periods in low, medium and high-infested fields as affected by the superimposed cropping strategies

Nutrient content	Low	Medium	High	Low	Medium	High
	1st cropping period			2nd cropping period		
	Concentration [%]					
Nitrogen (N)						
F	ns 1.49 b	ns 1.22 a	a 1.36 ab	ns 1.22 ns	a 1.13 ns	ns 1.45 ns
M	ns 1.48 a	ns 1.32 a	b 1.87 b	ns 1.37 a	b 1.37 a	ns 1.71 b
C	ns 1.46 a	ns 1.29 a	b 1.91 b	ns 1.34 ns	b 1.40 ns	ns 1.15 ns
Phosphorous (P)						
F	ns 0.17 b	ns 0.17 b	ns 0.14 a	a 0.11 a	a 0.13 a	b 0.15 b
M	ns 0.17 b	ns 0.17 b	ns 0.12 a	ab 0.13 ns	ab 0.15 ns	ab 0.15 ns
C	ns 0.17 b	ns 0.19 b	ns 0.13 a	b 0.14 ab	b 0.16 b	a 0.12 a
Potassium (K)						
F	ns 0.41 a	a 0.42 a	ns 0.49 b	a 0.44 a	ns 0.44 a	ns 0.50 b
M	ns 0.41 ns	ab 0.43 ns	ns 0.42 ns	ab 0.46 ns	ns 0.46 ns	ns 0.46 ns
C	ns 0.40 ns	b 0.45 ns	ns 0.44 ns	b 0.50 ns	ns 0.49 ns	ns 0.47 ns
Sulfur (S)						
F	ns 0.13 ns	ns 0.16 ns	ns 0.14 ns	ns 0.13 ns	ns 0.14 ns	ns 0.13 ns
M	ns 0.12 ns	ns 0.14 ns	ns 0.14 ns	ns 0.12 ns	ns 0.13 ns	ns 0.14 ns
C	ns 0.13 ns	ns 0.13 ns	ns 0.15 ns	ns 0.13 ns	ns 0.14 ns	ns 0.12 ns

Tukey test ($p<0.05$): Letters a, b denote significant difference, ns denotes no significant difference between fields (column), and between cropping strategies (rows), mean values (n=6)
DAS = days after seeding of maize; F = fertilizer, M = mucuna, C= control

Appendix 4: Content of N, P, K, and S in maize dry matter in the low-infested field as affected by superimposed cropping strategies

Nutrient content	Avg. yield	Cropping strategy					
		F	M	C	F	M	C
	[kg ha^{-1}]	Uptake [kg ha^{-1}]			Concentration [%]		
Leaves							
N	73.1	118.0 b	45.4 a	55.8 a	3.31 b	1.77 a	1.97 a
P	6.4	8.9 ns	4.9 ns	5.3 ns	0.24 ns	0.19 ns	0.19 ns
K	49.8	66.2 ns	39.8 ns	43.5 ns	1.85 ns	1.58 ns	1.55 ns
S	8.1	11.6 b	6.0 a	6.5 a	0.32 b	0.24 a	0.23 a
Stover							
N	75.2	115.0 b	51.4 a	59.3 a	0.67 ns	0.54 ns	0.58 ns
P	9.5	8.9 ns	9.7 ns	10.1 ns	0.05 ns	0.10 ns	0.10 ns
K	91.1	103.6 ns	95.7 ns	74.0 ns	0.61 ns	1.05 ns	0.70 ns
S	12.3	21.0 ns	7.9 ns	8.0 ns	0.12 ns	0.08 ns	0.08 ns
Grain							
N	56.9	89.1 b	39.4 a	42.2 a	1.23 ns	1.20 ns	1.21 ns
P	5.7	8.1 ns	4.5 ns	4.7 ns	0.11 ns	0.14 ns	0.13 ns
K	21.7	32.3 b	15.9 a	16.8 a	0.44 ns	0.49 ns	0.48 ns
S	6.5	11.3 ns	4.3 ns	3.8 ns	0.15 ns	0.13 ns	0.10 ns

Tukey test ($p<0.05$): Letters a, b, denote significant difference, ns denotes no significant difference between cropping strategies, mean values (n=3); F = fertilizer, M = mucuna, C = control

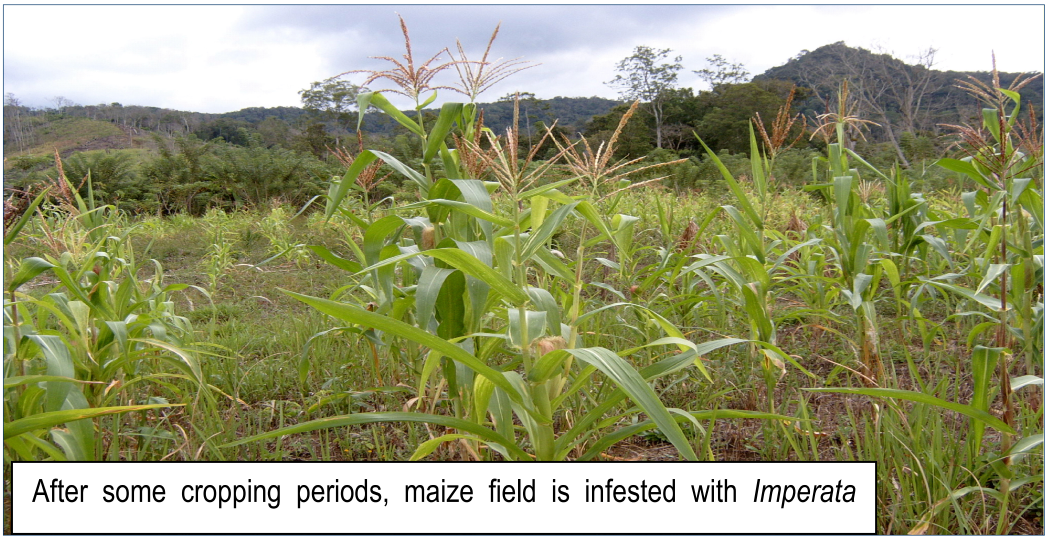
Appendix 5: Content of N, P, K, and S in maize dry matter in the high-infested field as affected by superimposed cropping strategies

Nutrient content	Avg. yield	Cropping strategy					
		F	M	C	F	M	C
	[kg ha^{-1}]	Uptake [kg ha^{-1}]			Concentration [%]		
Leaves							
N	23.1	52.2 b	7.8 a	9.3 a	2.94 b	1.52 a	1.44 a
P	2.0	3.3 ns	1.2 ns	1.5 ns	0.19 a	0.24 b	0.24 b
K	19.0	31.9 b	11.5 a	13.6 a	1.82 ns	2.27 ns	2.18 ns
S	3.0	6.3 b	1.2 a	1.2 a	0.35 b	0.23 a	0.22 a
Stover							
N	62.8	76.5 ns	37.1 ns	31.1 ns	0.75 ns	0.95 ns	0.99 ns
P	11.2	11.8 ns	8.3 ns	6.9 ns	0.12 a	0.21 b	0.23 b
K	42.9	61.5 b	25.0 a	20.0 a	0.58 ns	0.64 ns	0.67 ns
S	5.9	7.5 b	3.8 ab	2.4 a	0.07 ns	0.11 ns	0.08 ns
Grain							
N	4.9	10.6 ns	0.4 ns	3.8 ns	1.15 a	1.90 b	1.55 ab
P	0.5	1.1 ns	0.03 ns	0.5 ns	0.12 a	0.14 ab	0.15 b
K	1.9	3.9 ns	0.10 ns	1.6 ns	0.42 a	0.47 ab	0.52 b
S	0.6	1.2 ns	0.03 ns	0.4 ns	0.13 a	0.16 b	0.14 ab

Tukey test ($p<0.05$): Letters a, b, denote significant difference, ns denotes no significant difference between cropping strategies, mean values (n=3); F = fertilizer, M = mucuna, C = control

Appendix 6: The clearing of secondary forests for maize cultivation, still a common practice in Central Sulawesi, Indonesia especially at the rainforests margins

Appendix 7: Dynamic of *Imperata* invasion in maize cultivated fields

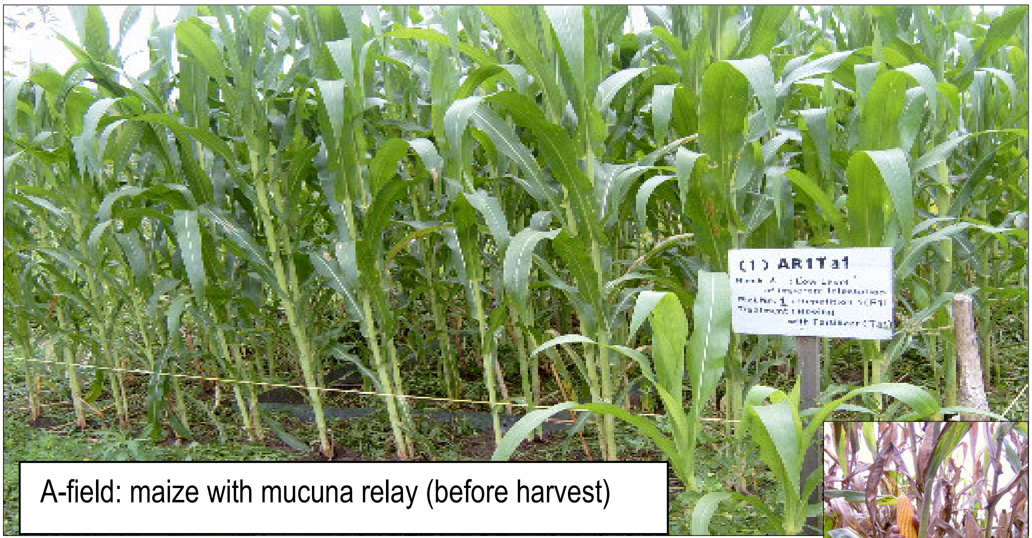


After some cropping periods, maize field is infested with *Imperata*

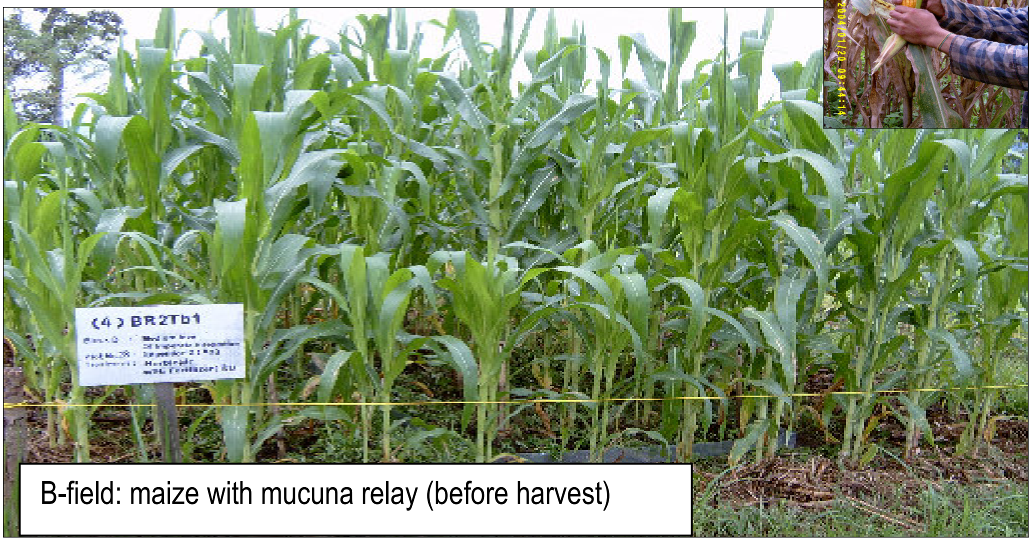
Invasion of *Imperata* weed in upland maize cultivation

Imperata cylindrica (L) Raeuschel or Beauv

Appendix 8: Experimental fields: maize growth with fertilizer application as cropping strategy following intensive land preparation in three fields differentiated by initial level of *Imperata* infestation



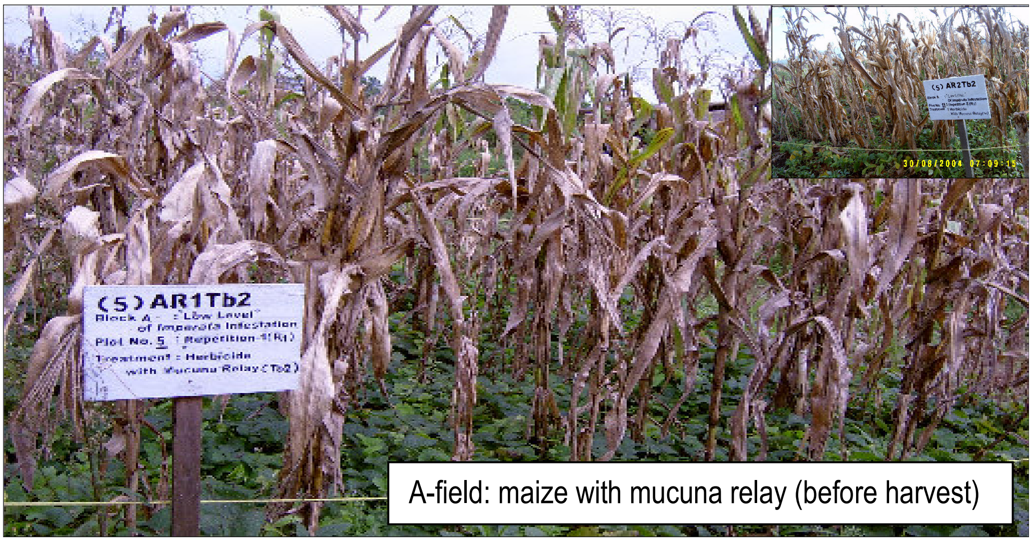
A-field: maize with mucuna relay (before harvest)



B-field: maize with mucuna relay (before harvest)

C-field: maize with mucuna relay (before harvest)

Appendix 9: Experimental field: maize growth with mucuna relay as cropping strategy following intensive land preparation in three fields differentiated by initial level of *Imperata* infestation



A-field: maize with mucuna relay (before harvest)

B-field: maize with mucuna relay (before harvest)

C-field: maize with mucuna relay (before harvest)

Appendix 10: Experimental fields: maize growth without any cropping strategy (no fertilizer and no mucuna relay) following intensive land preparation in three fields differentiated by initial level of *Imperata* infestation

A-field: maize without fertilizer or mucuna relay (after weeding)

B-field: maize without fertilizer or mucuna relay (after weeding)

C-field: maize without fertilizer or mucuna relay (after weeding)

Appendix 11: Experimental fields: maize growth in the low-infested field with fertilizer, mucuna relay, and without both as cropping strategy following minimum tillage by shallow hoeing

A-field: maize with fertilizer (after weeding)

A-field: maize with mucuna relay (after weeding)

A-field: maize without fertilizer and mucuna relay (after weeding)

Appendix 12: Experimental fields: maize in the high-infested field with fertilizer, mucuna relay, and without both as cropping strategy following minimum tillage by shallow hoeing

C-field: maize with fertilizer application

C-field: maize with with mucuna relay

C-field: maize without fertilizer and mucuna relay

Appendix 13: *Imperata* density and biomass response before and after in the fields of the first set of experimentation differentiated by the level of initial *Imperata* infestation

		F-value				
Source	df	ICBE	IBBE	ICAH1	ICAE	IBAE
Corrected Model	4	182.2	98.3	2.3	2.8	1.5
Intercept	1	2510.9	1004.4	68.2	27.7	35.4
Replication	2	5.2	0.7	0.7	2.3	1.1
Field	2	359.2 **	196.0**	3.9 *	3.2 *	2.0 ns
Error	49					
Total	54					
Corrected Total	53					

***, *, ns = significant at p<0.01, 0.05, and not significant, respectively;*
ICBE = Imperata shoots counts before experimentation, IBBE = Imperata biomass before experimentation,
ICAH1 = Imperata shoots counts after harvest of the 1st cropping period
ICAE = Imperata shoots counts after experimentation, IBAE = Imperata biomass after experimentation

Appendix 14: *Imperata* density and biomass response in the low, medium and high-infested fields of the first set of experimentation as affected by land preparation and cropping strategies

		F-value								
		Low			Medium			High		
Source	df	ICAH1	ICAE	IBAE	ICAH1	ICAE	IBAE	ICAH 1	ICAE	IBAE
Corrected Model	9	0.9	1.4	1.8	3.6	0.8	2.6	1.5	3.4	4.5
Intercept	1	28.9	66.6	15.9	142.8	9.7	23.0	24.8	110.3	55.3
REP	2	2.9 ns	1.0 ns	4.0 ns	20.0*	5.6 ns	2.2 ns	3.5 ns	7.8 ns	6.0 ns
LMTr	1	0.4 ns	0.1 ns	0.005 ns	1.3 *	10.3 ns	0.3 ns	7.7 ns	0.3 ns	1.2 ns
Error a	2									
CMTr	2	2.0 ns	3.4 ns	3.7 ns	0.6 ns	0.5 ns	8.4*	1.5 ns	1.1 ns	7.6*
LMTr x CMTr	2	0.9 ns	0.2 ns	0.7 ns	0.004 ns	0.8 ns	0.2 ns	3.6 ns	1.8 ns	0.9 ns
Error b	8									
Total	18									
Corrected Total	17									

**, ns = significant at p<0.01, 0.05, and not significant, respectively;*
ICBE = Imperata shoots counts before experimentation, IBBE = Imperata biomass before experimentation,
ICAH1 = Imperata shoots counts after harvest of the 1st cropping period
ICAE = Imperata shoots counts after experimentation, IBAE = Imperata biomass after experimentation
A: Low and C: High ICAE = Imperata shoots counts after experimentation (SQT+1 transformed)
LMTr = Land preparation method as treatment; CMTr = Crop management strategy as superimposed treatment

Appendix 15: Response of weeds other than *Imperata* in the fields of the first set of experimentation differentiated by the level of initial *Imperata* infestation

Source	df	F-value				
		W1	W2	W3	W4	TDW
Corrected Model	4	5.1	1.8	8.6	1.2	3.6
Intercept	1	160.5	162.1	513.2	205.7	666.9
Replication	2	1.2 ns	1.6 ns	6.3*	2.4 ns	5.0*
Field	2	9.0**	2.0 ns	10.9**	0.1 ns	2.2 ns
Error	49					
Total	54					
Corrected Total	53					

***, *, ns = significant at p<0.01, 0.05, and not significant, respectively*
W1 = weeds other than Imperata at weeding maintenance (60 DAS of maize) at 1st cropping period;
W2 = weeds other than Imperata after harvest (150) at 1st cropping period
W3 = weeds other than Imperata at weeding maintenance (60 DAS of maize) at 2nd cropping period
W4 = weeds other than Imperata after harvest (150) at 2nd cropping period
TDW = total weeds other than Imperata dry matter for two cropping periods

Appendix 16: Response of weeds other than *Imperata* in the low-infested field of the first set of experimentation

Source	df	F-value			
		W1	W2	W3	W4
Corrected Model	9	1.9	9.3	1.7	5.9
Intercept	1	90.0	246.8	154.7	402.8
REP	2	141.0**	9.9 ns	8.7 ns	14.0*
LMTr	1	0.8**	1.8 ns	1.6 ns	2.8 ns
Error a	2				
CMTr	2	1.1 ns	27.8**	0.1 ns	20.4**
LMTr x CMTr	2	1.6 ns	4.3 ns	0.06 ns	0.6 ns
Error b	8				
Total	18				
Corrected Total	17				

***, *, ns = significant at p<0.01, 0.05, and not significant, respectively*
W1 = weeds other than Imperata at weeding maintenance (60 DAS of maize) at 1st cropping period;
W2 = weeds other than Imperata after harvest (150) at 1st cropping period
W3 = weeds other than Imperata at weeding maintenance (60 DAS of maize) at 2nd cropping period
W4 = weeds other than Imperata after harvest (150) at 2nd cropping period
LMTr = Land preparation method as treatment; CMTr = Crop management strategy as superimposed treatment

Appendix 17: Response of weeds other than *Imperata* in the medium-infested field of the first set of experimentation

Source	df	F-value			
		W1	W2	W3	W4
Corrected Model	9	1.2	2.9	3.2	8.8
Intercept	1	56.8	113.2	471.1	342.4
REP	2	0.3 ns	47.4*	2.8 ns	4.3 ns
LMTr	1	0.1 ns	0.2 ns	0 ns	0.1 ns
Error a	2				
CMTr	2	0.1 ns	11.8*	10.6*	38.7*
LMTr x CMTr	2	2.0 ns	0.04 ns	0.9 ns	0.005 ns
Error b	8				
Total	18				
Corrected Total	17				

**, ns = significant at p< 0.05, and not significant, respectively*
W1 = weeds other than Imperata at weeding maintenance (60 DAS of maize) at 1st cropping period;
W2 = weeds other than Imperata after harvest (150) at 1st cropping period
W3 = weeds other than Imperata at weeding maintenance (60 DAS of maize) at 2nd cropping period
W4 = weeds other than Imperata after harvest (150) at 2nd cropping period
LMTr = Land preparation method as treatment; CMTr = Crop management strategy as superimposed treatment

Appendix 18: Response of weeds other than *Imperata* in the high-infested field of the first set of experimentation

Source	df	F-value			
		W1	W2	W3	W4
Corrected Model	9	2.8	5.0	2.3	3.2
Intercept	1	142.6	267.8	394.4	96.0
REP	2	0.2 ns	0.6 ns	1.0 ns	16.6*
LMTr	1	0.2 ns	10.0*	3.7 ns	0.2*
Error a	2				
CMTr	2	0.8 ns	17.5*	2.9 ns	8.4*
LMTr x CMTr	2	0.5 ns	0.04 ns	0.01 ns	0.2 ns
Error b	8				
Total	18				
Corrected Total	17				

**, ns = significant at p< 0.05, and not significant, respectively*
W1 = weeds other than Imperata at weeding maintenance (60 DAS of maize) at 1st cropping period;
W2 = weeds other than Imperata after harvest (150) at 1st cropping period
W3 = weeds other than Imperata at weeding maintenance (60 DAS of maize) at 2nd cropping period
W4 = weeds other than Imperata after harvest (150) at 2nd cropping period
LMTr = Land preparation method as treatment; CMTr = Crop management strategy as superimposed treatment

Appendix 19: Maize yield response for two cropping periods in the fields of the first set of experimentation differentiated by the level of initial *Imperata* infestation

Source	df	F-value			
		1st cropping period		2nd cropping period	
		MTDM1	HI1	MTDM2	HI2
Corrected Model	4	2.8	18.4	0.5	21.4
Intercept	1	322.2	205.1	131.7	280.8
Replication	2	0.6 ns	3.7*	0.09 ns	7.6**
Field	2	4.9*	33.1**	0.9 ns	35.1**
Error	49				
Total	54				
Corrected Total	53				

***, *, ns = significant at p<0.01, 0.05, and not significant, respectively*
MTDM1 = Maize total dry matter at 1st cropping period; MTDM2 = Maize total dry matter at 2nd cropping period
HI1 = Harvest index at 1st cropping period; HI2 = Harvest index at 2nd cropping period

Appendix 20: Maize yield response for two cropping periods in the low-infested field as affected by the land preparation methods and cropping strategies

Source	df	F-value					
		1st cropping period			2nd cropping period		
		Stover1	Grain1	MTDM1	Stover2	Grain2	MTDM2
Corrected Model	9	15.7	2.6	15.2	10.6	10.1	20.6
Intercept	1	1455.7	198.3	1378.7	477.2	267.3	794.3
REP	2	17.9*	4.4 ns	5.2 ns	0.3 ns	77.0*	1.8 ns
LMTr	1	67.2*	11.34 ns	31.5*	0.04 ns	15.4 ns	0.3 ns
Error a	2						
CMTr	2	55.8*	8.5*	54.4*	41.7*	38.1*	82.1*
LMTr x CMTr	2	1.9 ns	0.1 ns	1.2 ns	0.6 ns	1.5 ns	2.1 ns
Error b	8						
Total	18						
Corrected Total	17						

**, ns = significant at p< 0.05, and not significant, respectively*
Stover1 = Stover production at 1st cropping period; Stover2 = Stover production at 2nd cropping period
Grain1 = Grain production at 1st cropping period; Grain2 = Grain production at 2nd cropping period
LMTr = Land preparation method as treatment; CMTr = Crop management strategy as superimposed treatment

Appendix 21: Maize yield response for two cropping periods in the medium-infested field as affected by the land preparation methods and cropping strategies

Source	df	F-value					
		1st cropping period			2nd cropping period		
		Stover1	Grain1	MTDM1	Stover2	Grain2	MTDM2
Corrected Model	9	5.2	30.9	16.3	10.8	38.2	35.0
Intercept	1	699.4	1153.3	1198.3	282.6	716.2	833.0
REP	2	1.5 ns	25.8*	2.7 ns	6.1 ns	8.1 ns	16.8*
LMTr	1	3.0 ns	13.4 ns	10.4 ns	12.3 ns	0.6 ns	894.5*
Error a	2						
CMTr	2	18.8*	115.7*	66.6*	44.5*	160.5*	154.0*
LMTr x CMTr	2	0.4 ns	0.8 ns	0.4 ns	0.6 ns	1.7 ns	1.3 ns
Error b	8						
Total	18						
Corrected Total	17						

**, ns = significant at p< 0.05, and not significant, respectively*
Stover1 = Stover production at 1st cropping period; Stover2 = Stover production at 2nd cropping period
Grain1 = Grain production at 1st cropping period; Grain2 = Grain production at 2nd cropping period
MTDM1 = Maize total dry matter at 1st cropping period; MTDM2 = Maize total dry matter at 2nd cropping period
LMTr = Land preparation method as treatment; CMTr = Crop management strategy as superimposed treatment

Appendix 22: Maize yield response for two cropping periods in the high-infested field as affected by the land preparation methods and cropping strategies

Source	df	F-value					
		1st cropping period			2nd cropping period		
		Stover1	Grain1	MTDM1	Stover2	Grain2	MTDM2
Corrected Model	9	11.8	5.8	5.1	17.8	2.8	11.0
Intercept	1	1014.5	297.9	189.4	370.0	132.7	190.2
REP	2	4.4 ns	12.9*	5.9 ns	5.8 ns	10.8*	2.6 ns
LMTr	1	2.4 ns	29.6*	30.1*	1.7 ns	6.1 ns	22.9*
Error a	2						
CMTr	2	33.6*	15.9*	18.4*	69.4*	7.0*	46.7*
LMTr x CMTr	2	2.6 ns	3.5 ns	0.7 ns	4.9*	0.3 ns	0.9 ns
Error b	8						
Total	18						
Corrected Total	17						

**, ns = significant at p< 0.05, and not significant, respectively*
Stover1 = Stover production at 1st cropping period; Stover2 = Stover production at 2nd cropping period (SQT+1 transformed): Grain1 = Grain production at 1st cropping period
Grain2 = Grain production at 2nd cropping period
MTDM1 = Maize total dry matter at 1st cropping period
MTDM2 = Maize total dry matter at 2nd cropping period
LMTr = Land preparation method as treatment
CMTr = Crop management strategy as superimposed treatment

Appendix 23: Mucuna dry matter (DM) production response for two cropping periods in the fields of the first set of experimentation differentiated by the level of initial *Imperata* infestation

Source	df	F-value	
		1st mucuna DM (Mu1)	2nd mucuna DM (Mu2)
Corrected Model	4	1.0	1.6
Intercept	1	184.0	113.7
Replication	2	1.2 ns	0.1 ns
Field	2	0.9 ns	3.0 ns
Error	13		
Total	18		
Corrected Total	17		

ns = not significant at p< 0.05

Appendix 24: Mucuna dry matter (DM) production response in the low, medium and high-infested fields as affected by land preparation methods

Source	df	F-value					
		Low		Medium		High	
		Mu1	Mu2	Mu1	Mu2	Mu1	Mu2
Corrected Model	3	0.4	0.5	1.5	2.0	0.4	0.8
Intercept	1	74.1	42.5	32.5	30.2	66.7	52.0
Replication	2	0.6 ns	0.7 ns	1.5 ns	2.9 ns	0.3 ns	1.1 ns
LMTr	1	0.03 ns	0.05 ns	1.5 ns	0.1 ns	0.4 ns	.007 ns
Error	2						
Total	6						
Corrected Total	5						

ns = not significant at p< 0.05
Mu1 = mucuna dry matter at 1st cropping period; Mu2 = mucuna dry matter at 2nd cropping period; Data in deep hoeing with mucuna relay and herbicide application mucuna relay were combined since there was no significant difference; LMTr = Land preparation method as treatment

Appendix 25: Mucuna biological nitrogen fixation (BNF) response after two cropping periods in the fields of the first set of experimentation differentiated by the level of initial *Imperata* infestation as affected by the land preparation methods

Source	df	F-value	
		% Ndfa (maize as reference)	% Ndfa (weeds as reference)
Corrected Model	11	0.5	0.6
Intercept	1	4309.3	15908.4
REP	2	1.9 ns	0.005 ns
Field with mucuna relay	2	2.7 ns	1.7 ns
Error a	4	0.6 ns	0.6 ns
LMTr	1	0.05 ns	0.4 ns
Field with mucuna relay x LMTr	2	0.4 ns	0.5 ns
Error b	6		
Total	18		
Corrected Total	17		

ns = not significant at p<0.05; Ndfa = Nitrogen (N) derived from the air
LMTr = Land preparation method as treatment

Appendix 26: Plant system ^{15}N recovery in the fields of the first set of experimentation differentiated by the level of initial *Imperata* infestation

Source	df	F-value	
		% ^{15}N recovery in plant system	
		maize	$weeds_{TOTAL}$
Corrected Model	7	0.5	1.8
Intercept	1	277.3	146.0
Replication	5	0.4 ns	1.8 ns
Field with fertilizer	2	0.4 ns	1.7 ns
Error	10		
Total	18		
Corrected Total	17		

ns = not significant (p<0.05), data in deep hoeing with fertilizer and herbicide application with fertilizer were combined since there was no significant difference

Appendix 27: Soil system ^{15}N recovery in the fields of the first set of experimentation differentiated by the level of initial *Imperata* infestation

Source	df	F-value		
		% ^{15}N recovery in soil system		
		0-15 cm depth	15-30 cm depth	30-60 cm depth
Corrected Model	7	1.3	0.9	3.7
Intercept	1	309.9	54.2	147.3
Replication	5	1.5 ns	1.0 ns	5.2*
Field with fertilizer	2	0.8 ns	0.7 ns	0.1 ns
Error	10			
Total	18			
Corrected Total	17			

**, ns = significant and not significant at (p<0.05); data in deep hoeing with fertilizer and herbicide application with fertilizer were combined since there was no significant difference*

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