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Productivity and water use efficiency of important crops in the Upper Oueme Catchment: influence of nutrient limitations, nutrient balances and soil fertility.

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Dedication

This work is dedicated to:

Errol D. B. and Perla S. K. DAGBENONBAKIN,
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Abstract

Crop productivity and water use efficiency of important crops in the Upper Oueme Catchment: influence of nutrient limitations, nutrient balances and soil fertility.

The Upper Oueme catchment in the West African subhumid zone is a region in Northern Benin, which actually experiences major changes in land use, water availability, and population density. In the context of the IMPETUS project, the present work aimed to i) identify nutrients which are limiting productivity on the basis of soil and plant analysis, ii) compare effects of fertilizer application nutrition to current farmer's practice, iii) determine the water consumption per unit of biomass (maize) and per unit of area, and iv) assess (simplified) nutrient balances to predict long-term trends of nutrient availability and soil productivity.

Field experiments were carried out in 2001 and 2002 using a randomized complete block design with four treatments, 2001: n = 80, 2002: n = 109) at three sites: Beterou, Dogue, and Wewe. Soils of the sites had low fertility and were PLENTOSOL and Ferric-Profondic LUVISOL in Beterou, PLENTOSOL and LIXISOL in Dogue and ACRISOL or Plenthic-LIXISOL in Wewe. Treatments were: T0: farmer's practice or plots without mineral or organic fertilizer applied with exception of cotton, where farmers applied fertilizers as usual; T1M: 10 t ha^{-1}crop residues; T1F: 10 t ha^{-1} of farmyard manure in 2001; T2: mineral fertilizer at the rates recommended; T3M: mineral fertilizer as applied in T2 + 10 t ha^{-1} of crop residues for mulch in 2001 and 2002, while for T3F mineral fertilizer was applied as in T2 + 10 t ha^{-1} of farmyard manure. Residual effects of manure application were evaluated without further OM application.

Soil samples were taken before and at the end of the experiment to appreciate the nutritional status of plots. Leaves were sampled at critical stages for plant for nutrient assessment through critical Value Method CVM and Diagnosis and Recommendation Integrated System (DRIS). Yield (DM) of all the crops, their total biomass and harvest index were evaluated at harvest. A partial nutrient balance was calculated on the basis of tissue and product analysis for a high and a low – yielding sub-groups. Actual evapotranspiration was estimated by gravimetry, humidimetry and tensiometry for water use efficiency (WUE) of maize in Dogue in 2002. Rainfall during the crop growth was used to calculate rainfall use efficiency (RUE). Water or rainfall use efficiency was determined as the ratio between above ground biomass and rainfall for RUE or actual evapotranspiration for WUE.

Crop productivities were significantly affected by farmer’s practice and the type of organic matter applied. Organic or mineral fertilizer or the combination of both increased crop productivities, RUE and WUE of maize although a relatively high variability was observed between individual plots and farmers.

Nitrogen was the most limiting nutrient followed by potassium and phosphorous according to DRIS-Evaluation while the CVM method revealed most of the macronutrients as low or close to the critical level. However, only the nutritional imbalance index of maize decreased from 2001 to 2002. Standard nutrient levels and reasonable DRIS norms were established for N, P, K, Ca, Mg, S, Zn, Mn of maize, sorghum, cotton, yam and groundnut. They can be used to evaluate crop nutritional status, to correct nutritional imbalances and to improve crop productivities. They can also be used as a basis for calibrating the fertilization programs for these crops.

Negative nutrient balances were observed, as inputs of nutrients were insufficient to compensate outputs. The strategies to compensate the nutrient gap are to increase the recycling of residues, to increase the application of manure, or introduce fertilizers or a combination of all three.

Actual farmers' practices in maize, sorghum, groundnut and yam cropping systems lead to depletion in soil nutrient levels, as there is actually almost no return of nutrients to the fields and mineral fertilizer are only rarely applied.

When calculating the balance for a typical yam-cotton-maize-groundnut-sorghum rotation, the nutrient balances are negative by 177 kg ha^{-1} N, 33 kg ha^{-1} P and 163 kg ha^{-1} K. This leads to nutrient depletion (as actually found in the project area) and not sustains adequate yields.

The only desirable scenario could be the practice of integrated soil fertility management where mineral and organic fertilizers are combined. Here, one should as well take into account crop rotations with legumes to optimize nitrogen fixation, mineral fertilizer, and efficient management of crop residues. Management methods that limit nutrient losses and increase water use efficiency are some of the approaches that will be used to improve and sustain soil fertility and conversely to enhance crop production and in Upper Oueme Catchment.

Résumé

Productivité et utilisation efficiente de l’eau pour les principales cultures dans le Bassin Versant de l’Ouémé Supérieur : influence des limitations de nutriments, du bilan des nutriments et de la fertilité des sols.

Le bassin versant de l’Ouémé supérieur, situé dans la région septentrionale du Bénin dans la zone subhumide de l’Afrique de l’Ouest, connaît actuellement des changements notables de densité de population et conséquemment d’utilisation des terres. Le présent travail s’inscrivant dans le cadre du Projet IMPETUS vise notamment à :i) identifier les nutriments limitant la production agricole sur la base des analyses de sol et de végétaux, ii) comparer les effets de l’application des engrais à la pratique paysanne actuelle, iii) déterminer la consommation de l’eau ou de la pluie par unité de biomasse et de surface et iv) estimer le bilan partiel des nutriments afin de prédire les tendances à long terme de la disponibilité des nutriments et la productivité des sols.

A cet effet, des essais en milieu paysan ont été conduits sur trois sites : Bétérou, Doguè et Wèwè en 2001 et 2002 avec pour plantes test le maïs, le sorgho, l’arachide, le coton et l’igname. Le dispositif expérimental était un bloc complètement aléatoire de 4 traitements, 80 paysans en 2001 et 109 en 2002. Chaque paysan constitue une répétitionLes sols utilisés avaient une faible fertilité étaient des PLENTOSOLS et Ferric-Profondic LUVISOLS à Bétérou, PLENTOSOLS et LIXISOLS à Doguè et ACRISOLS ou Plentic LIXISOLS à Wèwè. Les traitements étaient : T0 : pratique paysanne ou parcelle sans aucun apport de fumure organique et minérale (à l’exception du coton où les paysans appliquent habituellement des engrais), T1M : 10 t ha^{-1} de résidus de récolte, T1F : 10 t ha^{-1} of fumier, T2 : fumure minérale à la dose recommandée, T3M : fumure minérale appliquée en T2 + 10 t ha^{-1} de résidus de récolte en 2001 et en 2002, T3F : fumure minérale appliquée en T2 + 10 t ha^{-1} de fumier en 2001.

Des échantillons de sol ont été prélevés et analysés au début et à la fin des essais pour apprécier le niveau de fertilité des parcelles. Les échantillons de feuilles ont été prélevés à des stades critiques pour l’appréciation du statut nutritionnel selon la méthode des valeurs critiques (MVC) et le Système Intégré de Diagnostic et de Recommandations (SIDR). Les rendements (matière sèche) de toutes les cultures, leurs biomasses totales et indices de récolte ont été estimés à la récolte. Un bilan partiel des nutriments a été estimé en subdivisant les rendements en sous-groupes de rendements en faible et élevé. L'évapotranspiration actuelle a été estimée par gravimétrie, humidimétrie et tensiométrie pour l'utilisation efficace de l'eau (WUE) du maïs à Doguè en 2002. La précipitation durant la période de croissance végétative été utilisée pour estimer l'utilisation efficace de la pluie (RUE). L'utilisation efficace de l'eau et de la précipitation a été déterminée par la biomasse totale aérienne rapportée à la précipitation durant la croissance végétative (RUE) ou l'évapotranspiration actuelle (WUE).

Les productivités des cultures ont été significativement affectées par la pratique paysanne et le type de matière organique appliquée. Les productivités des cultures leur RUE et WUE du maïs ont été améliorées par l'application d'engrais organiques, minéraux ou la combinaison des deux types. Toutefois, une forte relative variabilité a été observée entre les champs paysans et les localités.

L'azote était l'élément le plus limitant de la production suivi du potassium et du phosphore selon le SIDR alors que la MVC a révélé la plupart des macronutriments en faibles teneurs ou à la limite des seuils critiques. Cependant, seul le déséquilibre nutritionnel du maïs a décru de 2001 à 2002. Des teneurs standard et des normes SIDR acceptables en N, P, K, Ca, Mg, S, Zn et Mn pour le maïs, le coton, l'arachide, le sorgho et l'igname ont été établies. Elles peuvent être utilisées pour évaluer le statut nutritionnel des cultures, corriger les déséquilibres nutritionnels et améliorer les productivités de ces cultures. Elles peuvent aussi servir de base pour la calibration des programmes de fertilisation des cultures.

Des bilans négatifs en nutriments ont été observés étant donné que les importations de nutriments sont insuffisantes et ne compensent pas les exportations. Les stratégies pour compenser le déficit en nutriment sont l'augmentation du recyclage des résidus de récolte, l'accroissement de l'application du fumier ou des engrais minéraux ou la combinaison des trois.

La pratique paysanne actuelle conduit à un épuisement des sols en nutriments étant donné qu'aucune restitution des nutriments ne se fait et l'utilisation d'engrais minéraux se pratique rarement.

En estimant le bilan des nutriments pour une rotation typique igname-coton-maïs-arachide-sorgho de 5 ans, les bilans négatifs de 177 kg N ha^{-1}, 33 kg P ha^{-1}, 163 kg K ha^{-1} ont été obtenus. Ceci conduit à un épuisement en nutriment (comme c'est le cas dans la région du projet) et ne permet aucune stabilité des rendements.

Le seul scénario acceptable serait la pratique d'une gestion intégrée de la fertilité des sols où engrais minéral et organique sont combinés. Ici, la rotation des cultures avec les légumineuses pour optimiser la fixation de l'azote, l'utilisation des engrais minéraux, la gestion efficiente des résidus de récoltes seront prises en considération. Les méthodes de gestion qui limitent les pertes en nutriments et augmentent l'utilisation efficace de l'eau sont quelques approches qui peuvent être utilisées pour améliorer, maintenir la fertilité des sols et réciproquement accroître la production dans le bassin versant de l'Ouémé supérieur.

Zusammenfassung

Produktivität und Wassernutzungseffizienz wichtiger Kulterpflanzen im oberen Ouémé-Einzugsgebiet, Benin: Nährstoffmängel, Nährstoffbilanzen, Bodenfruchtbarkeit.

Das im subhumiden Westafrika gelegene obere Einzugsgebiet des Ouémé in Nordbenin unterliegt gegenwärtig starken Veränderungen der Landnutzung, der Wasserverfügbarkeit und der Bevölkerungsdichte. Ziele der vorliegenden Arbeit im Rahmen des IMPETUS-Projektes sind (i) die Identifizierung limitierender Nährstoffe für die pflanzliche Produktivität mit Hilfe von Boden- und Pflanzenanalysen, (ii) der Vergleich der Erträge bei aktueller Bewirtschaftung und bei veränderter Düngung (iii) die Bestimmung des Wasserverbrauchs bezogen auf die Biomasse (Mais) und auf die Fläche, (iv) die Erstellung (einfacher) Nährstoffbilanzen zur Vorhersage langfristiger Entwicklungen der Nährstoffverfügbarkeit und der Bodenproduktivität.

In den Jahren 2001 und 2002 wurden an den drei Standorten Beterou, Dogue und Wewe vollständig randomisierte Feldversuche mit vier Behandlungsvarianten durchgeführt (2001: n= 80, 2002: n=109). Alle Böden waren nährstoffarm (Plentosol und eisenreicher Luvisol in Beterou, Plentosol und Lixisol in Dogue, Acrisol bzw. Plenthic-Lixisol in Wewe). Die Behandlungen waren: T0: aktuelle Bewirtschaftung, d.h. Mineraldüngereinsatz bei Baumwolle, andere Kulturen ohne Verwendung jeglichen Düngers; T1M: 10 t ha^{-1} Pflanzenrückstände; T1F: 10 t ha^{-1} Stalldünger; T2: Mineraldünger nach Düngungsempfehlung; T3M: Mineraldünger wie in T2 + 10 t ha^{-1} Pflanzenrückstände als Mulch in 2001 und 2002, T3F: Mineraldünger wie in T2 + 10 t ha^{-1} Stalldünger. Residualeffekte der Stalldüngeranwendung wurden ohne weitere Verwendung organischen Düngers untersucht.

Die Nährstoffausstattung der Versuchsflächen vor Beginn und nach Ende des Experiments wurde anhand von Bodenanalysen untersucht. Die während wichtiger Phasen der Pflanzenentwicklung genommenen Blattproben wurden anhand der CVM- (Critical Value Method) und der DRIS-(Diagnosis and Recommendation Integrated System) Methode bewertet. Die Erträge aller untersuchten Kulturen, ihre Gesamtbiomasse sowie der Ernteindex wurden bestimmt. Für je eine Hochertrags- und Niedrigertragsfläche wurde eine Teilnährstoffbilanz anhand von Gewebe- und Produktanalyse berechnet.

Zur Bestimmung der Wassernutzungseffizienz von Mais wurde die aktuelle Evapotranspiration mittels Gravimetrie, Humidimetrie und Tensiometrie in Dogue 2002 abgeschätzt. Mit Hilfe der Niederschläge wurde die Regennutzungseffizienz (RUE) berechnet. Wasser- bzw. Regennutzungseffizienz wurden dabei bestimmt als das Verhältnis zwischen oberirdischer Biomasse und der Regenmenge bzw. der aktuellen Evapotranspiration.

Die Produktivität der einzelnen Kulturen wurde signifikant durch die Art der Düngung und die Art des organischen Düngers beeinflusst. Erträge, RUE und WUE wuchsen durch organische Düngung und Mineraldüngung, allein oder in Kombination. Dabei war jeweils eine starke Variabilität zwischen den einzelnen Versuchsflächen und den Landwirten zu beobachten.

Stickstoff, Kalium und Phosphor waren in dieser Reihenfolge die am meisten limitierenden Faktoren entsprechend der DRIS-Bewertung. Nach der CVM Methode waren die meisten der Makronährstoffe als gering oder zumindest nahe der kritischen Grenze zu bewerten. Allerdings nahm der Ernährungs-Ungleichgewichts-Index von 2001 nach 2002 nur für Mais ab. Eine Standard-Nährstoffversorgung und entsprechende DRIS-Werte für N, P, K, Ca, Mg, S, Zn, Mn und Mais, Sorghum, Baumwolle, Yams und Erdnuss wurde festgelegt. Diese Werte können zur Bewertung des Ernährungszustands, zur Korrektur von Ernährungsungleichgewichten und zur Verbesserung der Erträge verwendet werden. Sie eignen sich außerdem als Basis zur Kalibrierung von Düngungsprogrammen dieser Kulturen, die nachträglich validiert werden sollten.

Da die Einbringung von Nährstoffen häufig nicht ausreichte die Entnahme zu kompensieren, traten negative Nährstoffbilanzen auf. Strategien zur Vermeidung dieser Nährstofflücke bauen auf einer verstärkten Wiederausbringung von Pflanzenresten, der verstärkten Anwendung von Stalldünger, dem Einsatz von Mineraldünger bzw. Kombinationen dieser Möglichkeiten auf.

Da derzeit so gut wie keine Rückführung von entnommenen Nährstoffen auf die Felder erfolgt und Mineraldünger fast gar nicht eingesetzt wird, führt die gegenwärtige landwirtschaftliche Praxis in den Anbausystemen von Mais, Sorghum, Erdnuss und Yams zu einer kontinuierlichen Abnahme der Bodennährstoffe.

Die Berechnung der Nährstoffbilanz in einer typischen Fruchtfolge aus Yams, Baumwolle, Mais, Erdnuss, Sorghum ergab Nährstoffverluste von 177 kg ha^{-1} N, 33 kg ha^{-1} P und 163 kg ha^{-1} K. Dies führt zu der im Untersuchungsgebiet beobachteten Nährstoffverarmung und zu abnehmenden Erträgen.

Das einzig wünschenswerte Szenario wäre ein integriertes Bodenfruchtbarkeits-Management durch Kombination mineralischer und organischer Dünger. Dabei sollten sowohl Fruchtfolgen mit Leguminosen zur Optimierung der Stickstoffbindung, als auch der Einsatz von Mineraldünger und ein effektives Management der Pflanzenrückstände Eingang finden. Managementmethoden zur Begrenzung von Nährstoffverlusten und Verbesserung der Wassernutzungseffizienz sind mögliche Ansätze zur Erhaltung der Bodenfruchtbarkeit und der Verbesserung der Erträge im oberen Ouémé-Einzugsgebiet.

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Abbreviations

ANOVA	Analysis of variance
BMBF	German Ministry of Education and Science
BNF	Biological Nitrogen fixation
CRA-CF	Centre de Recherches Agricoles – Coton et Fibres
DM	Dry matter
DRIS	Diagnosis and Recommendation Integrated system
FM	Fresh matter
FYM	Farmyard manure
GLOWA	Global Change in the Hydrological Cycle
ha	Hectare
IMPETUS	Integratives Management-Projekt für eine Effizienten und Tragfähigen Umgang mit Süßwasser in Westafrika
INRAB	Institut National des Recherches Agricoles du Bénin
IPGRI	International Plant Genetic Resources Institute
IPCC	Intergovernmental Panel on Climate Change
kg	Kilogram
LS	Loam Sandy
M-DRIS	Modified Diagnosis and Recommendation Integrated System
OM	Organic matter
$p = 0$	Probability at a level equal to 0
$p \leq 0$	Probability at a level equal or lower than 0
PN_2	Proportion of N in groundnut derived from N_2 fixation
SL	Sandy Loam
t	Ton (equal to 1000 kg)
*	Level of significance 10 %
**	Level of significance 5 %
***	Level of significance 1 %

1. General Introduction

Sustainable management of natural resources is a pre-requisite for the continuing existence of mankind in the future. Water is considered as one of the most limiting of these natural resources in many parts of the world (Bonkoungou, 1996; Gamini *et al.,* 2003). As there is still a growing world population, this resource will become increasingly threatened, while the demand for food production will increase. Additionally, dramatic climatic changes are expected to influence the global water cycle in the near future (IPCC, 2001; Bonkoungou, 1996), which may cause additional problems in the management of this scarce resource. This was the motivation for the German Ministry of Education and Science (BMBF) to initiate a program on the changes expected in the global water cycle (GLOWA). Under this program, the project IMPETUS is a joint activity of the Universities of Cologne and Bonn to study the management of water resources in the Oued Drâa, South of Morocco, and the Ouémé Superieur, North of Bénin, and to develop scenarios how upcoming problems may be solved in the near future, resulting in a sustainable use of the scarce resource “water”.

As agricultural production depends on adequate water supply, and on the other hand may pose an additional threat on water resources in terms of quality and quantity, it has to be optimized, increasing the water use efficiency (WUE) of crop production, and minimizing contamination to surface and ground water. A proper soil management is thus imperative for both, sustainable agricultural production as well as for a sustainable water use. Within this context, the following study was undertaken to evaluate the actual nutrient status of important crops and solids in the project area “Ouémé Superieur”, possibilities to improve productivity without increasing the area for crop production and to optimize WUE of crop production by organic and inorganic fertilizers.

1.1. Constraints for Sustainable Agricultural Production in the Project Area

The soil provides nutrients for plant growth that are essential for animal and human nutrition (David *et al.,* 1996). A healthy soil provides a link to plant, animal, human health. According to David *et al.* (1996), history has repeatedly shown that mismanagement of the soil resource base can lead to poverty, malnutrition, and economic disaster.

Many nations have sought conservation policies to protect the soil resource base, to safeguard and to preserve the food resource base, and to maintain air and water quality; however, soil resources continue to be degraded both nationally and globally through salinization, erosion, loss of tilth and biological activity, and build up of toxic compounds (David *et al.,* 1996). Unfortunately, one distinctive characteristic of forests in the humid tropics is that the soils and their parent materials have been subjected to intensive weathering and leaching (Agboola and Unamma, 1991). The weathering process has resulted in a high proportion of kaolinitic clays, with a cation exchange capacity of 3-15 cmol kg^{-1} of soil. Under these conditions, cations from fertilizers are leached from the soil and quickly become unavailable to crops. The continually warm temperature and cycles of alternate wetting and drying in the lowland tropics are the major driving forces which accelerate the weathering of primary soil minerals and consequently the formation of the ultimate weathering products: iron and aluminum oxides and hydrous oxides, which strongly adsorb phosphate and molybdate, rendering it largely unavailable to many crops (Mekenzie, 1983; Goldberg *et al.,* 1996).

Formerly, traditional farming systems involving land rotation were able to maintain soil organic matter at a safe level by returning the land to fallow for extended periods. There are different ways of keeping tropical soils fertile. These include traditional and modern systems as outlined below.

1.1.1. Natural Fallow

The most common way of keeping tropical soils fertile is by fallowing. During the fallow period, the soil accumulates organic matter. Organic matter is very important in traditional farming practices as loss in soil organic matter causes deterioration of soil structure, resulting in soil compaction, low water and nutrient retention capacity, low infiltration rate and accelerated runoff and erosion declining soil productivity.

In soil of low organic matter, plant suffer from drought because the water retention capacity is low due to loss structure porosity; and because of water logging and poor aeration during periods of frequent rain as a result of low infiltration rate. Besides creating soil water imbalance, reduction in soil organic matter content leads to nutrients imbalance resulting in poor growth and very low yield (Agboola and Odeyime, 1972; Lal and Kang, 1982).

According to these authors, land rotation based on the fallowing is a system in which successive crops are interspersed with several years of fallowing which the land reverts temporarily to bush or forest. This reversion allows accumulation of vegetative matter, which restores the nutrients to the edaphic complex through litter fall, precipitation, nitrogen fixation and root decomposition. In turn, the process makes possible the regeneration of biomass, (total mass of living matter of the soil, both plants and animals which crops become a useful part) hence a change in physical, chemical and biological aspect of the soil. At the onset of fallow, various forms of weeds (annuals, ephemerals and semi-annuals) are the first colonizers.

1.1.2. Mulching

Mulching is a practice where the soil is covered through extended periods with either dead material or living plants of prostrate growth ("green mulch"). The advantages of living mulch could be that under the traditional farming system practice, a ground cover of living plants is always maintained (Agboola *et al.,* 1991). The plants include creeping cowpea, groundnut, yam, Mucuna pruriens, and sweet potato.

The advantages of such crops include:

- coverage of soil surface and reduction of evaporation, leading to increased moisture retention, decreased daily soil temperature fluctuation and increased microbial population and activities,

- reducing the impact of raindrops on the soil surfaces, thereby reducing soil wash and erosion,

- shading of the soil surface from direct rays of the sun, and therefore prevents excessive heating of the soil during the day,
- suppression of weeds,

- production of a harvestable crop, depending on the species,
- addition of nutrients from organic materials (leaf litter).

Covering the soil with plant residues, prunings from hedgerows, wood shavings, compost etc. has in part similar effects, and it is a useful alternative if light or water plus nutrient competition between main crops and green mulch might be limiting productivity (Agboola *et al.,* 1991; Agbo, 1999; Akondé (1995) cited by Agbo (1999)).

1.1.3. Supply of Organic Matter

It is well known fact that productivity of tropical soils can be sustained under continuous land use if soil erosion is controlled and soil organic matter and soil physical and nutritional characteristics are maintained at a favorable level (Agboola *et al.,* 1991). Different approaches to maintain a favorable level of soil organic matter are discussed below.

Green Manure

One of the earliest solutions to soil fertility problems was the use of green manuring which is defined as the growing an immature (mostly legume) crop which is ploughed under for the purpose of improving the soil physical and chemical status. The earlier concept was that green manure increased soil fertility and thereby allowed continuous arable cropping.

Faulkner (1934) suggested that yield could be maintained indefinitely by growing mucuna and annual crops in rotation. Greensill (1975) reported that nitrogenous inorganic fertilizers must accompany green manure, increasing yield and soil fertility. A highly productive green manure crop prevents leaching of plant nutrients and can mobilize other mineral elements.

Despite the advantages attributed to green manuring and mulching, local farmers have not been accepted these practices due to the following problems (Agboola *et al.,* 1991):

- no immediate (cash or kind) income; thus farmers consider this unnecessary (unproductive) labour,

- improvements on tropical soils are only effective at a short term,
- additional and difficult labor required for working residues in with harrow etc…,
- it does not fit to most farmers' traditional mixed or sequential cropping systems and is therefore not easily accepted,
- it requires what the farmer consider unnecessary labour,
- considerable energy-human or animal would be required to plough in green manure shortly before the planting of the main crop, and it might negatively affect its establishment due to allelopathic substances, mechanical barriers for germination and seedling growth (Ashok *et al.,* 2003, Kato-Noguchi 2003).

Presently the quantity of soil N fixed by the legumes decreases due to lack of P, Mn toxicity on acid soils (Horst *et al.,* 1997), and the lacking supply of appropriate strains of *Rhizobium spp*. Liming, addition of this costly nutrient and a proper inoculant to the soil is beyond the reach of many farmers.

Farmyard manure and compost

Before the advent of inorganic fertilizers, compost and farmyard manure (FYM) constituted the principal source of nutrients to crops. They have long been recognized as useful to maintain the organic matter status and to ameliorate soil physical properties. Feeding the green manure crop to cattle and adding the farmyard manure to the soil is more effective and economical than ploughing under the crop as a green manure (Agboola *et al.,* 1991). However, any substantial increase in soil organic matter content of tropical soils would require rather sizeable amounts and continuous application of farmyard manure over a long period. According to Agboola (1982) maintenance of soil fertility and productivity with continuous application of FYM is possible. Seven and a half tons per hectare of FYM per annum seems an optimal level, at least for cotton and sorghum; it may be slightly lower for groundnut. Soil fertility and productivity tend to build up with time under continuous use of FYM (Agboola *et al.,* 1991; Toyi *et al*., 1997; INRAB, 2002). Rotation seems clearly superior to continuous cropping of arable crops.

Since the population of Benin is increasing at the rate of 4% annually (ISNAR, 1995) and other facilities are competing for land requirement, it is becoming increasingly difficult to leave any piece of land to fallow longer than ten years considered as the minimum period required for the land to recuperate. According to INRAB (2002) the fallow duration passed from fifteen to one year.

Diagnostic research carried out in the different parts of Benin has indicated that sustainable agricultural development is being seriously compromised by declining soil fertility (Koudokpon (1992) cited by Wennink *et al.* (2000)), Van der pol *et al*. (1993)). This has been attributed to soil mining and to the fact that few farmers are following the traditional practice of leaving land fallow to restore soil fertility. In the south of the country, where population pressure is very high, land is now more or less permanently used (Agbo and Bediye, 1997; Alohou and Hounyovi, 1999) cited by Wennink *et al.* (2000)). In the North of the Benin, the cultivation of cotton has led to an increase in the duration that the land is cropped, as compared to conventional farmer's practices (Berkhout *et al.* (1997) cited by Wennink *et al.* (2000)).

The imbalance between soil nutrient input and nutrient output, the degradation of soil by erosion and decline of soil organic matter, the increasing invasion of agricultural fields by weeds such as *Striga* and *Imperata* spp and the very low crop productivity are the observed results of that low soil fertility (Van der pol *et al.* (1993), Sanguiga *et al.* (1996), Gbehounou (1997)).

Presently, the price of inorganic fertilizer is rising daily, and peasant farmers cannot afford its use; therefore the more viable alternate is to develop low input technology for soil fertility maintenance.

Agricultural research in Benin is increasingly focusing on the restoration and maintenance on soil fertility. Several technologies have been developed, tested and made available to the extension services, but they have not been widely adopted (Alohou and Hounyovi (1999) cited by Wennink *et al.* (2000)).

Due to the low crop productivity and high evapotranspiration caused by the aforementioned factors, water use efficiency of the crop is also affected. Practical methods to reduce unproductive evaporation from soils and to conserve water could be the use of organic matter and mineral fertilizer.

1.2. Nutrient Assessment

The relationship between yield and plant nutrient concentration is a premise to use the plant analysis as diagnostic criterion. Diagnosis methods dealing on plant tissue analysis play a key role on precise definition and interpretation of the nutritional plant status, since it reveals greater consistency of nutrient relations, compared separately to each nutrient content, as well as in relation to the tissue age (Beaufils (1973) cited by Gualter *et al.* (2005)).

Using established critical or standard values, or sufficient ranges, a comparison is made between analytical data, result with one or more of these known values or ranges in order to access the plant's nutritional status. Another system of plant analysis interpretation is called DRIS, Diagnostic and Recommendation Integrated System, a method using ratios of element contents to establish a series of values that will identify those elements from the most to the least deficient. There is on the other hand, the Compositional Nutrient Diagnosis (CND) method (Parent and Dafir, 1992) that relies on studies developed by Aitchison (1982), which involve statistical composition data analysis, based on the establishment of multinutrient variables weighed by the geometrical mean of the nutritional composition. The CND method was used by Gualter *et al.* (2005) to compare DRIS and M-DRIS for diagnosing the nutritional status of eucalypt plantations in Central-Eastern Minas Gerais State, Brazil. In this study, DRIS, M-DRIS, and CND methods were compared by means of specific norms, based on the frequency of concordant diagnoses (FCD) derived from the fertilization response potential (FRP). The means of FCD of DRIS vs M-DRIS, DRIS vs CND, M-DRIS vs CND were calculated for each comparison as follows:
1st: the nutrients N, P, K, Ca, and Mg were considered separately in the DCF evaluation of the FRP,
2nd: the FCD of the FRP for all sites, considering all 5 nutrients together, diagnosed the stands for discordances for just one nutrient. This kind of comparison expresses the highest level of similarity among the methods,
3rd: the FCD of the FRP considering all sites for the factor most limiting growth by deficiency (p), and the main factor limiting through excess. This evaluation was less rigorous but more adequate from a practical point of view.

The concordance or level of coincidence was lower when M-DRIS was included into the comparisons.

Therefore, the match between the methods may vary according to the nutrient concentration in the plant and according to the diagnosis method. The methods differ, however, as M-DRIS and CND do not establish any reference for the diagnosis, at least in the way they have been used by Gualter *et al.* (2005). Here, M-DRIS was sensitive to the effects of dilution or concentration. When analyzing selected stands of a low-productivity subpopulation with different levels of nutrient concentration in the trees, M-DRIS did not detect any limitation by deficiency, but indicated either a positive or virtually no response to fertilization, DRIS and the CND, on the other hand, were both able to detect these responses.

If growth limitations of the analyzed stands were of a non-nutritional nature, M-DRIS would appear more appropriate. However, if the low productivity were a consequence of nutritional problems as well, DRIS or CND would be the methods of choice, provided the non-nutritional problems will be solved too.

1.2.1. Critical Value Method or Critical Nutrient Level

Plant nutrient concentrations have long been used to diagnose nutritional problems in plants (Tyner, 1946; Viets *et al.,* 1954; Beaufils and Sumner, 1977). The oldest method of using tissue analysis as a diagnostic tool (Tyner, 1946) is the “critical value method” (CVM).

The critical level of a nutrient has been defined as that concentration in a specific plant of growth at which a 5 or 10 % of reduction in yield occurs, or that concentration which is associated with the breaking point of the nutrient response curve, or that concentration which is at the midpoint of the transitional zone between deficiency and sufficiency levels (Ulrich and Hills, 1973). The CNL approach is widely used but it is limited by that fact accurate interpretation of foliar values can be obtained only when sampling is restricted to that same growth stage at which the standard reference values for nutrients were established. This drawback is a direct result of using the dry matter, which changes directly with age, as the sole basis for expressing nutrient composition (Beaufils ,1971; 1973).

The usual methods for leaf analysis interpretation are based on the comparison of the nutrient concentration with critical reference values (sufficiency range approaches). Concentration values above or below reference values are associated with decrease in vegetative growth, yield, and quality. These methods consider the association of isolated concentration values with deficiency or excess, without considering the nutritional balance.

The CVM uses nutrient concentrations in an effort to separate limiting from non-limiting nutrient conditions.

Melsted *et al.* (1969) determined the critical concentrations for 11 essential elements for maize, soybeans, wheat, and alfalfa. The levels were determined after conducting experiments at a number of locations for several years.

Hylton *et al.* (1967) have shown that the critical level of an element can shift rather widely if an interfering or complimentary element is present.

The CNL or CVM had some advantages and disadvantages.

Advantages

Conventionally, leaf analysis has provided a guide for fertilizer application according to the sufficiency range (Carpena *et al.,* 1969; Del Amor *et al.,* 1984). The deficiency or excess of an element has a clear influence on its ratios with other elements (Llorente, 1966; Carpena *et al.,* 1969).

Disadvantages

While CVM can be used to make accurate diagnoses, some of its disadvantages are according to Tyner (1946) Bailey *et al.* (1997):

- critical nutrient values vary with the concentration of other nutrients,
- critical values vary with plant age and varieties and,
- CVM does not diagnose which nutrient is “most limiting” when two or more nutrients are simultaneously deficient.
- Unfortunately, the results of such analyses can be difficult to interpret, simply because the minimum or critical concentration of a nutrient in plant tissue for optimum growth varies both with crop age and with changes in the concentrations of other nutrients.

A new concept for plant analysis interpretation has been proposed by Beaufils (1971; 1973) as a means to overcome some of these difficulties.

1.2.2. Diagnosis Recommendation and Integrated System (DRIS)

The Diagnosis and Recommendation Integrated System (DRIS) is based on nutrient balance (ratios) and is considered by some to be more accurate in its diagnoses. Diagnosis made using DRIS are based on relative rather than on absolute concentrations of nutrients in plant tissue, and as such should be comparatively independent of crop age.

The DRIS has been regarded by some to be capable of providing nutrient diagnoses via foliar analyses regardless of the origin or age of the plant. It is designed to assess relative nutrient imbalances or deficiencies or both, in plant tissue (Beaufils, 1973; Sumner, 1977a; 1977b; 1979, 1981; 1982). The DRIS approach also provides the relative order of nutrient need, and since the level of one nutrient is compared with those of all others, nutrient balance is an inherent part of the system. Furthermore, the overall status of nutrient balance in the plant is shown by the absolute sum of all of the individual DRIS indices. In its present form, the DRIS procedure is used to measure deviations of certain nutrient ratios in plant tissues from corresponding nutrient previously established as reference values, or norms. Based on these comparisons, a set of indices is produced denoting a relative sufficiency or deficiency of each element diagnosed. Since DRIS is based on ratios and nutrient balance, it would be possible to have all low nutrient levels in a plant, and still have the nutrient ratios within the optimal range. This is much more likely a problem where a relatively few number of norms are being used for a crop. Use of critical values or sufficiency ranges for samples taken at the right growth stage ensures that this problem does not occur.

Two features of the DRIS procedure distinguish it from other systems of nutrient diagnosis.

- First, providing that norms for specific crops are derived from a sufficiently large data base. However, Elwali *et al.* (1981) using a small data base (90 observations in each of the low-and high-yield subpopulations) concluded that local calibration is necessary to improve the accuracy of DRIS diagnosis. DRIS diagnoses are applicable irrespective of varietal or geographic variables or both (Sumner, 1979). Escano *et al.* (1981), however, have suggested that at least for maize, use of locally calibrated norms may be more accurate in diagnosing nutrient deficiencies than norms developed from plant materials gathered in other geographic regions.

- Second, assuming that nutrient ratios in plant tissues remain constant throughout the growing season, correct diagnoses using the DRIS procedure are possible regardless of the physiological age of the plant (Sumner 1977b; 1977c).

Advantages

DRIS has two main advantages over the conventional approaches:

- firstly, DRIS determines the sufficiency of each nutrient in relation to others in the plant, calculating a nutrient index simultaneously for each nutrient. This identifies not only the nutrient most likely to be limiting, but also the order in which other nutrients are likely to become limiting,

- secondly, DRIS calculates a nutrient imbalance index (NII), which indicates the overall nutrient balance in the plant. It provides a means of simultaneously identifying imbalances, deficiencies and excesses in crop nutrients, and ranking them in order of importance (Walworth and Sumner, 1986).

Additionally, there are other advantages of the DRIS approach:

- all factors which can be quantitatively or qualitatively expressed are considered simultaneously in making a diagnosis;
- after being developed for a plant species, the DRIS can be used irrespective of the used cultivar or local conditions;
- DRIS is less dependent on crop age than the critical level approach; and DRIS ranks the nutrients in order of their requirement by the plant (Beaufils 1973; Sumner 1978; 1979).

Disadvantages

Though DRIS is considered an improvement over the CVM, it has a disadvantage in that each time it is used, it predicts that one or more nutrients are limiting. Consequently, there is no mechanism to distinguish when nutrients are limiting and when they are not. This can result in erroneous diagnoses for situations in which nutrients do not limit yield. A possible means of avoiding this problem is to incorporate nutrient concentrations into the calculation of DRIS indices. Walworth *et al*. (1984) did this, initially with maize, and derived a dry matter index value.

However, although DRIS diagnoses may prove useful, they should always be used in conjunction with established crop and soil fertility evaluation procedures before recommendations are decided upon.

Despite many advantages providing from the DRIS, a number of modifications have been proposed including the use of only one method for calculating nutrient indices, and incorporating nutrient concentrations.

Modifications on DRIS

Originally, the method eliminated the leaf dry weight component in the analysis by using only element ratios in the calculation. Accordingly it was claimed that for the DRIS analysis the plant can be sampled at any time rather than at standard physiological stages (Kelling and Schulte, 1997). However, an M-DRIS modifications was proposed to separate limiting from non-limiting nutrients (Halmark *et al.,* 1987). This modification re-introduced the dry weight component into the analysis. According to Hallmark *et al.* (1992), in M-DRIS, all nutrients with index values more negative than the DM index are diagnosed as deficient while those with values equal to or larger than the DM index are designated as sufficient.

In previous research, Bervely *et al.* (1984) found that derivation and interpretation of DRIS diagnoses could be simplified by:

- using a logarithmic transformation of nutrient ratio data;
- using of population parameters rather than high-yield subpopulation values;

- using a single index calculation method and,
- incorporating a measure of the probability of yield response to a treatment.

The modification, described by Elwali and Gascho (1984**)**, is that any two nutrients (X and Y) are considered to be in optimum balance $\left[f(X/Y)=0\right]$ if their ratio in a sample was within the range describing by the norm (mean value) for that parameter. Using this modification of the original DRIS formula lessens the risk of wrongly declaring severe imbalances among nutrients.

Synthetic research on DRIS

Beaufils (1973) used the survey approach by using the world's published literature and plotting elemental leaf content vs. yield, a distribution that is normally skewed. To normalize the distribution curve, the yield component is divided into low- and high-yield groups. Walworth (1986) suggested that the data bank for determining DRIS norms have at least several thousand entries be randomly selected, and that at least 10 % of the population be in high-yield subgroup. It is also important that the cut-off value used to divide the low-from the high-yielding subgroups has to be such that the high-yield data subgroup remains normally distributed. Selecting the elemental content mean, the ratio and product of elemental means are with the largest variance, which in turn maximizes the diagnostic sensitivity.

Previous work indicates that the detrimental effects of tissue age, leaf position and cultivars on the accuracy of deficiency diagnoses can be minimized using DRIS (Sumner and Beaufils, 1975; Beaufils and Sumner, 1977; Sumner, 1977; Hallmark *et al.,* 1984; Hallmark *et al.,* 1985; Sumner, 1979). DRIS methodology has been used successfully to interpret the results of foliar analyses for a wide range of long-term cash crops such as sugarcane (Elwali and Gascho, 1984) and short-term cash crop such as vegetables and wheat (Meldal-Johnson and Sumner, 1980; Amundson and Koehler, 1987). This approach has been used successfully to diagnose nutritional disorders on different crops such as rubber (Beaufils, 1957), potatoes (Medal-Johnson, 1975), sugarcane (Beaufils and Sumner, 1976; Jones and Bowen, 1981; Elwali and Gascho, 1984), maize (Beaufils, 1971; Sumner, 1977), soybean (Bervely, 1979), oranges (Bervely *et al.,* 1984, Bervely, 1987) and mango (Schaffer and Larson, 1988). Some of the above studies confirmed the general utilization of the DRIS norms in many annual crops, regardless of the variety and age of the crop at sampling when the norms were obtained from broad data bases. However, it is well known that in lemon trees, leaf nutrient contents are influenced by sampling date and rootstock.

By using DRIS, many of the problems associated with or related to dry matter accumulation have been reduced. Research with several crops including sugar cane, maize, soybeans, alfalfa and wheat has shown that the effects of tissue age, leaf position and cultivar can be minimized using the DRIS approach (Sumner *et al.,* 1975; Sumner, 1977a; 1977b; 1977d; Sumner, 1979; Erickson *et al.,* 1982). For example, maize samples taken over a wide array of growth stages (30 to 110 days) may show widely varying nutrient concentrations (53, 50 and 89 % change for N, P and K respectively) whereas the ratios of these nutrients and the DRIS indices are much more consistent (Sumner, 1979).

It has generally been accepted that once a sufficient number of samples have been included in the data base and the norms correctly established, the norms are applicable across broad geographic regions or are even universal (Beaufils, 1971; Sumner, 1979). However, some data for alfalfa (Kelling *et al.,* 1986) and maize (Escano *et al.,* 1981) have shown that increased precision can be obtained by developing norms that are calibrated locally.

DRIS norms have been developed for several field, forest and horticultural crops, and have been applied as an additional tool for nutritional status diagnosis in the United States, Canada, and China (Lopes, 1998; Hallmark and Bervely, 1991).

The two new methods use individual nutrient concentration values, instead of ratios.

Investigations by Woods and Villiers (1992), in South Africa, pointed out that DRIS can be successfully applied in nutrient diagnosis of ‘Valencia’ sweet orange groves. The authors correlated yield (kg per plant) and quality (fruit mass) with DRIS indexes, working in a database with more than 1,700 observations. DRIS norms were also evaluated in field fertilization trials and successfully associated with increases in yield and fruit quality.

Cerda *et al.* (1997) developed DRIS norms for nutrient status diagnosis in ‘Verna’ lemons, cultivated in Murcia and Alicante, Spain. DRIS norms determinations were influenced by scion/rootstock combination and by sampling time. However, under high salinity conditions, DRIS was not efficient to indicate if the nutritional deficiency was caused by high salinity or lack of fertilizers.

Rodriguez *et al.* (1997) developed DRIS norms for 'Valencia' sweet orange, considering differences in plant age and in rootstock, in several regions within the four more important states in Venezuela. In their study, standard population was selected from a group of the top-20 %-yielding tree. Norms calculated were compared with those previously developed and in general, the results agreed with previous investigations. The authors suggested that DRIS can be an economical, fast and reliable alternative to traditional nutrient diagnosis. In Brazil, investigations about DRIS in citrus are rare. Creste (1996), in 'Siciliano' lemon, organized a databank with leaf analysis in fruiting terminals from plants with different ages, rootstocks and harvest years. Standard populations were grouped according to yield above 80 ton ha^{-1}. After calculation of DRIS norms, the method was evaluated under field conditions. DRIS was considered an efficient method, especially because it takes into account deficient or excess nutrients in an order of importance.

Santos (1997) utilized a databank of leaf analysis from an N, P, K-fertilization field trial network and commercial groves in São Paulo State to evaluate DRIS. Among three DRIS index calculation methods, the one proposed by Jones (1981) showed more advantages.

Citrus nutritional status can be affected by numerous factors such as soil and climatic effects, scion/rootstock combination, depth of root system, pests and diseases.

1.3. Objectives of the Study and Working Hypotheses

This research was carried out in the framework of sub-project A3 of IMPETUS Project in Benin, whose objectives are:

1.3.1. Objectives of Sub-Project A3

Objectives of the sub project A3 were to:

1. provide an integrated view of the current status of cycles and management of water in sub-humid tropics,

2. develop models and calculate scenarios of this aspect under different conditions (global warming, demographic development, soil degradation), including possible influences on the local climate, and
3. suggest approaches for a sustainable and economic use of water, considering socio-economic and ecological aspects and constraints.

   This project has chosen the Ouéme Supérieur as
   - the water shed is supposed to undergo a dramatic change in the coming years in many aspects which refer to the demand for water and soil resources when current trends continue; the area will likely suffer a similar development which occurred in the past two to three decades in the Sahelian and northern parts of the sub-Sahelian zone,
   - it is important for agricultural production,
   - the availability of an area, which is still in a “near-natural” condition and may serve as a reference to sites of intensive human use.

1.3.2. Research Objectives

The main objectives of the present study were to identify nutrient and soil fertility constraints, which prevent higher per area and per unit of water productivity and elaborate fertilizer recommendations.

Specific objectives were to:

1. identify those nutrients which are limiting productivity on the basis of soil and plant analysis, compare plots with optimum nutrition to current farmer’s practice with respect to productivity over a two years period,
2. compare effects of fertilizer application nutrition to current farmer’s practice,
3. determine the water consumption per unit of biomass (maize) and per unit of area,
4. assess (simplified) nutrient balances for the prediction of long-term trends of nutrients availability and soil productivity.

1.3.3. Working Hypotheses

Three hypotheses have been formulated for the objectives above. These are:

1. nutrient deficiencies and low supply of organic fertilizers limit productivity in cropping systems of the “Oueme Superieur” and WUE of maize in Dogue,

2. nutrient balances of actual farming systems are negative,
3. improvement of fertilizer supply will increase yields and WUE of crop production in the project area.

2. Materials and Methods

2.1. Site Description

2.1.1. Location

The field trials were established in Upper Ouémé Catchment in the Republic of Benin, West Africa (Figure 1).

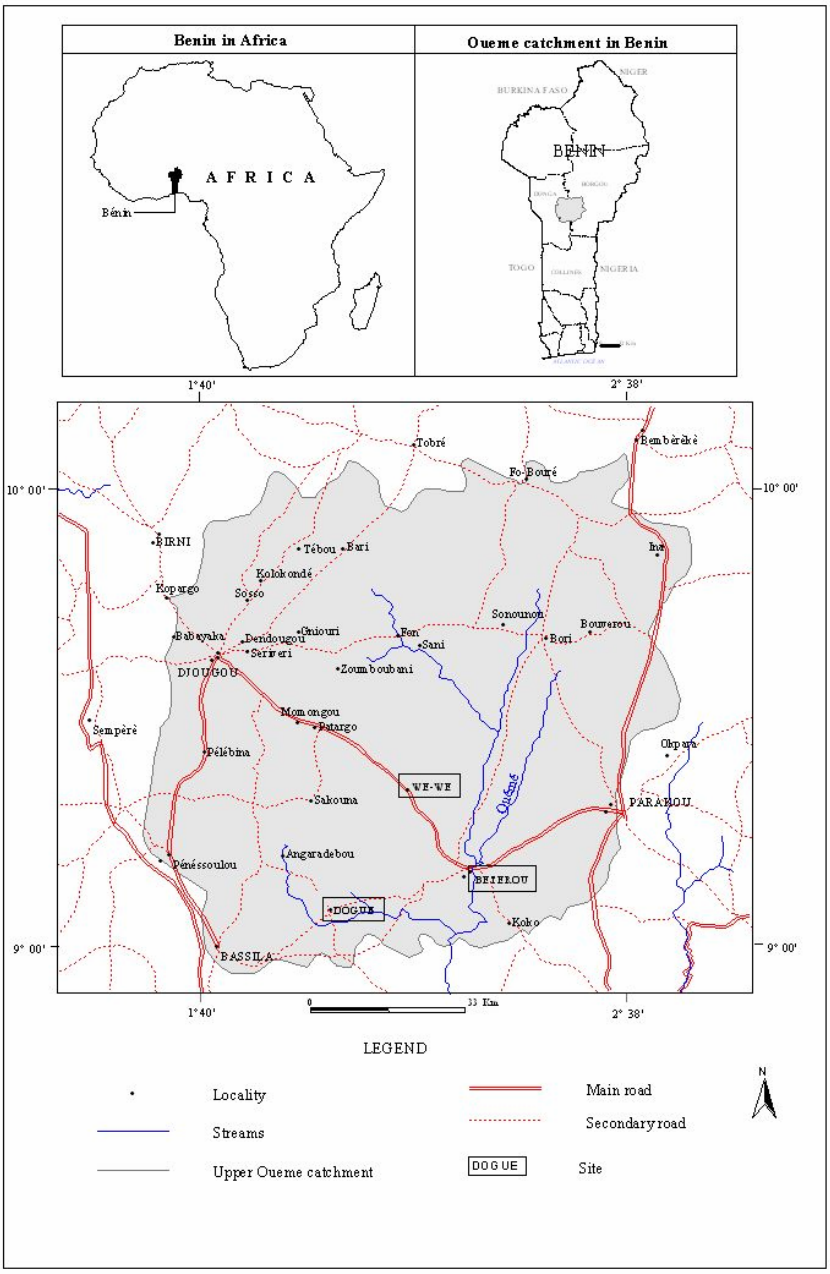
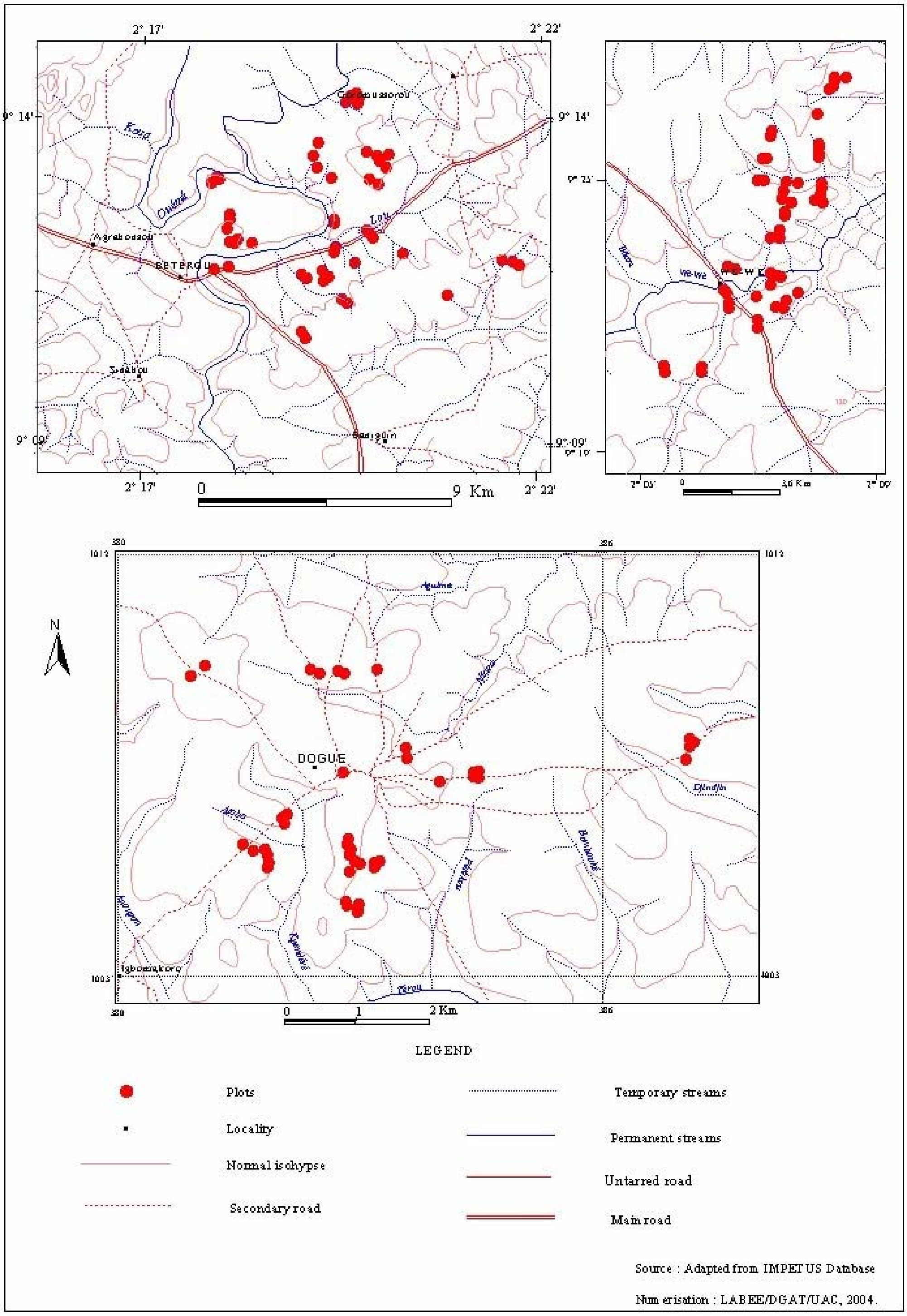


Figure 1 Map: Location of the project area Upper Ouémé Catchment

The experiments were carried out in 2001 and 2002 at three sites: Beterou (southern Borgou Department), Dogue (southern Donga Department), and Wewe (border of southern Borgou and southern Donga Departments), at a distance of about 45, 87 and 80 km, respectively, from Parakou (Figure 2).



Source : Adapted from IMPETUS Database

Numérisation : LABEE/DGAT/UAC, 2004.

Figure 2: Map of the distribution of the field plots at the three sites

Beterou is located at 9°23 N and 2°07 E, Dogue at 9°06 N and 1° 56 E and Wewe at 9°12 N and 2° 16 E. The distribution of the plots at the different sites is shown in figure 2.

2.1.2. Climate

The climate on the three sites is Soudano-Guinean. The rainfall distribution is unimodal with two seasons: a rainy season from mid of April to mid of October, and the subsequent dry season.

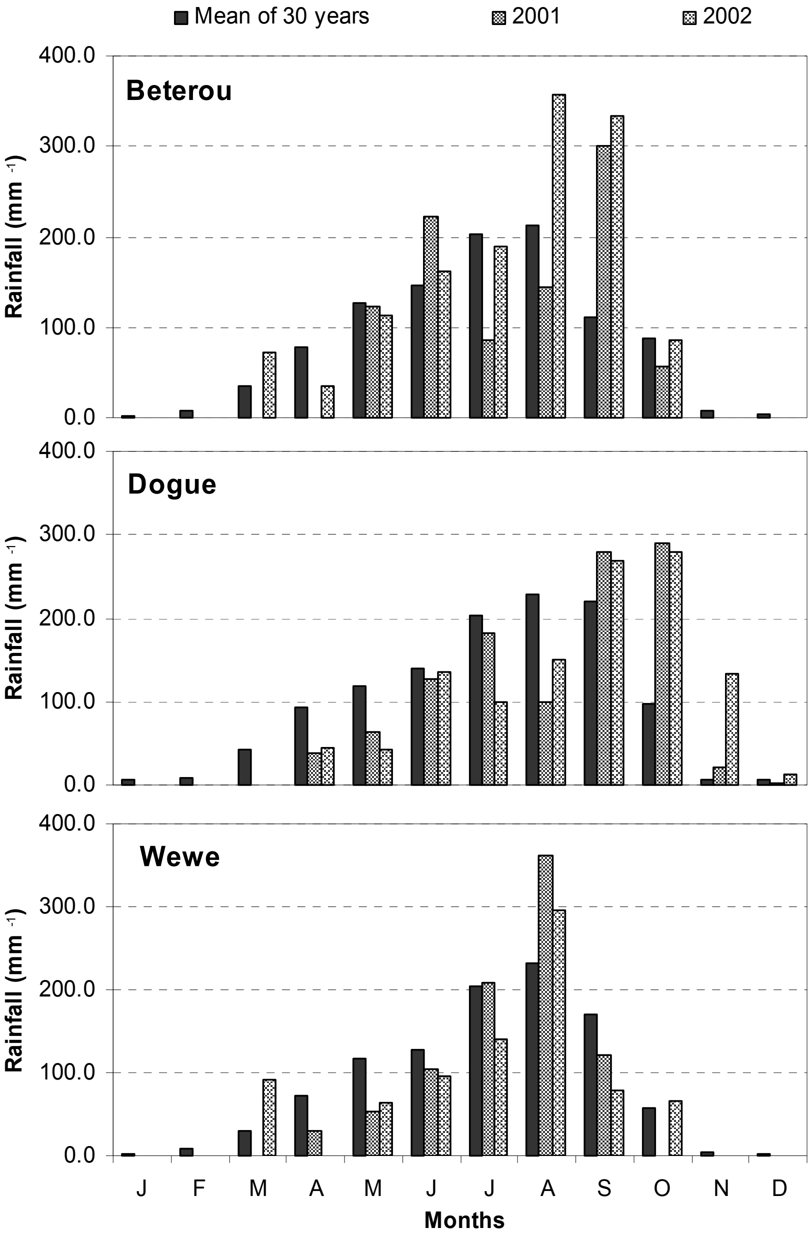


Figure 3: Comparison of annual average rainfall from 1971 to 2000, 2001 and 2002

(Source: Impetus data base, 2002)

Data from weather stations close to the field plots (Partago for Wewe, Bassila to complete Dogue). Averaged over the last 30 years, total annual rainfall was 1,023.5 mm for Wewe (from Partago station), 1167.6 mm for Dogue (from Bassila and Dogue) and 1018.4 mm for Beterou (Figure 3).
The temperature does not vary much within the year. The maximal temperature is 40°C in the dry season, the minimum is 10°C and the average is 25.
On the average, rainfall shows a peak in August. First rainfalls begin in March, and are significant from May to September, the period of intensive farming activities. Rainfall ceases in November or December at all three sites (Figure 3)
Harmattan (cold and dry wind) and the monsoon (warm and humid wind) are two wind systems in the north of Benin, with harmattan as the dominating system.

The natural vegetation in the region is a tree/shrub savanna with the dominating species: *Pterocarpus erinaceus, Anogeissus leïocarpus, Vitellaria paradoxa, Parkia biglobosa, Burkea africana, Nauklea latifolia, Daniella oliveri, and Phoenix reclinata.*

Plantations with perennials comprise *Anacadium occidentale, Tectona grandis,* and *Mangifera indica.*

Population of adventives is not neglected. These are: Panicum maximum, Pennisetum pedicellatum, Pennicetum unisetum, Imperata cylindrica, Combretum racemosum, Combretum hypopilinum, Sida latifolia, Sida acuta, Commelina diffusa, Andropogon spp, etc...

2.1.3. Soil Characterization at the Different Sites

A summary on soil conditions immediately before starting the experiments is indicated in Table 1 (Details for all individual plots are listed in Annex (1 -6) :

Soil textures found in the top 20 cm were loamy sand with 3-10 % of clay and 76-86% of sand, and sandy loam with 7-13 % of clay and 73-80 % of sand on all site.

Organic matter and total nitrogen contents in the experimental soils varied from low (1, 5% and 03 % resp.), to intermediate (2.5% and 0.3%, resp.). On most plots, organic matter contents were low, and higher levels (OM >2.5 %) were only found in exceptional cases. All sites showed weakly acid (6.1< pH < 6.5) to neutral (6.6 < pH < 7.3) soils. C/N ratios ranged between 10 and 18, indicating largely uninhibited mineralization, the higher values found on sites which have been cleared recently and/or which may still contain carbon from slash and burn. The highest C/N ratios were found on plots in the forest of Wewe.

The potassium content ranged from low (<0.15 cmol kg^{-1}) in Dogue to intermediate (0.15 < K < 0.30 cmol kg^{-1}) supply in Beterou and Wewe and in some plots of Dogue. Others individual plots that presented high levels of available K were sites following fallow and those on which cotton crop were produced. There were 42 out of 174 and 9 out of 24 respectively on lighter and heavier soils in Beterou, only 3 out of 63 on heavier soils in Dogue, 2 out of 92 and 10 out of 52 respectively on lighter and heavier soils in Wewe. The CEC (<15 cmol kg^{-1}) was low in the three site.

In summary, it results that soils in three locations have low soil fertility.

Table 1: Overview of soil characteristics (plough layer: 0 – 20 cm) at the beginning of the experiment (in *parenthesis) Standard deviation*

Sites	Physical properties				Chemical properties					
	Clay	Silt	Sand	Texture	P	K	pH	N	OM	C/N
	-------[%]------				Mg kg^{-1}	Cmolkg^{-1}		------[%]-----		
Lighter soils										
Beterou										
Mean	6.8	9.7	82.9	**LS**	11.1	0.25	6.7	0.064	1.53	14.1
	(1.1)	*(1.4)*	*(1.5)*		*(4.3)*	*(0.04)*	*(0.1)*	*(0.009)*	*(0.23)*	*(0.8)*
Dogue										
Mean	7.2	9.8	81.8		4.0	0.12	6.4	0.058	1.26	12.76
	(0.8)	*(2.4)*	*(2.9)*		*(1.3)*	*(0.03)*	*(0.1)*	*(0.013)*	*(0.21)*	*(0.8)*
Wewe										
Mean	7.2	11.0	81.2		6.3	0.14	6.6	0.058	1.26	16.7
	(0.9)	*(2.0)*	*(2.0)*		*(2.5)*	*(0.03)*	*(0.1)*	*(0.016)*	*(0.17)*	*(9.4)*
Heavier soils										
Beterou										
Mean	8.8	11.7	78.2	**SL**	17.6	0.31	6.7	0.061	1.66	15.5
	(1.5)	*(1.4)*	*(1.5)*		*(11.8)*	*(0.07)*	*(0.1)*	*(0.019)*	*(0.69)*	*(2.3)*
Dogue										
Mean	8.6	13.8	76.7		5.2	0.15	6.4	0.064	1.42	13.1
	(0.7)	*(1.9)*	*(1.8)*		*(3.1)*	*(0.03)*	*(0.1)*	*(0.008)*	*(0.21)*	*(0.5)*
Wewe										
Mean	9.6	14.2	75.6		8.1	0.20	6.8	0.068	1.47	13.3
	(1.8)	*(1.9)*	*(1.7)*		*(3.8)*	*(0.07)*	*(0.1)*	*(0.011)*	*(0.27)*	*(2.3)*

2.1.4. Crop Varieties

Varieties of crops were *Dioscorea rotundata* for yam, *Sakarabougourou* with long vegetation period for sorghum, DMR-ESRW1 for Maize, RMP 12 G1 for groundnut and STAM 18 A for cotton. These varieties of crops used during the two years of the experiment were provided by the farmers for yam and the "*Institut National des Recherches Agricoles du Bénin* (INRAB) for the other crops.

2.2. Treatments and Field Layout

The experiment design was a randomized completed block. There were as many farmers as blocks or replicates depending on the site. Treatments were:

T0: plots without fertilizer or organic matter applied

T1: plots with organic matter:

T1F: organic matter as farmyard manure

T1M: organic matter as mulch from the preceding crop, where manure was not available

T2: plots with mineral fertilizer

T3: plots with mineral fertilizer and organic matter, again divided into:

T3F: with farmyard manure

T3M: with mulch

Organic matter was either farmyard manure provided by individual farmers or crop residues (groundnut, maize, yam, cotton, sorghum or fallow) at 10 t ha^{-1}, applied only in 2001. In 2002, the residual effect of the manure was compared with the mulching at the same amount because no farmyard manure was applied. Notice that, plots on which manure was applied in 2001 were not cleared from crop residues.

Mineral fertilizer applications are summarized in table 2:

Table 2: Mineral fertilizer application rates (kg·ha^{-1}) used in the experiment

Nutrients	**Maize**		**Sorghum**		**Cotton**		**Peanut**		**Yam**	
	2001	**2002**	**2001**	**2002**	**2001**	**2002**	**2001**	**2002**	**2001**	**2002**
N	60	75	23	28	51	51	10	10	30	42
P	40	40	46	46	46	46	40	20	30	30
K	0	24	0	28	28	28	0	0	60	60

The nitrogen content in the manure ranged from 1.4 % to 1.75 %, P between 0.18 % and 0.31 %. K contents were more variable and amounted from 0.70 % to 5.50 %, whereas Ca ranged between 0.66 % and 1.46 %, and Mg between 0.24 % and 0.66 % (Table 3).

Table 3: Average composition of manure (DM) applied on the three different sites in 2001.

Sites	***N***	***P***	***K***	***Ca***	***Mg***	***Na***	***Mn***	***Zn***
	------------------------------[%]--------------------------						***-----[mg kg^{-1}]---***	
Dogue	*1.59*	*0.24*	*1.51*	*0.66*	*0.36*	*0.05*	*542.19*	*49.57*
Wewe	*1.62*	*0.27*	*2.76*	*1.08*	*0.45*	*0.02*	*310.96*	*47.17*
Beterou	*1.59*	*0.23*	*1.54*	*0.87*	*0.32*	*0.04*	*442.97*	*84.93*

DM: dry matter

Periods and type of fertilizers applied were:

Maize

N was applied as DAP and NPK at the sowing period respectively in 2001 and 2002 and urea at 40-45 days after sowing in both years of the experiment.

Sorghum

TSP and urea were applied at the sowing period and urea banding 40-45 days after sowing date in 2001, whereas NPK and urea were applied at sowing in 2002.

Cotton

NPK and urea after were applied at the first weeding (2 weeks after sowing). Additional urea was applied at about 40 days after sowing in 2001 and 2002.

Groundnut

TSP and Urea were applied at sowing in 2001 and NPK at sowing in 2002.

Yam

Mineral fertilizers applied at planting in 2001 were TSP, KCl and urea. It was NPK, KCl and urea in 2002. Table 4 shows the numbers of farmers involved in this experiment in 2001 and 2002.

Table 4: Number of farmers involved in the fertilizer trials in 2001 and 2002 at the three sites

Sites	Maize		Sorghum		Yam		Peanut		Cotton		Total	
	2001	2002	2001	2002	2001	2002	2001	2002	2001	2002	2001	2002
Beterou	8	14	5	4	6	11	7	7	7	14	33	50
Dogue	12	7	4	2	6	7	2	2	0	4	24	22
Wewe	6	12	6	4	7	9	6	6	0	6	23	37
Total	26	33	15	10	19	27	12	15	7	24	80	109

Due to the in parts bad growth of maize and sorghum resulting from low soil fertility in 2001, cowpea was sown at the beginning of the rainy season on maize and sorghum fields for green mulch.

Due to the later onset of the rainy season in 2002, the sowing of cowpea was delayed and maize, sorghum or yam were planted in association with cowpea After the harvest of cowpea, the main crops started with their main growth period.

2.3. Field Management and Observations

The cultural practices corresponded to those of the individual farmers.

The cropping sequence during the experiment is summarized in tables 5 - 9.

The cropping sequence was continued only with certain farmers while other peasants abandoned their field.

Table 5: Cropping sequence with cotton (*Gossypium hirsutum L*) as crop in 2001

Sites	Crop 2000	Crop 2001	Crop 2002
Beterou	Cotton	Cotton	Groundnut
Beterou	Groundnut	Cotton	Abandoned
Beterou	Maize	Cotton	Cotton
Beterou	Maize	Cotton	Groundnut
Beterou	Maize	Cotton	Abandoned
Beterou	Maize+Sorghum	Cotton	Maize
Beterou	Sorghum	Cotton	Maize
Beterou	Sorghum	Cotton	Cotton
Beterou	Sorghum	Cotton	Abandoned
Dogue	Fallow	Cotton	Cotton
Dogue	Cotton	Cotton	Abandoned
Wewe	Yam	Cotton	Maize
Wewe	Yam	Cotton	Sorghum
Wewe	Abandoned	Cotton	Abandoned

Table 6: Cropping sequence with sorghum (*Sorghum bicolor L*) as crop in 2001

Sites	Crop 2000	Crop 2001	Crop 2002	Off season 2002
Beterou	Yam	Sorghum	Abandoned	Abandoned
Beterou	Yam	Sorghum	Cotton	Abandoned
Beterou	Yam	Sorghum	Cotton	Bean
Beterou	Yam	Sorghum	Sorghum	Abandoned
Dogue	Abandoned	Sorghum	Abandoned	Abandoned
Dogue	Bean	Sorghum	Groundnut	Yam
Dogue	Abandoned	Sorghum	Maize	Pimento
Wewe	Yam	Sorghum	Groundnut	Bean
Wewe	Maize	Sorghum	Yam	Bean

Table 7: Cropping sequence with maize (*Zea mays*) as crop in 2001

Site	Crop 2000	Crop 2001	Crop 2002	Off season 2002
Beterou	Cotton	Maize	Yam	Abandoned
Beterou	Abandoned	Maize	Abandoned	Abandoned
Beterou	Cotton	Maize	Sorghum	Bean
Beterou	Cotton	Maize	Abandoned	Abandoned
Beterou	Cotton	Maize	Maize	Bean
Beterou	Cotton	Maize	Yam	Bean
Beterou	Fallow	Maize	Sorghum	Abandoned
Beterou	Sorghum	Maize	Sorghum	Bean
Beterou	Yam	Maize	Abandoned	Abandoned
Wewe	Abandoned	Maize	Abandoned	Abandoned
Wewe	Yam	Maize	Groundnut	Bean
Wewe	Sorghum	Maize	Groundnut	Bean
Wewe	Abandoned	Maize	Sorghum	Bean
Wewe	Groundnut	Maize	Sorghum	Bean
Wewe	Sorghum	Maize	Yam	Bean
Wewe	Abandoned	Maize	Yam	Bean
Dogue	Cotton	Maize	Maize	Abandoned
Dogue	Fallow	Maize	Abandon	Abandoned
Dogue	Groundnut	Maize	Maize	Abandoned
Dogue	Sorghum	Maize	Yam	Abandoned
Dogue	Yam	Maize	Sorghum	Abandoned
Dogue	Yam	Maize	Groundnut	Abandoned

Table 8: Cropping sequence with yam (*Dioscorea rotundata*) as crop in 2001

Sites	Crop 2000	Crop 2001	Crop 2002
Beterou	Groundnut+Sorghum	Yam	Cotton
Beterou	Sorghum	Yam	Groundnut
Beterou	Fallow	Yam	Groundnut
Dogue	Fallow	Yam	Sorghum
Dogue	Fallow	Yam	Maize
Dogue	Fallow	Yam	Abandoned
Wewe	Abandoned	Yam	Abandoned
Wewe	Abandoned	Yam	Maize
Wewe	Sorghum	Yam	Maize

Table 9: Cropping sequence with (*Arachis hypogea L*) as crop in 2001

Site	Crop 2000	Crop 2001	Crop 2002	Off season 2002
Beterou	Cotton	Groundnut	Yam	Abandoned
Beterou	Cotton	Groundnut	Cotton	Abandoned
Beterou	Cotton	Groundnut	Abandoned	Abandoned
Beterou	Maize	Groundnut	Groundnut	Abandoned
Beterou	Sorghum	Groundnut	Abandoned	Abandoned
Beterou	Yam	Groundnut	Maize	Abandoned
Wewe	Abandoned	Groundnut	Abandoned	Abandoned
Wewe	Sorghum	Groundnut	Yam	Abandoned
Wewe	Maize	Groundnut	Yam	Abandoned
Dogue	Sorghum	Groundnut	Maize	Groundnut

Normally, in theses sites, plots of cotton, maize and sometimes groundnuts are cleared twice, yam and sorghum once. These operations were done by hand using hoe or animal haul.

Plants samples from farmers' field were taken at harvest and analyzed (see below). Crop residues were transported to the corral built by farmers who own oxen. The production of farmyard manure was done with our technical assistance. Mulching was done on plots of those farmers who did not have own animals.

Plots were laid out at a size of 8m x 8m. Soil samples were taken for analysis and experiments were installed in June 2001. Yam plots were laid out in existing farmer's fields. Farmers had planted this crop between February and April 2001. Thus, the planting density varied according to ethnic tradition, site conditions and farmer's habits. It varied from 4800 to 6800 plants ha^{-1} in 2001 but was set to 10000 plants ha^{-1} on all the sites in 2002.

Two grains of maize and groundnut were sown and thinned to 62500 plants ha^{-1}; sorghum and cotton were sown as one pinch and later thinned to two plants per spot, resulting in a plant density of 111000 plants ha^{-1} for groundnut, and 62500 plants ha^{-1}, for both cotton and sorghum.

Maize and sorghum were spaced at 80 cm between and 40 cm within rows, groundnut at 60 cm between, and 15 cm within rows, and cotton at 80 cm between, and 20 cm within rows.

During the plant growth, plant samples were taken for ^{13}C and ^{15}N discrimination and comprised the third leaf or leaf pairs from top. Growth stage was less important for these analyses.

The second type of sampling was done at critical stage of plant for nutrient assessment through CVM and Diagnosis and Recommendation Integrated System (DRIS). For this type of evaluation, the procedures of sampling are listed in table 10 according to Leo M *et al*. (1973) and FAO (2000).

Table 10: Sampling scheme for plant parts and growth stage for critical values and DRIS evaluation

Plant	Sampled plant part	Plant growth stage
Maize	Entire leaf fully developed above or below the whorl	Shooting to silking
Sorghum	Second leaf from top of the plant	Prior to heading
Cotton	Youngest fully mature leaves on main stem	First bloom or appearing of first squares
Peanut	Mature leaves from both the main stem and either cotyledon lateral branch	Blooming stage
Yam	Youngest fully expanded leaves on any branch	185-215 days after planting

Nitrogen, P, K, Ca, Mg, S, Zn, and Mn were determined in these samples.

The harvest was done on a (2 x 2) m^2 area and repeated thrice per plot and per crop in 2001 and 2002. Fresh weights of leaves, straw, grain, cob, spike, stems, pod husk, fiber, and tuber were taken and sub-samples were oven dried at 60-65ºC until constant weight for dry matter.

The yield was determined using the formula below:

Yield (kg ha^{-1}) = $\left(P * DM * 100/4\right)$ with DM (%) = $(Ps/Pf) * 100$

where Pf is fresh matter of the sample (straw, cob, stem, spike etc…), Ps their percentage of dry matter and P total weight of the sample taken from the field The formula of grain at 14 % of water content for maize and sorghum is:

$$P * n * Pf \frac{Pfgr * DM * 100}{Pfcorn * 86}$$

With DM (%) = $(Ps/Pf) * 100$ and n the ratio between weight of grain and maize of a sample, Pf is fresh matter of the sample (maize, pod, etc…), Ps their percentage of dry matter and P total weight of the sample taking from the field For groundnut, the water content of conservation is 9% so the coefficient of 100/91 is used for the determination of yield.

For yam the fresh and dry matter of yield was determined using the number of hills on which the tuber is grown.

All theses samples were ground and composite samples of theses sub-samples were taken for N, P, K, Ca, Mg, S, Zn, and Mn determinations in the laboratory of the Institute of Plant Nutrition in Bonn.

2.3.1. Soil and Plant Analysis

2.3.1.1. Soil samples

The soil was classified (Table 11) in 2004 according to one team constituted by Igue *et al.* using CPCS (1967) and WRB (1998).

Soil samples for 20 cm depth (plough layer) were taken just before initiation of the experiments to identify the initial fertility status of the plots. Some soil profiles were dug and described for the different sites according to the "Guidelines for Soil Profile Description" FAO (1990).

Table 11: Soil description according to French Classification and WRB Classification

Sites	Localities	Altitudes	Types of soil	
			Classification Française (1)	**WRB classification (2)**
Beterou	9°14007/2°/20935	304 m	Sol ferrugineux tropical moyennement profond, induré à mi-profondeur Moderately Deep Tropical Ferruginous soil with a mid-depth hardpan	PLINTHOSOLS
	9°12331/2°/18662	276 m	Sol ferrugineux tropical très concrétionné sur migmatite *Tropical Ferruginous soil on migmatite with high concretions content*	Ferric Profondic LUVISOLS
	9°10788/2°/18080	297 m	Sol ferrugineux tropical très concrétionné sur granite *Typic Tropical Ferruginous soil on granite with high concretions content*	Ferric Profondic LUVISOLS
Wewe	9°22474/2°/07109	340 m	Sol ferrugineux tropical typique sur migmatite *Typic Tropical Ferruginous soil on migmatite*	ACRISOLS or Plinthic LUVISOLS
	9°23897/2°/05940	328 m	Sol ferrugineux tropical induré à partir de 55 cm sur granite bariolé d'altération *Tropical ferruginous soil with a hardpan starting at 55cm depth, on mottled clay.*	Plinthic LUVISOLS
Dogue	9°05562/1°/56253	309 m	Sol ferrugineux tropical sur horizon *d'altération kaolinitique et carapacé* *Tropical ferruginous soil on a kaolinitic alteration layer*	PLINTHOSOLS
	9°05559/1°/55561	321 m	Sol ferrugineux tropical hydromorphe Hydromorphous Tropical Ferruginous soil	LIXISOLS

(1): CPCS (1967) (2): WRB (1998).

The following analyses were carried out on the soil samples:

- Soil texture (five fractions) by Robinson pipette (Tran *et al.,* 1978);
- pH determined in water (a soil/water ratio of 2:1) using a pH meter with glass combination electrode with a WTW pmx 2000;
- total N determined using the macro Kjeldahl procedure described by Jackson (1958) with a Gerhardt Vapodest;

- organic C determined using the method described by Walkley and Black (1934) and the organic matter content calculated by multiplying organic C by 1.724;
- C, N, and S were determined by an automatic Elemental Analyser EuroEA 3000 according to the Dumas method;
- P was extracted with calcium-acetat-lactat-extraction (CAL) and determined by colour development in the extract with molybdenum blue and photometric measurement;
- To determine the C and N isotope discrimination, isotope ratios were measured from finely ground plant material in a Europa Scientific 2020 mass spectrometer;
- Micronutrient levels were determined after extraction of soil samples with 01 N HCl, made to volume, and filtered through Whatman No1. Analysis was done with a Perkin-Elmer flame atomic absorption spectrophotometer, Model 70PE 1100 B.

2.3.1.2. Plant material

Plants were sampled as described above. After air drying, material was further dried at 70°C to a constant weight, pre-ground by a Brabender mill and stored dry.

For elementary analysis, plant material was finely ground by a planetary mill (Retsch).

The following analyses were carried out on the plant material:
C, N, and S determined by elemental analysis in the EuroEA 3000.
Further elemental composition was determined after dry ashing in porcelain crucibles at 550°C in a muffle furnace, dissolving the ash in concentrated nitric acid, evaporation to dryness on a sand bath (to precipitate silicate), and taking up with concentrated nitric acid again, and transferred to volumetric flasks with several rinses of ultra pure water (MilliporeQ).
P was determined using the molybdo-vanadate blue method, with a spectral photometer (model Eppendorf Digitalphotometer 6114) at wavelengths of 465 and 665 µm.

K, Ca, Mg, and micronutrients determined on a Perkin-Elmer PE 1100 B atomic absorption spectrophotometer.

2.3.1.3. Diagnosis and Recommendation Integrated system (DRIS) Methodology

For this study, the population was divided into high and low yielding subpopulations using the mean + interval of confidence as criteria for cut-off.

The nutrient ratio was calculated for both of the high and low yielding population so that each of the nutrients determined in the tissue appeared in the denomination and again in the numerator in ratio with each of the other element (for example N/P and P/N). For each form of expression, the variance for both of the high and low yielding populations was calculated. A variance ratio for each nutrient ratio is also determined by dividing the variance of the low yielding population by the variance of the high yielding population (Elwali, 1985; Amundson, 1987; Payne, 1990). For each pair of nutrients, the form of expression, which gave the highest variance ratio, was selected as the parameter to be used for DRIS-evaluation. The mean of the selected parameters for the high yielding population became the foliar diagnostic norms were then used, along with the standard deviation, to calculate DRIS indices for diagnostic purposes.

The means and standard deviation (SD) of DRIS reference parameters in the high yielding subpopulation were then programmed for diagnostic purposes using the following general calibration formula (Hallmark, 1987; Westerman, 1990; Rathfon, 1991; Bailey, 1997).

X index = $\left[f\left(\frac{X}{A}\right) + f\left(\frac{X}{B}\right) + \cdots - f\left(\frac{M}{X}\right) - f\left(\frac{N}{X}\right) - \cdots \right]$

- Where $f\left(\frac{X}{A}\right) = 100\left[\left(\frac{X}{A}\right)/\left(\frac{x}{a}\right) - 1\right]/CV$

- when $\frac{X}{A} > \frac{x}{a} + SD$

-

- and $f\left(\frac{X}{A}\right) = 100\left(1 - \left(\frac{x}{a}\right)/\left(\frac{X}{A}\right)\right)/CV$

- when $\frac{X}{A} < \frac{x}{a} - SD$

$\frac{X}{A}$ is the ratio of concentrations of nutrients X and A in the sample while $\frac{x}{a}$, CV, SD are the mean, coefficient of variation, and standard deviation for the parameter $\frac{X}{A}$ in the high-yielding population respectively. Similarly, other nutrient ratios $\frac{X}{B}$, $\frac{M}{x}$ and $\frac{N}{x}$ etc. are calibrated against the corresponding DRIS reference parameters, $\frac{x}{b}$, $\frac{m}{b}$ and $\frac{n}{x}$, etc.. Nutrient indices calculated by this formula can range from negative to positive values depending on whether a nutrient is relatively insufficient or excessive with respect to all other nutrients considered. The more negative is the index value for a nutrient, the more limiting is that nutrient.

- A measure of nutritional balance among any group of nutrient (nutritional balance index) is obtained by adding the values of DRIS indices for that group of nutrients irrespective of sign. The closer the value of this index to zero the better is the balance among those nutrients.

The means and coefficients of variation (CVs) for DRIS reference parameters in high-yielding subpopulations are used in a special calibration formula described by Beaufils (1973).

2.3.1.4. Nutrient balance

Nutrient balance model

Net changes in the nutrient pool (ΔN) per year (t=0 to 365) were determined according to: $\sum_{t=0}^{t=365} inputs$ - $\sum_{t=0}^{t=365} ouputs$ (Frissel, 1978; Pieri, 1992).

The following Ins and OUTs were assessed:

In1	Application of crop residues or manure
In2	Application of inorganic fertilizer
In3	Atmospheric deposition
In4	Biological fixation
Out1	Nutrient removal in harvest product
Out2	Nutrient removal in crop residues

Out3	Losses by leaching
Out4	Losses by wind erosion
Out5	Volatilization/denitrification

The algebraic sum of inputs and outputs makes up the nutrient balance. Ideally, the approach assumes that all inputs and outputs can be measured; however, values from the existing literature could be coupled with the data on, nutrient of organic and mineral fertilizers applied, crop yields and residues with their nutrient concentrations removed. For a crop, the inputs (In) and outputs (Out) are: (In 1.1): Application of crop residues, (In 1.2): Application of manure, (In 2): Inorganic fertilizer, (In 3): Atmospheric deposition (Wet and dry); (In 4): Biological fixation of N_2 Symbiotic. (Out 1): Nutrient removal in harvest product; (Out 2): Nutrient removal in crop residues; (Out 3): leaching losses; (Out 4): Erosion and runoff; Wind erosion, water erosion; (Out 5): Volatilization/denitrification of N. The internal fluxes are: (d) Dissolution of minerals; (fix) Fixation of P; (m) Mineralization of organic matter; (r) Immobilization of nutrients. Values below for N, P and K are in kg ha^{-1} $year^{-1}$.

It had been described in this study, only parameters measured for the partial balance.

Inputs

Application of organic fertilizer

The nutrient contents in the organic materials *(In 1)* applied were calculated by multiplying the quantities applied with the nutrients content (N, P and K) of the manure applied or crop residues of the previous year.

Application of mineral fertilizer

The amount of N, P, and K in the mineral fertilizer (*In 2)* applied on the plot was taken into account for the calculation.

Biological fixation

This parameter was calculated only for groundnut.

The proportion of N in groundnut derived from N_2 fixation PN_2 was determined after 80-85 days after the planting of groundnut by comparing the ^{15}N

abundance of N in groundnut ($\delta^{15}N_{ref}$). The ($\delta^{15}N_{ref}$) was assumed to provide a measure of the $\delta^{15}N$ of plant-available soil mineralized during the season. These values were compared each other taking into account the treatments, and those of sorghum seemed to be the reference crop of groundnut because the percentages obtained were very close to the value found in literature while no clear trend was observed with those of maize, cotton, and yam. The proportion of N derived from N_2 was calculated (after Shearer and Kohl, 1986) as

$$PN_2(\%) = 100(\delta^{15}N_{ref} - \delta^{15}N_{VB})/(\delta^{15}N_{ref} - B)$$

where B is 0.7 (Peoples *et al.*, 1992).

Estimates of PN_2 were made on a whole plant basis in 2002. This proportion of N_2 obtained was used for the calculation of the amount of N_2 fixed each year as: N amount = (PN_2/100)*(crop N at final harvest).

Non symbiotic N fixation depends on the amounts of dry matter produced but was neglected for the balance as it constitutes only a small fraction of n imports.

Outputs

Nutrient removal by crops

The amount of nutrients removed from the system *via* crops depends on the fraction of the crop removed from the field and the concentration of nutrients therein: Out 1N: N = (N% x grain kg ha^{-1}) + (N% x residues kg ha^{-1}); Out 1P : P= (P% x grain kg ha^{-1}) + P % x residues kg ha^{-1}); Out 1 K: K= (K % x grain kg ha^{-1}); + (K% x residues kg ha^{-1}).

For the comparison with nutrient balance assessed by the other authors, only the parameters used for the partial nutrient balance (In1.1, In1.2, In2, In4 and Out 1, Out 2,) in the present work will be taken into account.

2.3.1.6. Water consumption

Due to the difficulties to assess ETR for all the crops, this parameter was collected only for maize in 2002 in Dogue.

The ETR expresses the need in real water of a plant (Aho and Kossou (1997) cited by Adjikouin, 2002). Its assessment takes into account the available water in soil (FAO, 1987). It was calculated according to the formula of Rijtema and

Aboukhaled (FAO, 1987). It has been supposed that ETR is equal to the Maximum Evapo-transpiration (ETM) to the moment where the fraction (p) of the available water in soil (RU) at rooting depth (D) is exhausted. Once the fraction (p) of the available total water in soil is dried up at rooting depth (RU.D), the ETR falls below ETM until a strong rain and becomes a function of the quantity of the remaining water in soil ((1-p) RU.D).

Based on this hypothesis, the relation can be described as:

ETR = ETM = $\frac{-dRt.D}{dt}$ when $\frac{-dRt.D}{dt} \geq$ (1-p) Ru.D (1)

ETR = $\frac{Rt.D}{(1-p)RU.D} \cdot ETM$ = when RtD$\leq$ (1-p) Ru.D (2),

Where Ru.D = quantity total of available water in soil at rooting depth, and Rt.D = actual quantity of available water at rooting depth, p = fraction of the available water in the soil when ETR = ETM.

Due to difficulties to measure "p" under the local conditions (structure of soil, density of vegetation), approximated values of p according to FAO (1987) have been adopted. According to these authors, maize is classified in the group of culture 4 as indicated in table 12.

Table 12 Fraction (p) of plant available soil water in drying soils as related to the maximum evapo-transpiration (ETM) for maize according to FAO (1987)

ETM mm/ day								
2	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
0,875	*0,8*	*0,7*	*0,6*	*0,55*	*0,5*	*0,45*	*0,425*	*0,4*

While integrating and replacing equations (1) and (2) one gets:

ETR = $\frac{RU.D}{t}$ [1-(1-p) e$^{\frac{-ETM.t}{(1-p)RU.D}+\frac{p}{1-p}}$] when t $\geq$ t'

t' is the time (in days) where ETR = ETM, so t'= $\frac{p \cdot RU.D}{ETM}$

ETR calculated in this way represents the mean real evapotranspiration per day in mm over the observation period.

The maximal evaporation is calculated from the following formula: ETM = Kc·ETP where

ETP = site-specific potential evapotranspiration during the cultivation period, and
Kc= crop-specific coefficient for maize (Figure 4).

Measures of soil water content RU

Due to the presence of lateritic crusts in the subsoil, rooting depth of plants never exceed 60 cm. Thus, three soil layers of 20 cm each were considered. Soil samples were taken at five points according to the method of diagonals.
For each horizon, the mass humidity (W) is calculated according to the formula: W= [(Pf-Ps) / Ps] · 100, where W = moisture content in % of the dry weight of soil, Pf = fresh weight, and Ps = dry weight.
These values of the soil moisture W are used to calculate the volumetric water content *Ǿs* through the formula *Ǿs=W· d a,* where *da* represents the specific weight of the dry soil determined with a cylinder of 100 cm^3.
Hydrous profiles have been constructed with values of volumetric water contents. The interpretation of water profiles shows the distribution of water in the soil, its loss by evaporation, and the infiltration/movement.
The useable soil water content has been determined according to the equation: RU = (H_{cc} - $H_{pF4,2}$) da · 0,1, where RU = useful reserve of water in mm of water per cm of soil thickness, H_{cc} = humidity of soil at field capacity (in %) of fine soil (< 2mm), $H_{pF4,2}$ = soil water content at the permanent wilting point (in %).
The apparent specific gravity (da) of the soils has been determined by the method of core sampling. A metallic cylinder of known volume, sharpened on one side, was used to take undisturbed soil samples. The sample was maintained in the cylinder, and then transported to the laboratory for drying. The dry matter of the soil sample was divided by its volume to obtain the apparent specific weight.

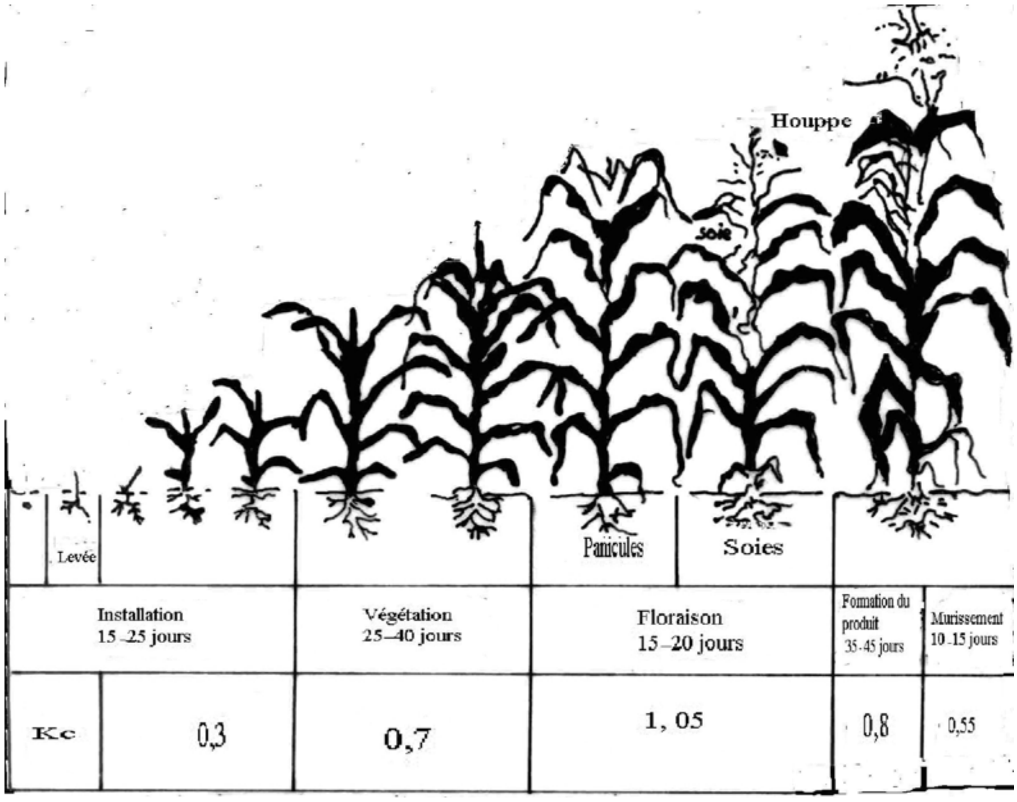


Figure 4: Growth period of maize (according to Hanway, 1966)

Water-use efficiency

Water-use efficiency according Lambers *et al.* (1998) refers to the quantity of water lost during the production of biomass or the fixation of CO_2 in photosynthesis. It is defined in two ways. First, the water-use efficiency of productivity is the ratio between (above-ground) gain in biomass and loss of water during the production of that biomass; the water loss may refer to total transpiration only, or include soil evaporation. Second, the photosynthetic (instantaneous) water-use efficiency is the ratio between carbon gain in photosynthesis and water loss by transpiration. Instead of the ratio of the rates of photosynthesis and transpiration, the leaf conductance for CO_2 and vapor can be used.

In this study, rainfall use efficiency (RUE) was determined by the ratio between total biomass of each crop and the amount of annual rainfall. Additionally, water-use efficiency (WUE) was determined in Dogue using the ratio between total biomass and real evapo-transpiration according to Rijtema and Aboukhaled (1987) see above.

Data analysis

The statistical analysis was done by using ANOVA procedure of SAS for PC (SAS, 1996) and Minitab (1996).

The yield data were analyzed for each year separately as the technology varied in part between both years. A test of sites conditions was done by using the treatment T0. It provides the reference to farmer’s practices. T1 was used to test the influence of organic matted influenced the production. The analysis of variance between treatments was done to compare the difference between the productivity relative to treatments. This analysis was done for the yield and total biomass of the five crops used for this experiment.

The comparison of the variance ratio (Levene’s test) of each pair of nutrients between the two subpopulations was done. This is to test the variability of each pair of ratio of nutrients between low- and high- yielding sub-populations for DRIS-Evaluation.

The comparison of mean of each nutrient between the two subpopulations was done. It allowed comparing the nutrient status at a critical period of low- and high- yielding sub-populations. The Student conformity test allowed comparing DRIS norms established with literature data was done.

3. Results and Discussion

3.1. Effect of Fertilizer Application on Crop Productivity and Rainfall or Water Use Efficiency

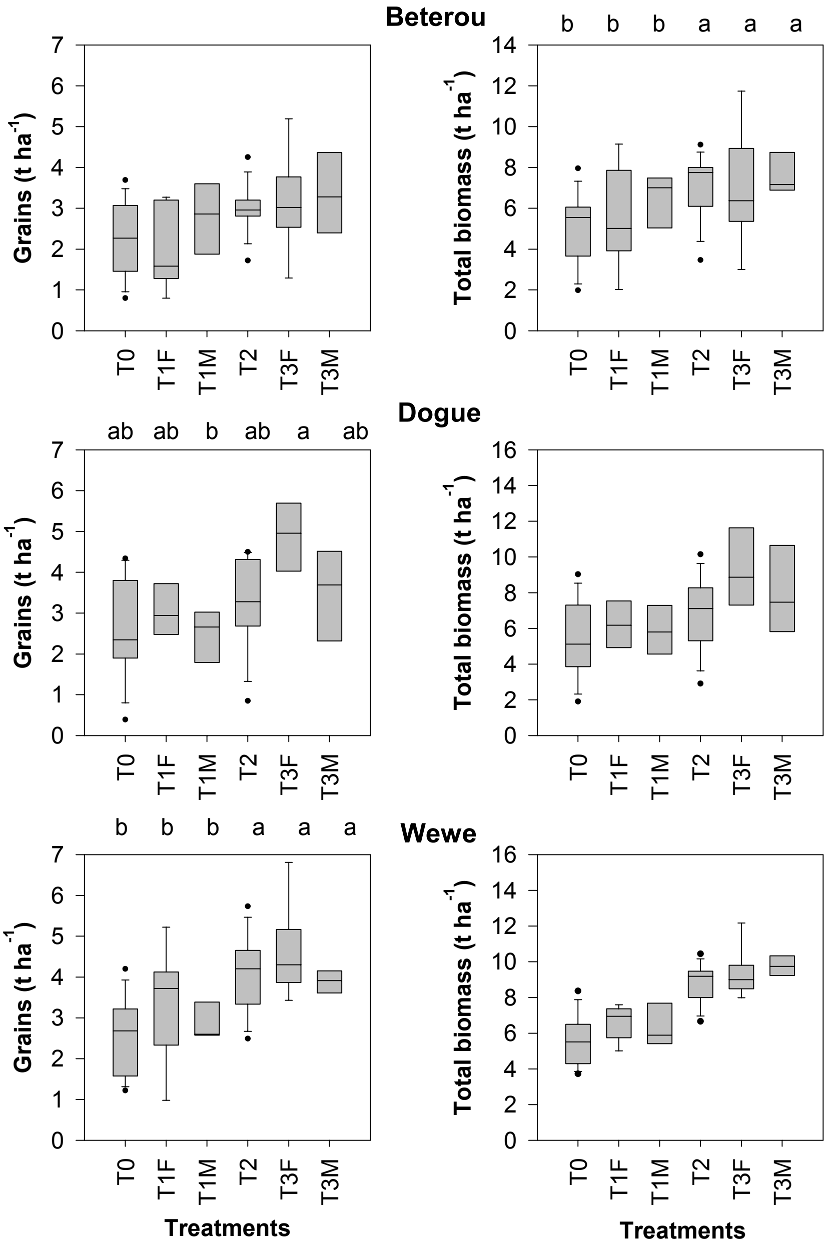
3.1.1. Maize Productivity

3.1.1.1. Grain and total biomass of maize

A considerable variation between treatments and within each treatment was observed for grain, total biomass, RUE at all sites. The difference of the mulching material or for the preparation of manure might be one cause for the variability observed. This variability seemed to be especially relevant in 2002.

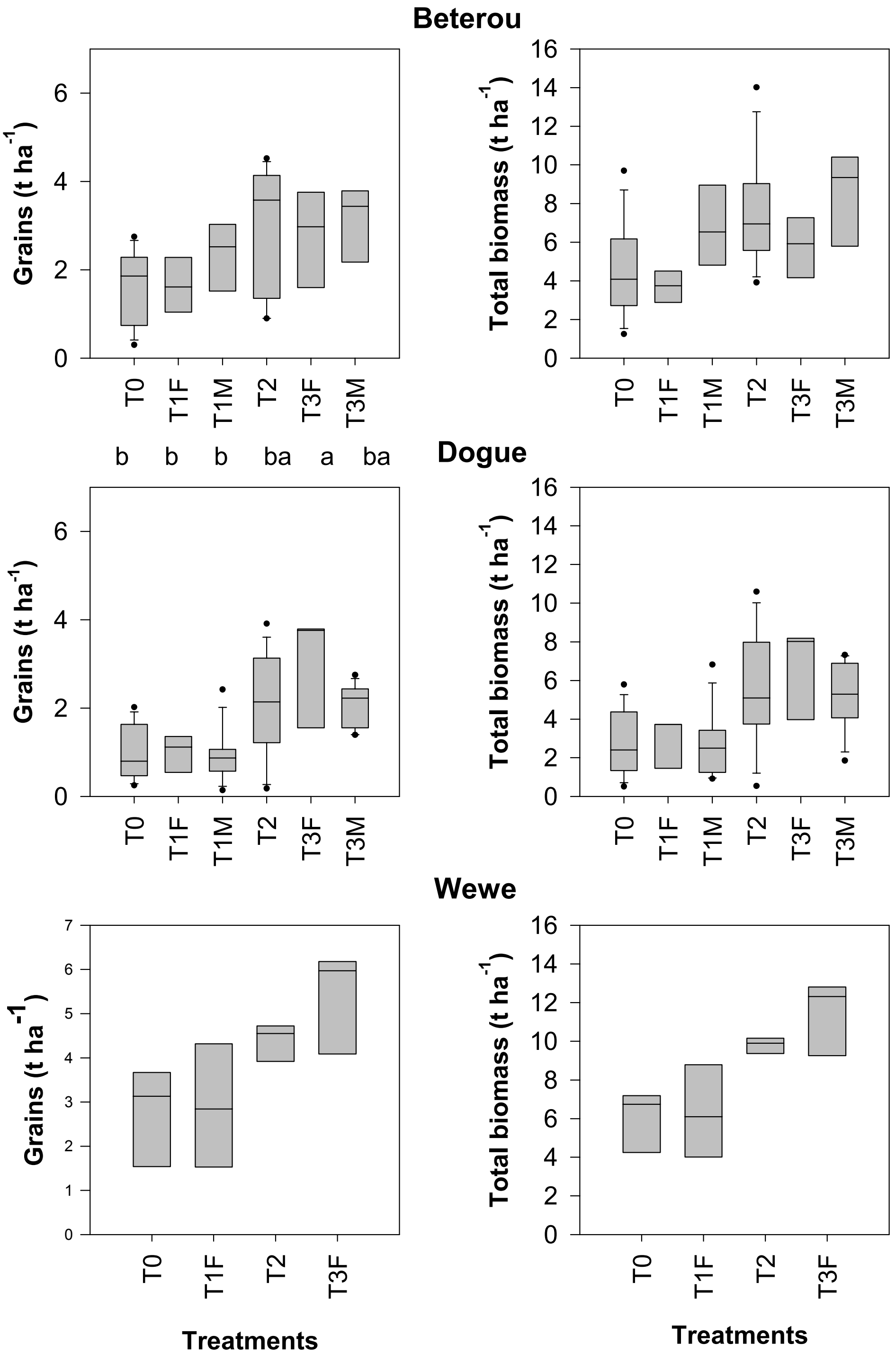
Greatest yields of grain and total biomass (Figures 5 and 6) were obtained with maize produced with the application of crop residues, farmyard manure, mineral fertilizer and the mixing of manure with mineral fertilizer compared to farmer's practice except at Beterou where farmer's practice gave the highest yield. The application of organic matter or mineral fertilizer or both together improved the grain yield and total biomass of maize in Upper Oueme. The effect of mineral fertilizer was more pronounced than application of organic matter.

Yield increases with all treatments compared with farmer's practice at the three sites except in Dogue where the combination of mineral and manure did not improve the grain yield of maize (Table 13). Yield increases of 40 %, 38 %, and 48 % of maize grain were reported by INRAB (2001) respectively at Sokka, Kokey and Birni-Lafia (three INRAB research sites in the north of Benin) after the application of 3t ha^{-1} of manure combined with 150 kg ha^{-1}NPK and 50 kg ha^{-1} urea were applied on maize. The importance of combination of manure and mineral fertilizer was reported by INRAB (2002). This report showed the need to combine mineral fertilizer with organic matter application under the conditions of Northern Benin. Toyi *et al.* (1997) reported that the application of 10 t ha^{-1} of manure every three years increased the maize yield from 29 to 76% depending on the sites when considering the plot without manure application as reference. There was, however, an exception at Dogue where the highest yield was obtained by using residues of cotton, sorghum and yam.



T0: Farmer's practice T1F: 10 t ha^{-1} of farmyard manure of 2001
T1M: 10 t ha^{-1}of crop residues T2: 60 N 40 P_2O_5 (2001)
T3F: 60 N 40 P_2O_5 + 10 t ha^{-1} farmyard manure T3M: 60 N 40 P_2O_5 +10 t ha^{-1}of crop residues
Means with the same letter are not significantly different

Figure 5: Grains and total biomass of maize (*Zea mays*) as affected by organic and inorganic fertilizer application compared to farmer's practice at three locations in Upper Oueme catchment of Benin in 2001



T0: Farmer's practice

T1F: Residual effect of 10 t ha^{-1} of farmyard manure of 2001

T1M: 10 t ha^{-1}of crop residues

T2: 75 N 40 P_2O_5 24 K_2O

T3F: 75 N 40 P_2O_5 24 K_2O + Residual effect of 10 t ha^{-1} farmyard manure of 2001

T3M: or 75 N 40 P_2O_5 24 K_2O + 10 t ha^{-1}of crop residues

Means with the same letter are not significantly different

Figure 6: Grains and total biomass index of maize (*Zea mays*) as affected by organic and inorganic fertilizer application compared to farmer's practice at three locations in Upper Oueme catchment of Benin in 2002

The high increase of yield and total biomass observed could be attributed to the high variability between treatments and within different farmers which applied same treatment. Variability might have been caused by using C-rich and N-poor organic matter which could lead to N fixation by soil microorganisms before n becomes again plant available. This was repeatedly observed on plots where mulch or mulch combined with mineral fertilizer was applied. Growing cowpea just before the installation of the experiment in 2002 in order to supply the N of the soil by the N from the biomass of this crop did not help to overcome the bad growth of the maize crop already observed in 2001. There is a kind of competition between maize and cowpea on some of the plots because of the lack of precipitation just before the sowing date of maize and cowpea was harvested after the sowing of maize. Good maize growth was observed only after cowpea harvest. The type of crop residues applied or used for the manure and differences in farmer’s practice can in part explain the high variability observed in our experiments in the upper Oueme valley.

The partially high increase of productivity observed in 2002 could also be explained by the cumulative effects of organic matter and mineral fertilizer applied during the two years of the experiment.

The combination of crop residues and mineral fertilizer showed higher grain yields and total biomass compared to treatments where only mineral fertilizer or crop residues were respectively applied (Figure 5). However, a contrary trend to this observation was found at Wewe where application of mineral fertilizer alone showed a higher total biomass (Figure 5). This may largely be attributed to the N immobilization after application of C rich and N poor crop residues as mulch. In the second year, mineral fertilizer gave the highest yield in Beterou and Dogue. A similar trend was observed when combining of mineral fertilizer and crop residues was applied (Figure 6).

Organic matter as manure appeared to be more favorable than the application of only crop residues or mineral fertilizer, and may be advantageous to improve yields. This trend was even more pronounced in 2002 when the yield obtained with the residual effect of manure was compared with those of 10 t ha^{-1} of crop residues.

All the treatments improved yield in all sites compared to farmer’s practice.

Table 13: Maize yields, harvest index and RUE for the treatments relative (%) to farmers practice (=T0) at three sites of Upper Oueme Catchment. In bold: highest and lowest values, resp. Ic= confidence interval

Treatments	Grain	Total biomass	RUE	WUE	Harvest index
Beterou					
2001					
T1F	120.8	143.6	138.0	-	**83.9**
	(38.0)	*(41.8)*	*(41.8)*	-	*(8.8)*
T1M	**115.4**	**122.8**	**114.0**	-	96.2
	(27.6)	*(36.1)*	*(34.1)*	-	*(18.1)*
T2	154.8	156.6	156.6	-	98.4
	(86.2)	*(67.9)*	*(64.5)*	-	*(16.8)*
T3F	**194.6**	**184.5**	**177.3**	-	**102.4**
	(83.6)	*(97.5)*	*(87.6)*	-	*(9.3)*
T3M	158.9	162.2	150.8	-	94.8
	(134.2)	*(127.6)*	*(115.1)*	-	*(24.2)*
2002					
T1F	226.3	227.1	**227.1**	-	**111.1**
	(104.4)	*(130.4)*	*(130.4)*	-	*(28.4)*
T1M	239.6	216.6	226.2	-	138.6
	(213.9)	*(185.1)*	*(209.7)*	-	*(100.0)*
T2	**176.4**	**157.8**	**166.4**	-	118.3
	(130.3)	*(115.2)*	*(132.6)*	-	*(89.9)*
T3F	**372.0**	**233.3**	**227.1**	-	**216.4**
	(366.9)	*(219.8)*	*(203.9)*	-	*(272.7)*
T3M	293.1	151.1	148.1	-	190.4
	(358.0)	*(119.4)*	*(111.0)*	-	*(212.3)*
Doguè					
2001					
T1F	146.4	135.3	135.3	-	107.2
	(38.8)	*(26.9)*	*(26.9)*	-	*(15.1)*
T1M	161.0	153.7	153.7	-	102.4
	(89.9)	*(69.0)*	*(69.0)*	-	*(14.8)*
T2	**246.1**	**215.6**	**215.6**	-	**112.8**
	(160.1)	*(96.8)*	*(96.8)*	-	*(35.8)*
T3F	**94.0**	**95.8**	**95.8**	-	**98.2**
	(22.9)	*(17.8)*	*(17.8)*	-	*(13.6)*
T3M	160.5	153.9	153.9	-	103.9
	(73.7)	*(52.5)*	*(52.5)*	-	*(16.4)*
2002					
T1F	310.4	264.5	264.5	264.5	116.9
	(129.7)	*(98.3)*	*(98.3)*	*(98.3)*	*(29.8)*
T1M	**120.6**	158.7	170.5	158.7	**94.4**
	(83.6)	*(158.1)*	*(180.4)*	*(158.1)*	*(34.4)*
T2	345.3	**360.3**	**390.0**	**360.3**	**133.4**
	(274.4)	*(420.8)*	*(480.2)*	*(420.8)*	*(56.7)*
T3F	139.4	**120.8**	**120.8**	**120.8**	112.1
	(65.3)	*(34.4)*	*(34.4)*	*(34.4)*	*(27.9)*
T3M	**401.4**	334.3	334.3	334.3	130.4
	(265.3)	*(184.9)*	*(184.9)*	*(184.9)*	*(89.2)*
Wèwè					
2001					
T1F	**124.1**	**109.3**	**109.3**	-	109.5
	(61.7)	*(17.8)*	*(17.8)*	-	*(42.7)*
T1M	163.9	142.1	142.1	-	**115.6**
	(6.1)	*(24.5)*	*(24.5)*	-	*(19.0)*
T2	181.6	165.3	165.3	-	108.5
	(48.9)	*(25.7)*	*(25.7)*	-	*(19.7)*
T3F	169.9	161.6	161.6	-	106.0
	(56.3)	*(50.8)*	*(50.8)*	-	*(20.1)*
T3M	**224.7**	**216.9**	**216.9**	-	**103.2**
	(65.9)	*(4.5)*	*(4.5)*	-	*(28.9)*
2002					
T1F	**107.6**	**106.6**	**106.6**	-	**101.9**
	(19.3)	*(25.3)*	*(25.3)*	-	*(9.2)*
T2	212.4	185.4	185.4	-	108.7
	(152.6)	*(82.6)*	*(82.6)*	-	*(29.6)*
T3F	**231.7**	**200.6**	**200.6**	-	**113.0**
	(109.4)	*(42.5)*	*(42.5)*	-	*(29.8)*

T0: Farmer's practice T1F: 10 t ha^{-1} of farmyard manure or its residual effect in 2002 T1M: 10 t $ha^{-1}$of crop residues T2: 60 N 40 P_2O_5 in 2001 and 75 N 40 P_2O_5 24 K_2O in 2002 T3F: 60 N 40 P_2O_5 + 10 t ha^{-1} of farmyard manure (2001) and 75 N 40 P_2O_5 24 K_2O + Residual effect of 10 t ha^{-1} of previous farmyard manure (2002) T3M: 60 N 40 P_2O_5 + 10 t $ha^{-1}$of crop residues in 2001 and 75 N 40 P_2O_5 24 K_2O + 10 t $ha^{-1}$of crop residues (2002)

However, significant difference was observed in Dogue during the two years and in Wewe only in 2001. A similar result was reported by Dagbenonbakin *et al.* (2004). Without mineral fertilizer, the application of crop residues seemed better than farmyard manure in Beterou in 2002 whereas the combination of these two types of fertilizers seemed to be less favorable. It will be better in this site to apply either mineral fertilizer or organic matter but in order to increase the productive potential of soil, the combination of both mineral and organic matter would be recommended even if no increase of yield and total biomass was observed in some plots of the experiment (which in part can be explained by other effects such as bird damage, disease etc...). Furthermore, a two year experiment probably may be too short to observe differences due to changes in soil fertility attributable to proper soil organic matter management.

3.1.1.2. Rainfall use efficiency and water use efficiency of maize

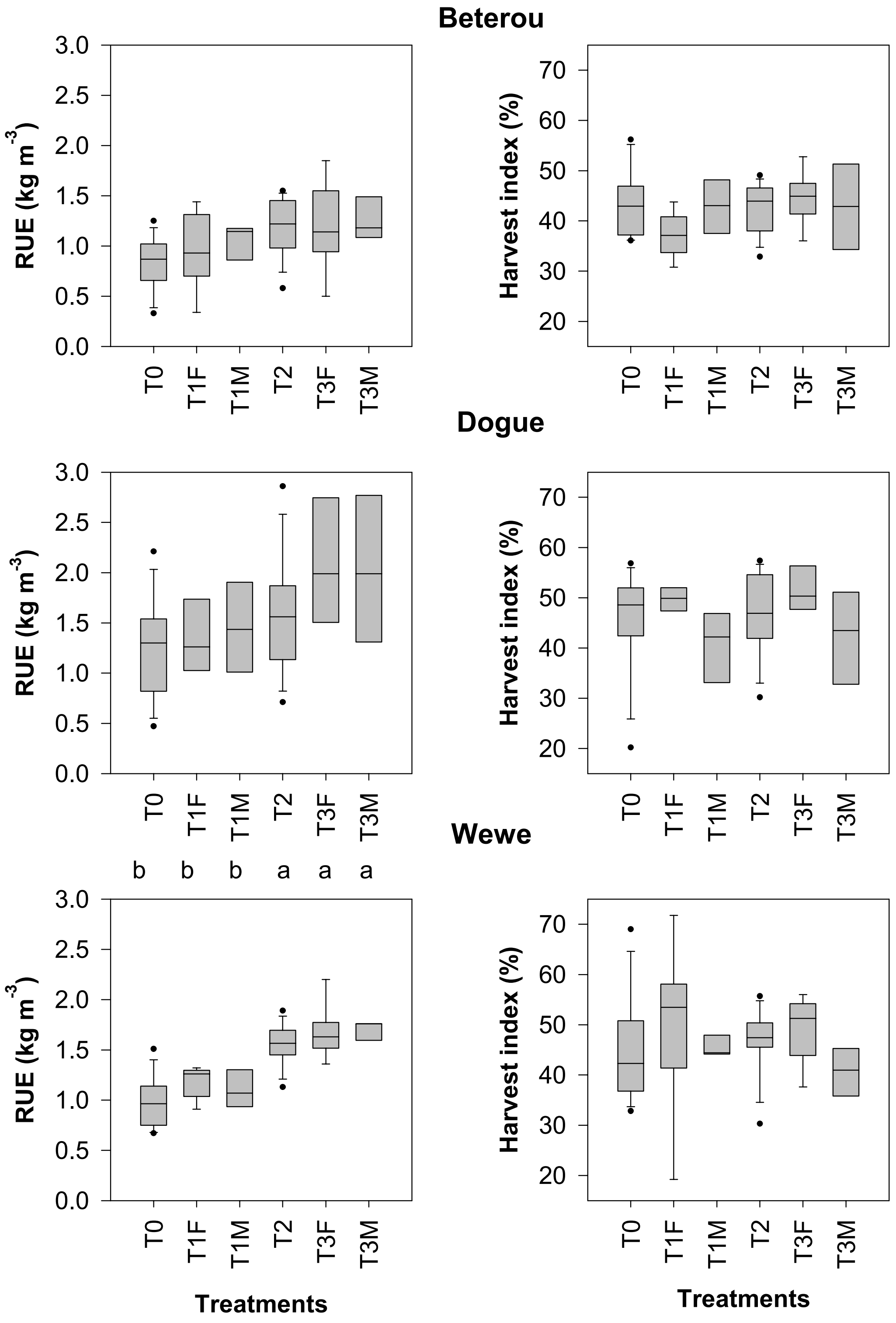
Rainfall water use efficiency (i.e. the yield or biomass produced per unit of rainfall or water available) is largely determined by the productivity on the individual plots. Thus, the trend of the respective data largely coincides with the results obtained for yield and biomass production. Therefore, the respective results will be only shortly addressed.

In general, the highest efficiency was obtained on plots where mineral fertilizer is combined with organic matter application, especially as manure (Figure 7).

In 2002, water use efficiency (WUE) and RUE presented the same trend in Dogue but the WUE was higher than RUE (Figure 8).

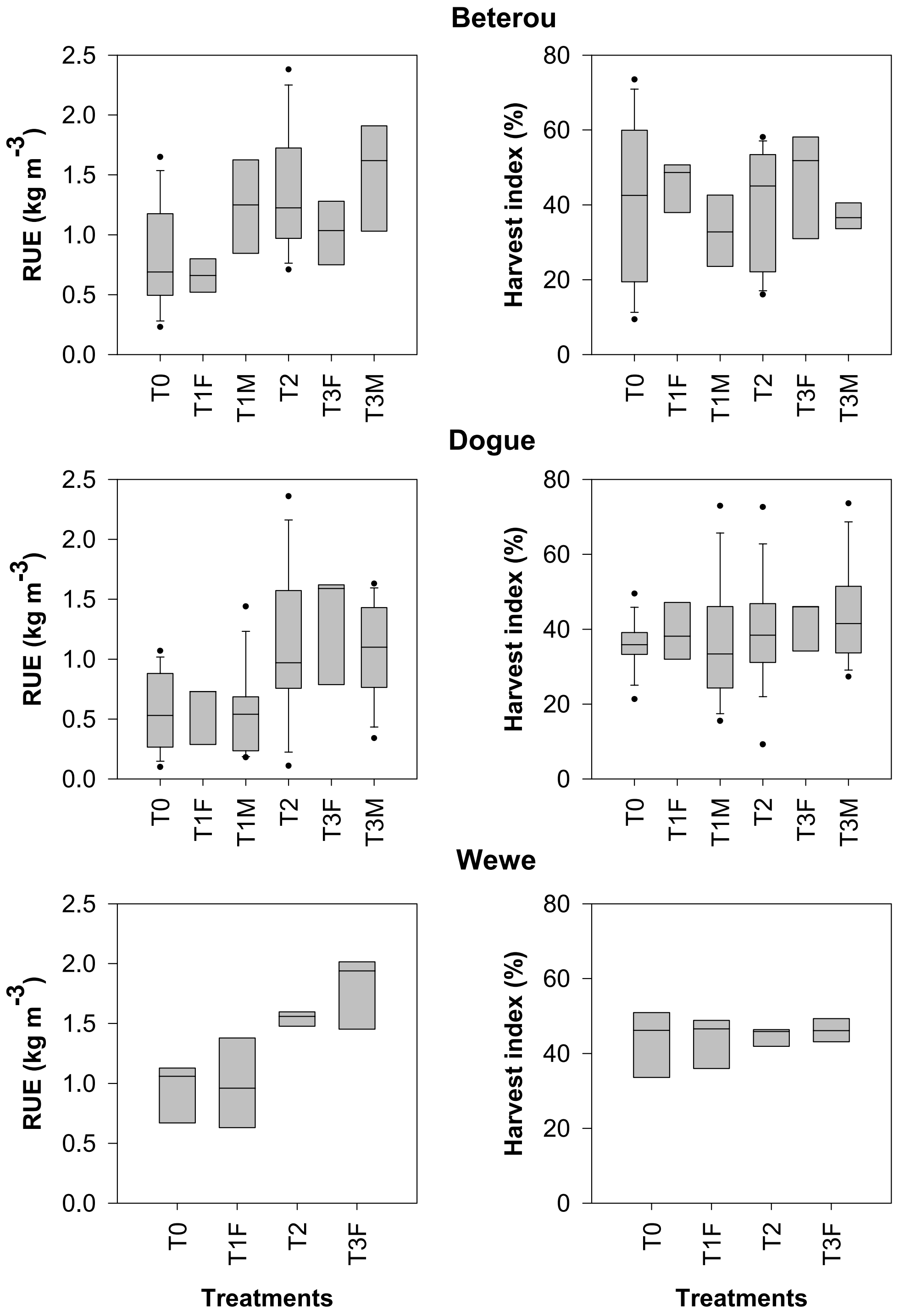
The cumulative effect of crop residues or residual effect of manure, of mineral fertilizer and of the combination of both organic and mineral fertilizers improved the RUE in 2002 compared to T0. The effectiveness of mulching with crop residues to increase cereal yields generally increased with time, but strongly depended on rainfall, soil conditions and the site specific land use history.

This increase of RUE or WUE was not very important with only the residual effect of manure in 2002. However, Ji and Unger (2001) reported that soil water accumulation is affected in decreasing order by water application amount, potential evaporation, straw mulch and soil clay content. This could explain the high value of WUE compared to RUE.



T0: Farmer's practice
T1F: 10 t ha^{-1} of farmyard manure (2001)
T1M: 10 t ha^{-1}of crop residues
T2: 60 N 40 P_2O_5 (2001)
T3F: 60 N 40 P_2O_5 + 10 t ha^{-1} farmyard manure
T3M: 60 N 40 P_2O_5 +10 t ha^{-1}of crop residues
Means with the same letter are not significantly different

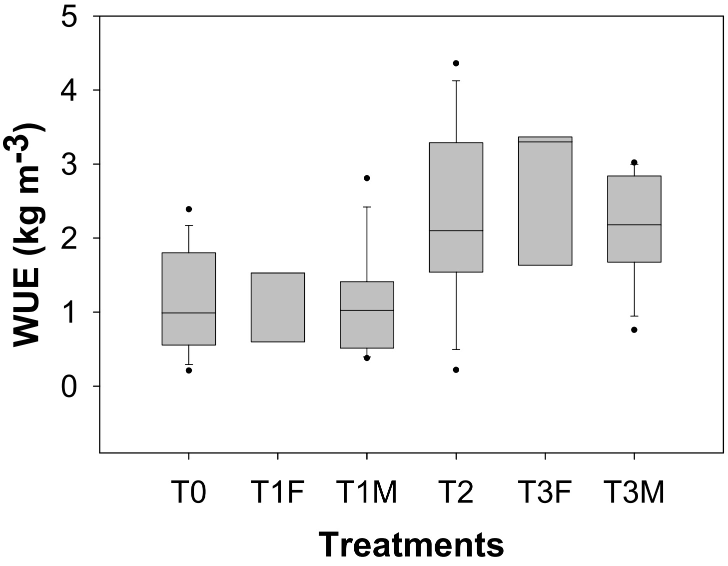
Figure 7: RUE and harvest index of maize (*Zea mays*) as affected by organic and inorganic fertilizer application compared to farmer's practice at three locations in Upper Oueme catchment of Benin in 2001



T0: Farmer's practice
T1F: Residual effect of 10 t ha^{-1} of farmyard manure of 2001
T1M: 10 t ha^{-1}of crop residues
T2: 75 N 40 P_2O_5 24 K_2O
T3F:75 N 40 P_2O_5 24 K_2O + Residual effect of 10 t ha^{-1} farmyard manure of 2001
T3M:75 N 40 P_2O_5 24 K_2O + 10 t ha^{-1}of crop residues

Figure 8: RUE and harvest index of maize (*Zea mays*) as affected by organic and inorganic fertilizer application compared to farmer's practice at three locations in Upper Oueme catchment of Benin in 2002

The production of grain, its total biomass and the production of biomass per water and rainfall units were improved in both years by the combination of crop residues and mineral fertilizer, mineral fertilizer alone or in combination of mineral fertilizer with manure. A clear grouping of yields based on the different treatments was obtained but there was no clear trend with the total biomass, the RUE and the WUE (Figures 7, 8 and 9). It is likely due to the variability inside the treatments of different farmers. This situation could be explained by the soil condition on the farmer's field and further factors mentioned above.



T0: Farmer's practice
T1F: Residual effect of 10 t ha^{-1} of farmyard manure of 2001
T1M: 10 t $ha^{-1}$of crop residues
T2 or 75 N 40 P_2O_5 24 K_2O
T3F: or 75 N 40 P_2O_5 24 K_2O + Residual effect of 10 t ha^{-1} farmyard manure of 2001
T3M: or 75 N 40 P_2O_5 24 K_2O + 10 t $ha^{-1}$of crop residues

Figure 9: Water use efficiency of maize (*Zea mays*) as affected by organic and inorganic fertilizer application compared to farmer's practice at Dogue in Upper Oueme catchment of Benin in 2002

Several agronomic options are likely to have an impact on water use efficiency (WUE). Turner (2004) reported that at least half of the increase in rainfall use efficiency may be attributed to improved agronomic management. Practices like minimum tillage, rotations, fertilizer use, improved weed/disease/insect control and timely planting were identified. This author concludes that most of the agronomic options for improving rainfall use efficiency are those which make more water available for the crop. Therefore, factors which have an influence on the soil water accumulation must also have an impact on WUE. On the other hand, it was reported that organic matter may improve soil moisture content. Thus, Nyakatawa and Reddy (2000) found that poultry litter improves soil moisture holding capacity and Jones *et al.* (1969) showed that leaving crop residues on the surface increases soil moisture content. When discussing factors which have an impact on soil water accumulation, Baumhardt *et al.* (1991) conclude that residue-retaining conservation tillage systems have the added benefit of increasing the amount of precipitation stored as soil water.

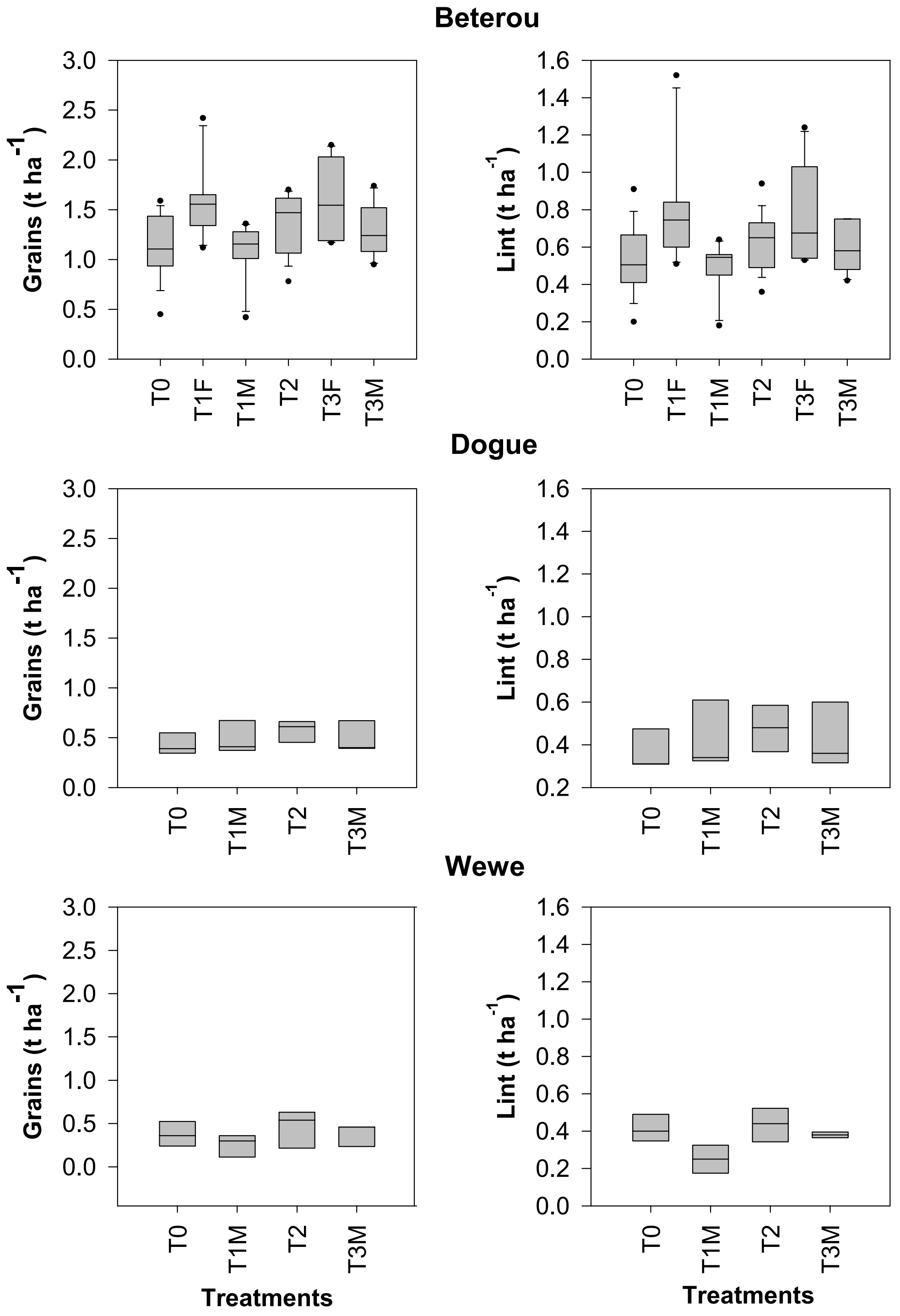
In addition, Smika and Wicks (1968) showed that a fallow period is one approach for increasing water storage efficiency. In this study, there are three out of the four plots used for the mulching in Dogue which had 10 to 12 years of fallowing according to farmers. Despite fallowing, low yields and WUE were obtained compared to other treatments without such a period of fallowing. This indicates that soil fertility at these sites has decreased to an extent where nutrient levels and possibly soil structure have deteriorated and nutrient and water uptake do not meet any more plant requirements.

3.1.2. Cotton Productivity

3.1.2.1. Cotton seed, lint and yield

There is a considerable variation on grain and lint yield of cotton within and between each treatment due to the heterogeneity of the plots. Besides intrinsic variabilities due to edaphic differences, the type of crop residues applied (see Table 5) or used to prepare the manure before its application could be one further factor contributing to the high variability. High variability was observed in Beterou due to farmer’s practice as far as soil fertility management is concerned. Lower cotton grains and lint were observed in Wewe and Dogue. Cotton is less produced in these villages than in Béterou. Thirteen farmers in 2001 and seven in 2002 in Beterou were involved in the production of this crop while there are three and four respectively in Dogue and Wewe. So farmers in Beterou experienced in producing this crop, handled technical aspects better than their colleagues of Wewe and Dogue, which might have additionally influenced the results on the different experimental plots but which were unavoidable under the given circumstances.

There were significant differences proving the positive effects of the applied treatments on the production of total biomass, for seed yield, lint yield, and cotton-yield, but there was no grouping possible between treatments due to the variability observed within plots.



T0: Farmer's practice
T1F: 10 t ha^{-1} of farmyard manure
T1M: 10 t ha^{-1}of crop residues
T2: 51 N 46 P_2O_5 28 K_2O
T3F: 51 N 46 P_2O_5 28 K_2O + 10 t ha^{-1} farmyard manure
T3M: 51 N 46 P_2O_5 28 K_2O + 10 t ha^{-1}of crop residues

Figure 10: Seed and lint yields of cotton as affected by organic and inorganic fertilizer application compared to farmer's practice at three locations in Upper Oueme catchment of Benin in 2001

The expected and possible yield of this variety of cotton seed in this area is about 1580 kg ha^{-1} DM (CRA-CF, 2002), which contrasted with the yield obtained in this study by the farmers of Dogue and Wewe, possibly due to poorer soil conditions and inadequate management by the farmers. In Beterou, the similar trend was observed with some farmers but with others, due to the best soil conditions, highest values compared to those of CRA-CF (2002) were observed.

In 2001, the effect of manure application was pronounced at Beterou (Figure 10). An important increase of yield was observed with manure and its residual effect (T3 F) taking farmer's practice as reference respectively in 2001 and 2002 (Table 14) in Beterou while this was not the case in Dogue and Wèwe. This might be due to the fact that farmers in general already apply mineral fertilizers to cotton at rates which are only slightly lower than the amounts used in our experiments which are based on the recommendations of INRAB. Mineral fertilizer application (T2) showed the best increase of yield followed by crop residues (T1M) and its combination with mineral fertilizer (T3M) in Dogue and in Wewe. Similar results were found by INRAB (2001) where increases were 18 % at Sokka, 13 % at Kokey and 12 % at Birni-Lafia, respectively, compared with the unfertilised control. However, Kouyaté (1997) reported that at Koula, the yield of the cotton seed increased by about 60 % after adding crop residues to the soil. However, a depressive effect of the application of crop residues or its combination with mineral fertilizer on the production of cotton seed was observed in Beterou and Wewe in our experiments (Table 14). Yield increases were observed for two years of mineral fertilizer application on cotton. The residual effect of after manure application in 2001 seemed to be pronounced.

The depressive effects after application of mulch (in form of crop residues) observed in our experiments are likely to be attributed to the largely high C/N-ratios of the crop residues leading to microbial N fixation during carbon-rich organic matter decomposition. Yield increases by the combination of mineral fertilizer and organic matter were low and not consistent in our experiments, likely due to the same cause (residues with a high C/N ratio).

3.1.2.2. Total biomass

At all three sites in 2001, the total biomass was influenced by mineral fertilizer and organic matter application and only in Beterou in 2002 (Figures 11 and 12)
Increases of total biomass compared to farmer’s practice in Wewe were observed with the mineral fertilizer (T2) application, whereas mulching with crop residues applied on cotton in Dogue (Table 14) enhanced total biomass in 2001 (in contrast to seed and lint yields in Dogue). The similar trend was observed in 2002 with the combination of mineral fertilizer and the residual effect or manuring at Beterou taking T0 as reference (Table 14).

An increase in 2001 with the combination of mineral fertilizer and crop residues at Beterou and Dogue were observed, while in Wewe, applying only crop residues reduced the production of total biomass.

Total biomass increased with mineral fertilizer application rates lint yield declined rather than increased could be attributed to other deficiencies showing up where N and P were supplied at least adequately.

Table 14: Cotton grain, lint yields, harvest index and RUE for the treatments relative (%) to farmers practice (=T0) at three sites of Upper Oueme Catchment. In bold: highest and lowest values, resp. Ic= confidence interval

Treatments	Grain	Fiber	Fiber grain	Total biomass	RUE	Harvest index
Beterou						
2001						
T1F	135.1	**160.3**	**146.6**	130.6	130.5	102.6
	(22.6)	*(55.0)*	*(34.8)*	*(8.3)*	*(10.2)*	*(15.3)*
T1M	**95.5**	**97.5**	**96.3**	**100.9**	**100.9**	**104.2**
	(10.5)	*(17.0)*	*(13.2)*	*(28.2)*	*(28.2)*	*(28.5)*
T2	124.9	127.3	125.6	132.2	130.2	96.0
	(14.0)	*(16.2)*	*(14.5)*	*(10.7)*	*(10.9)*	*(12.0)*
T3F	**135.2**	141.6	137.9	129.6	128.2	105.3
	(14.1)	*(10.9)*	*(9.7)*	*(13.7)*	*(16.0)*	*(13.7)*
T3M	127.5	129.6	128.3	**131.9**	**131.9**	**95.8**
	(46.8)	*(46.2)*	*(46.2)*	*(10.4)*	*(10.4)*	*(29.8)*
2002						
T1F	**141.3**	**140.7**	**140.8**	118.0	113.9	100.1
	(14.4)	*(12.3)*	*(12.8)*	*(17.0)*	*(17.0)*	*(3.5)*
T1M	116.9	124.8	120.2	134.9	141.4	96.3
	(43.6)	*(34.2)*	*(38.6)*	*(34.6)*	*(40.2)*	*(6.4)*
T2	112.4	115.7	113.7	**113.8**	**113.8**	98.9
	(20.8)	*(27.7)*	*(23.5)*	*(23.7)*	*(37.4)*	*(5.6)*
T3F	108.7	**104.2**	106.5	**172.5**	167.8	102.2
	(22.6)	*(10.8)*	*(16.6)*	*(78.3)*	*(83.9)*	*(5.3)*
T3M	**92.9**	104.6	**98.1**	166.7	**175.0**	**95.5**
	(42.8)	*(38.4)*	*(40.1)*	*(131.3)*	*(140.2)*	*(5.3)*
Doguè						
T1M	**114.8**	114.2	**114.4**	**107.2**	**107.2**	108.4
	(21.5)	*(17.5)*	*(18.8)*	*(13.3)*	*(13.3)*	*(26.3)*
T2	**132.7**	**125.9**	**129.4**	117.9	117.9	**114.8**
	(49.7)	*(30.0)*	*(40.2)*	*(10.8)*	*(10.8)*	*(50.0)*
T3M	116.1	**113.5**	114.9	**126.1**	**126.1**	**92.9**
	(14.6)	*(18.1)*	*(16.2)*	*(11.5)*	*(11.5)*	*(13.7)*
Wèwè						
T1M	**58.6**	**60.4**	**60.2**	**63.9**	**63.9**	87.7
	(33.1)	*(21.8)*	*(26.1)*	*(28.6)*	*(28.6)*	*(15.9)*
T2	**107.1**	**105.5**	**107.6**	**116.7**	**116.7**	**84.6**
	(52.1)	*(30.5)*	*(39.4)*	*(47.7)*	*(47.7)*	*(17.5)*
T3M	95.2	93.7	95.1	107.9	108.7	**88.6**
	(30.6)	*(22.0)*	*(25.6)*	*(40.0)*	*(39.4)*	*(5.0)*

T0: Farmer's practice

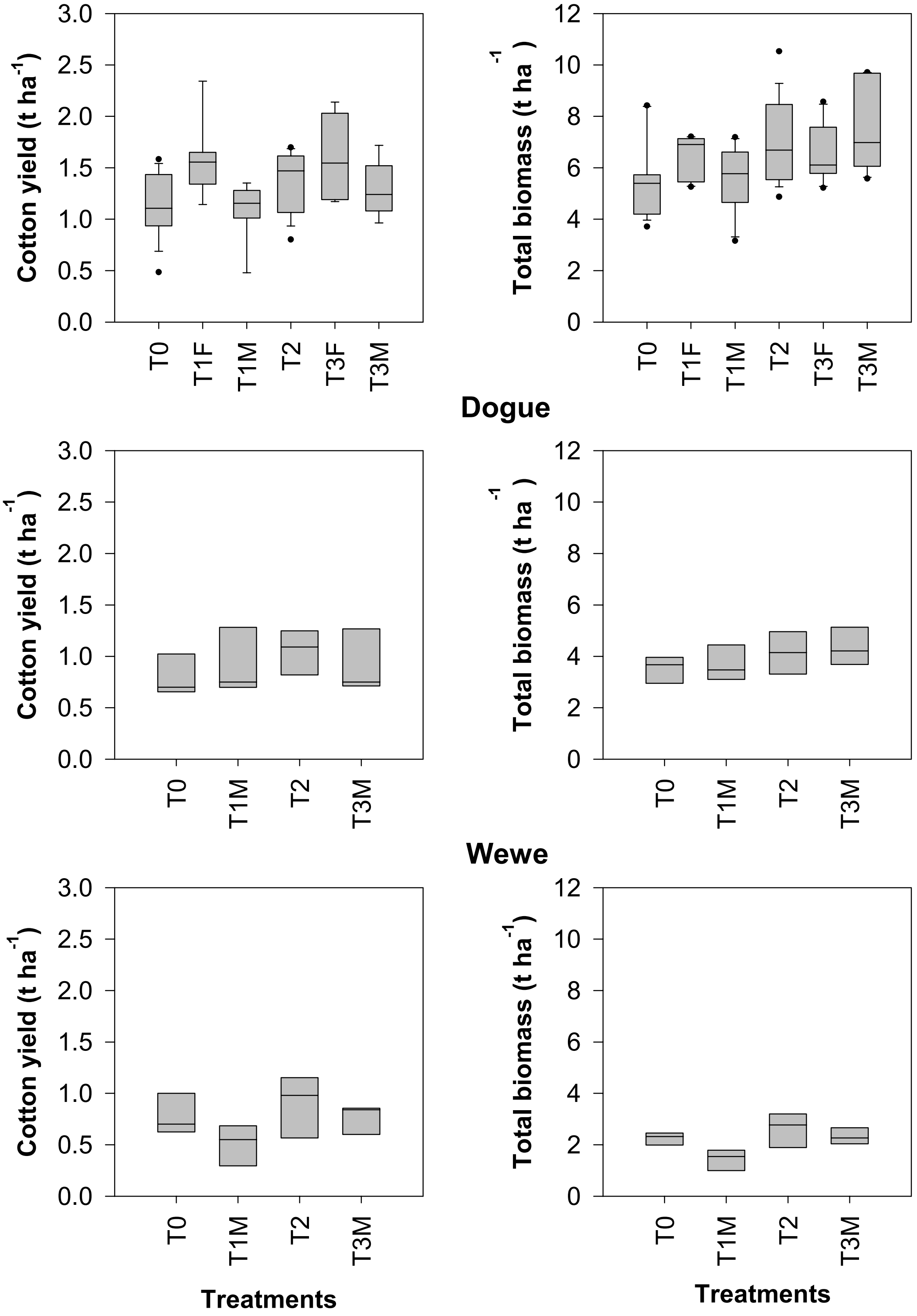
T1F: 10 t ha^{-1} of farmyard manure (2001) or its residual effect (2002)

T1M: 10 t ha^{-1}of crop residues

T2: 51 N 46 P_2O_5 28 K_2O

T3F: 51 N 46 P_2O_5 28 K_2O + 10 t ha^{-1} farmyard manure (2001) or 51 N 46 P_2O_5 28 K_2O + residual effect of manure (2001)

T3M: 51 N 46 P_2O_5 28 K_2O + 10 t ha^{-1} of crop residues (2001 and 2002)

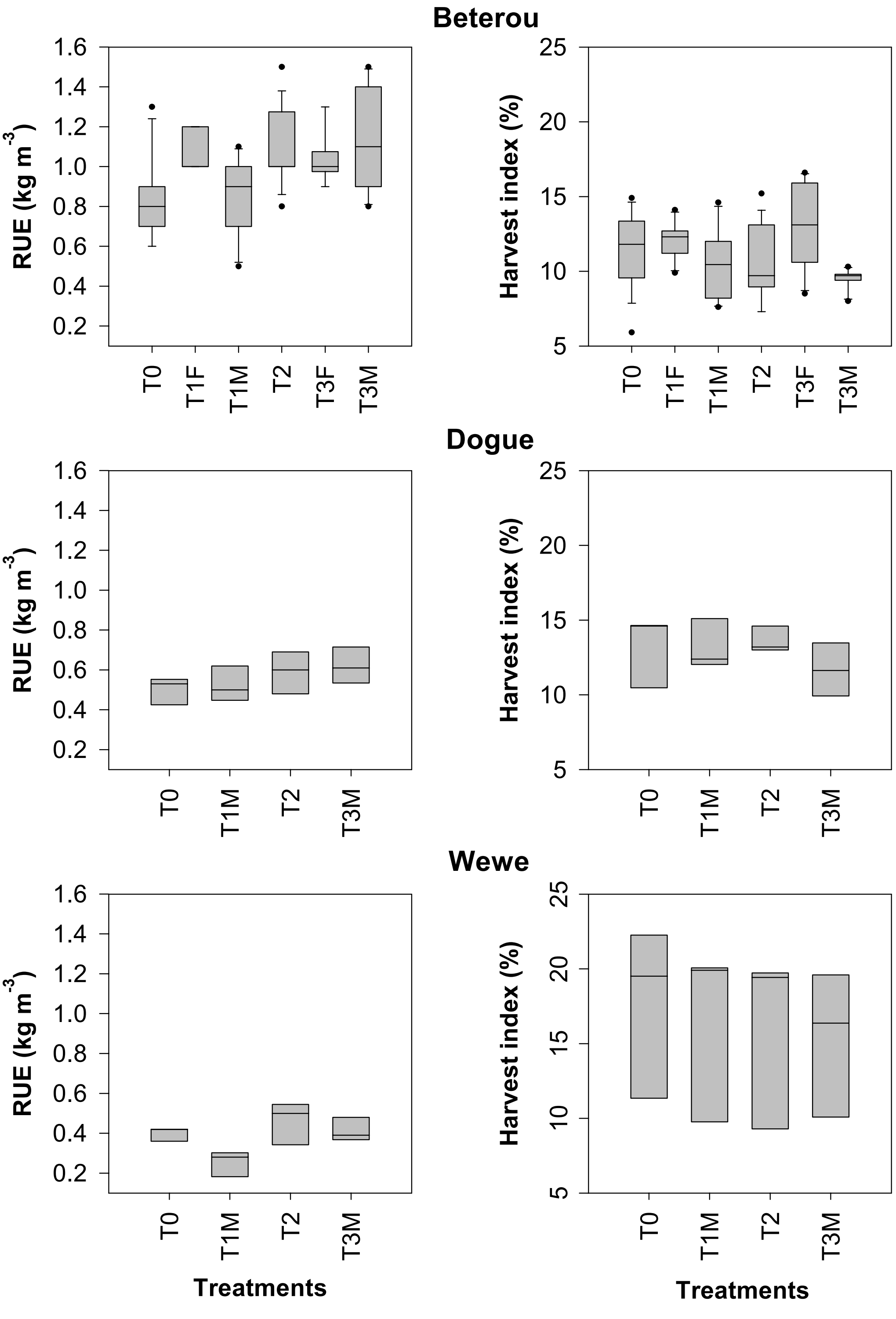


T0: Farmer’s practice T1F: 10 t ha^{-1} of farmyard manure (2001 T1M: 10 t $ha^{-1}$of crop residues

T2: 51 N 46 P_2O_5 28 K_2O T3F: 51 N 46 P_2O_5 28 K_2O + 10 t ha^{-1} farmyard manure (2001)

T3M: 51 N 46 P_2O_5 28 K_2O + 10 t $ha^{-1}$of crop residues (2001)

Figure 11: Cotton yield and total biomass as affected by organic and inorganic fertilizer application compared to farmer’s practice at three locations in Upper Oueme catchment of Benin in 2001

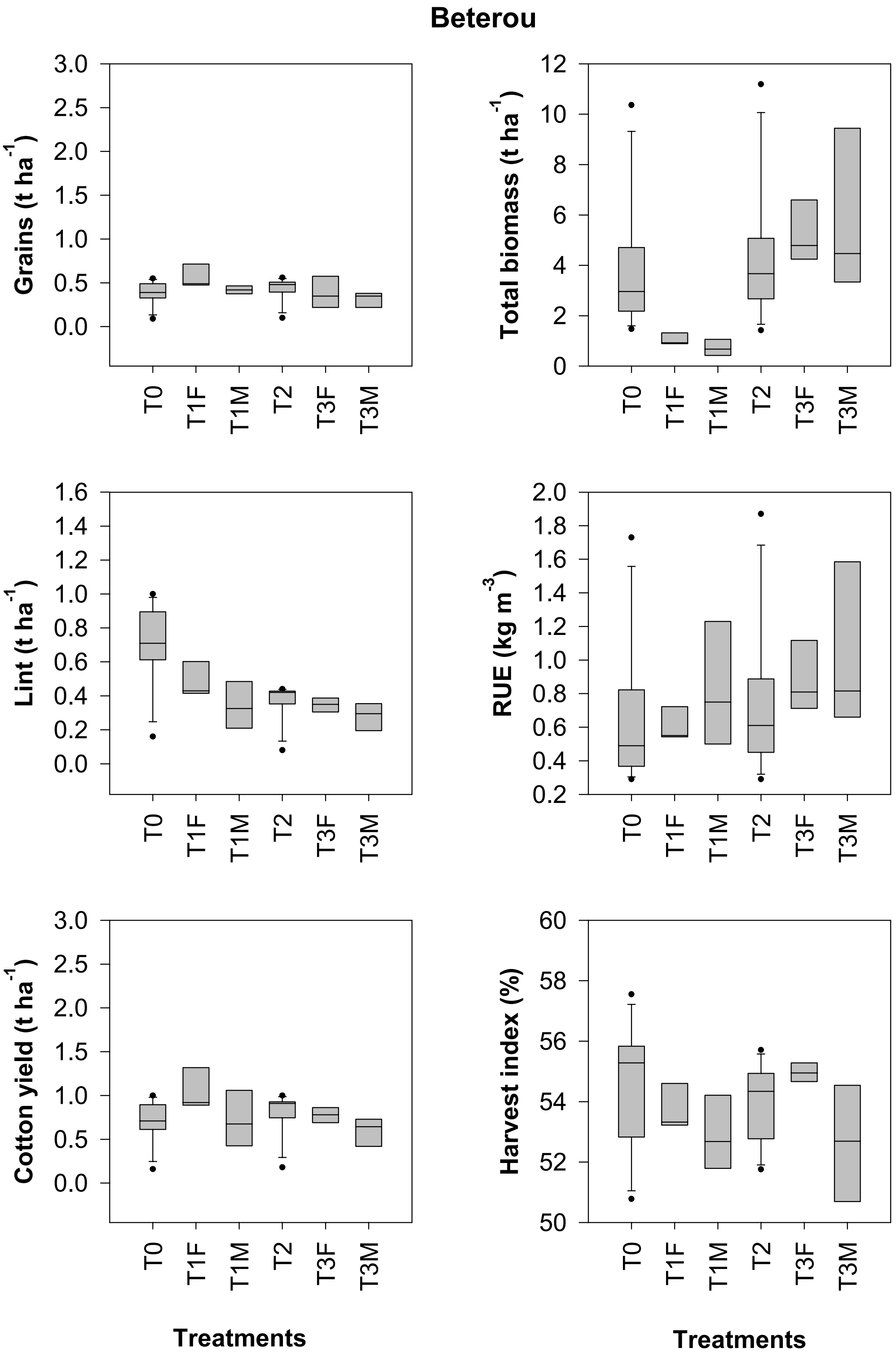


T0: Farmer's practice T1F: 10 t ha^{-1} of farmyard manure (2001 T1M: 10 t ha^{-1}of crop residues

T2: 51 N 46 P_2O_5 28 K_2O T3F: 51 N 46 P_2O_5 28 K_2O + 10 t ha^{-1} farmyard manure (2001)

T3M: 51 N 46 P_2O_5 28 K_2O + 10 t ha^{-1}of crop residues (2001)

Figure 12: Rainfall use efficiency and harvest index of cotton as affected by organic and inorganic fertilizer application compared to farmer's practice at three locations in Upper Oueme catchment of Benin in 2001.



T0: Farmer's practice
T1F: 10 t ha^{-1} of crop residues (2002) or residual effect of manure (2002)
T1M: 10 t ha^{-1}of crop residues + residual effect of manure (2002)
T2: 51 N 46 P_2O_5 28 K_2O
T3F: 51 N 46 P_2O_5 28 K_2O
T3M: 51 N 46 P_2O_5 28 K_2O + 10 t ha^{-1}of crop residues (2001)

Figure 13: Some parameters of cotton as affected by organic and inorganic fertilizer application compared to farmer's practice at Beterou in 2002.

3.1.2.3. Rainfall use efficiency and harvest index

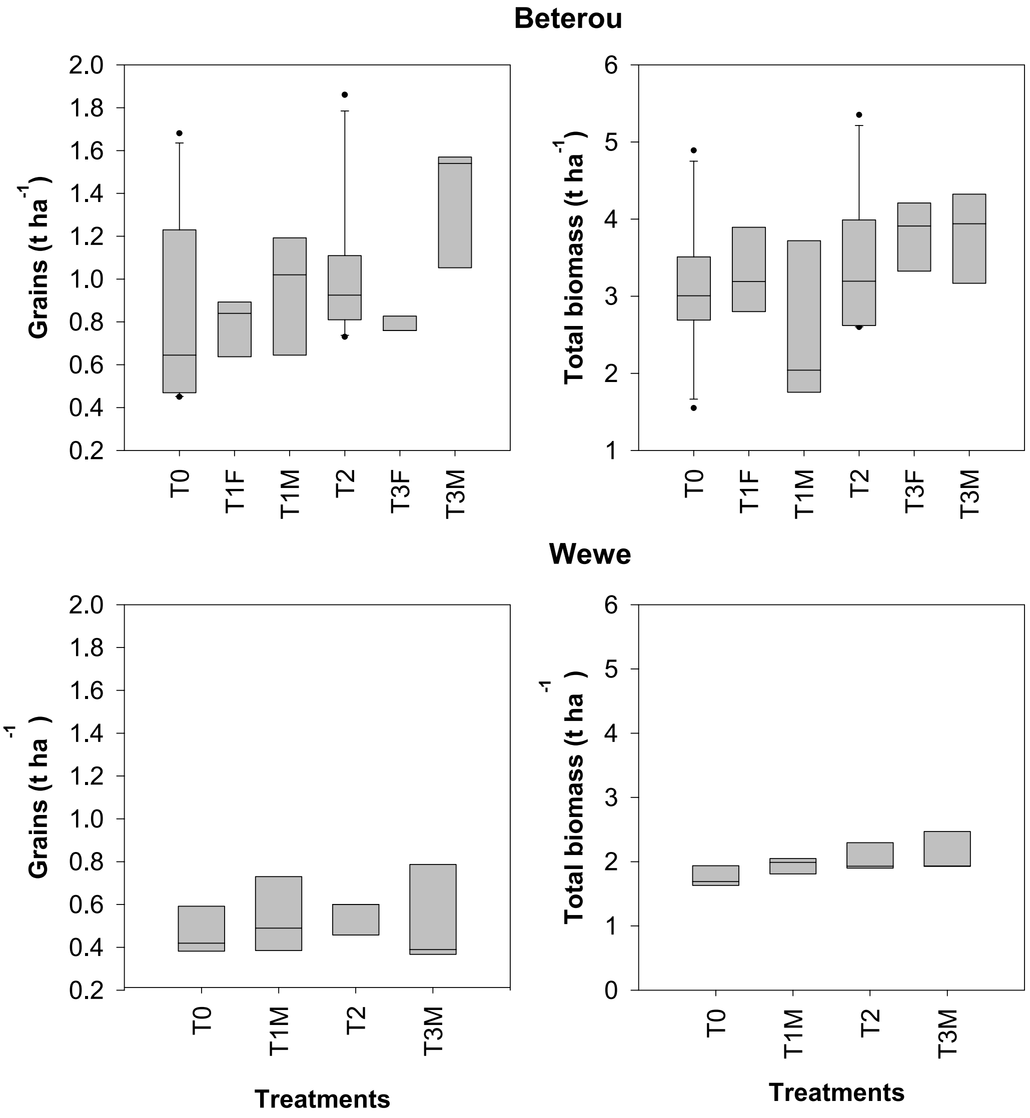
The trend of respective data largely coincides with the results obtained for yield and biomass production. High variability between treatments and within each treatment, due to the high variation with the yields and total biomass was observed on rainfall use efficiency RUE and harvest index in both years in Beterou. High variability of harvest index within each treatment was observed in Wewe. The higher RUE was observed in Beterou while the lower was found in Dogue. The low yield and total biomass observed in Dogue and the low number (3) of farmers (possible experimental bias) could explain this difference.

3.1.3. Groundnut

3.1.3.1. Grain

There was a considerable variability of grain yields between plots and no clear trends could be observed in both 2001 and 2002 for groundnut.

In 2002, based on the grain, in both Beterou and Wewe, there is a considerable variation between treatments whereas in 2001, a relatively low variation based on total biomass, was observed with some treatments in both sites (Figures 14 and 15).

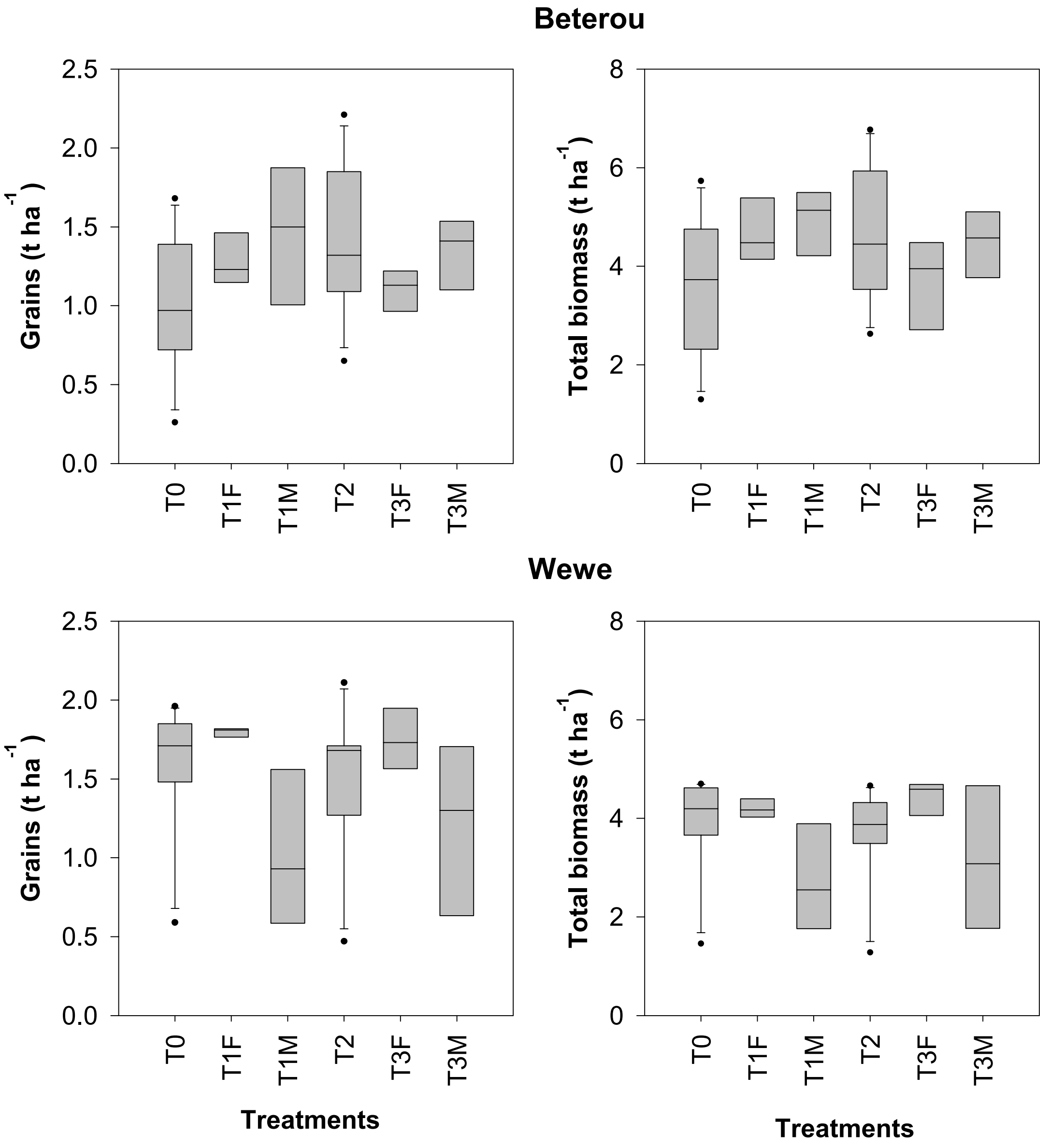


T0: Farmer's practice T1F: 10 t ha^{-1} of farmyard manure (2001) T1M: 10 t ha^{-1}of crop residues

T2: 10 N 40 P_2O_5 (2001) T3F: 10 N 40 P_2O_5 with 10 t ha^{-1} farmyard manure (2001)

T3M: 10 N 40 P_2O_5 with 10 t ha^{-1}of crop residues (2001)

Figure 14: Grains and total biomass of groundnut (Arachis hypogea) as affected by organic and inorganic fertilizer application compared to farmer's practice at three locations in Upper Oueme catchment of Benin in 2001.



T0: Farmer's practice T1F: Residual effect 10 t ha^{-1} of farmyard manure (2002) T1M: 10 t ha^{-1}of crop residues

T2: 10 N 20 P_2O_5 (2002) T3F: 10 N 20 P_2O_5 2002 + residual effect of 10 t ha^{-1} farmyard manure (2001)

T3M: 10 N 20 P_2O_5 +10 t ha^{-1} of crop residues (2002)

Figure 15: Grains and total biomass of groundnut (Arachis hypogea) as affected by organic and inorganic fertilizer application compared to farmer's practice at three locations in Upper Oueme catchment of Benin (on-farm experiment, 2002).

There was a tendency towards increasing grain yields with fertilizer application and manuring in Wewe in 2002 compared with 2001 in spite of no particular trend observed for grain yields in Wewe.

Table 15: Groundnut yields, harvest index and RUE for the treatments relative (%) to farmers practice (=T0). In bold: highest and lowest values, resp. Ic= confidence interval

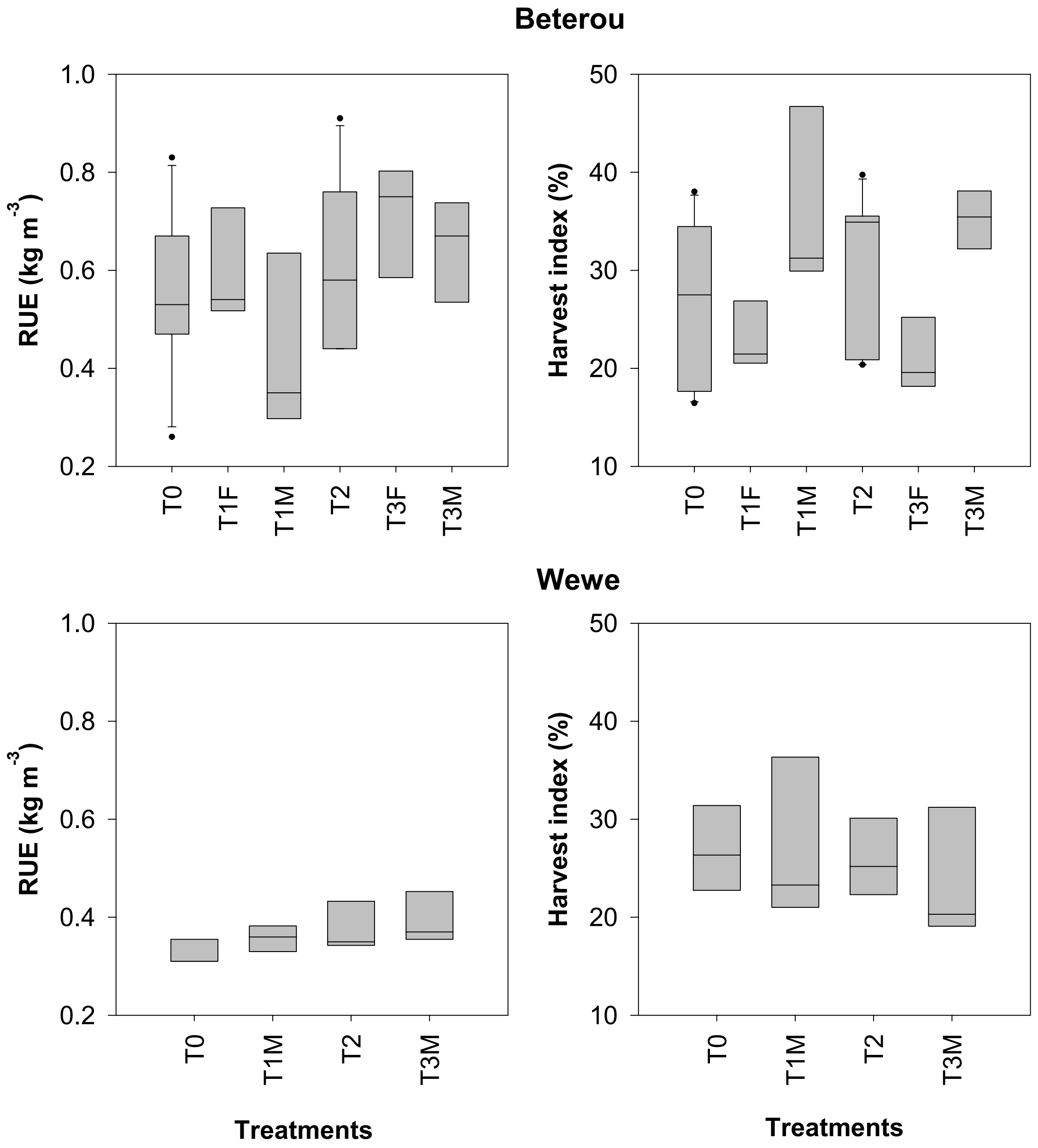
Treatments	Grain	Total biomass	RUE	Harvest index
Beterou				
2001				
T1F	**110.2**	**91.6**	**91.8**	118.2
	(62.8)	*(8.5)*	*(11.0)*	*(65.6)*
T1M	124.6	108.1	108.0	**119.2**
	(52.7)	*(51.4)*	*(51.2)*	*(17.1)*
T2	138.9	117.6	117.6	117.5
	(32.5)	*(24.0)*	*(24.0)*	*(10.7)*
T3F	118.2	107.7	108.2	**109.0**
	(72.0)	*(37.2)*	*(38.5)*	*(64.2)*
T3M	**181.9**	**156.5**	**156.4**	115.3
	(56.5)	*(37.1)*	*(37.0)*	*(20.2)*
2002				
T1F	162.2	143.1	143.2	109.8
T1F	*(51.3)*	*(31.5)*	*(31.4)*	*(11.0)*
T1M	121.8	123.0	118.1	**95.7**
T1M	*(63.8)*	*(53.9)*	*(49.8)*	*(20.7)*
T2	**111.7**	**112.9**	**108.3**	97.4
T2	*(51.8)*	*(50.3)*	*(47.1)*	*(16.4)*
T3F	**264.8**	**227.2**	**238.2**	112.3
T3F	*(195.8)*	*(118.8)*	*(114.8)*	*(28.4)*
T3M	242.6	177.5	185.2	**128.8**
T3M	*(225.4)*	*(124.5)*	*(122.0)*	*(36.1)*
Wèwè				
2001				
T1M	111.9	**110.1**	**110.1**	**101.8**
T1M	*(16.1)*	*(18.3)*	*(18.3)*	*(21.0)*
T2	**115.6**	119.4	119.4	96.8
T2	*(28.9)*	*(32.7)*	*(32.7)*	*(2.1)*
T3M	**110.6**	**121.8**	**121.8**	**89.7**
T3M	*(29.7)*	*(9.9)*	*(9.9)*	*(16.2)*
2002				
T1F	94.9	94.4	94.4	100.9
T1F	*(14.6)*	*(13.6)*	*(13.6)*	*(5.8)*
T1M	**76.5**	**89.5**	**92.0**	**85.0**
T1M	*(18.9)*	*(19.9)*	*(15.1)*	*(9.4)*
T2	81.5	96.7	**99.8**	85.7
T2	*(13.8)*	*(18.6)*	*(15.2)*	*(11.0)*
T3F	**105.6**	95.9	92.6	110.7
T3F	*(12.7)*	*(7.9)*	*(4.6)*	*(6.3)*
T3M	102.4	**99.8**	96.6	**103.0**
T3M	*(7.6)*	*(2.6)*	*(6.9)*	*(10.2)*

T0: Farmer's practice T1F: 10 t ha^{-1} of farmyard manure (2001) or its residual effect (2002)

T1M: 10 t ha^{-1}of crop residues T2: 10 N 40 P_2O_5 (2001) or 10 N 20 P_2O_5 (2002)

T3F: 10 N 40 P_2O_5 with 10 t ha^{-1} farmyard manure (2001) or 10 N 20 P_2O_5 + residual effect of manure (2002)

T3M: 10 N 40 P_2O_5 with 10 t ha^{-1}of crop residues (2001) or 10 N 20 P_2O_5 + 10 t ha-1of crop residues (2002)

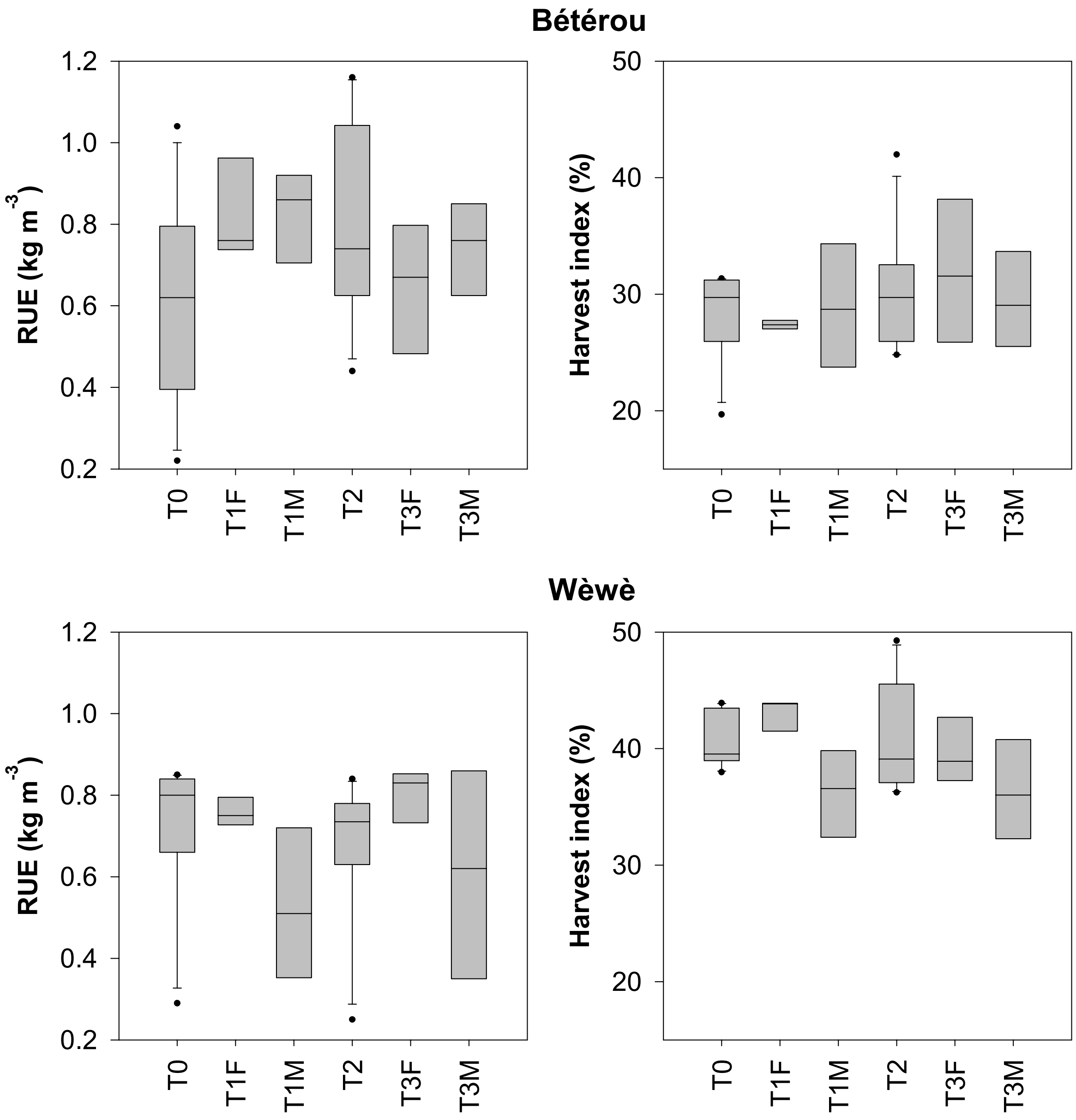


T0: Farmer's practice T1F: 10 t ha^{-1} of farmyard manure (2001) T1M: 10 t ha^{-1}of crop residues

T2: 10 N 40 P_2O_5 (2001) T3F: 10 N 40 P_2O_5 with 10 t ha^{-1} farmyard manure (2001)

T3M: 10 N 40 P_2O_5 with 10 t ha^{-1}of crop residues (2001)

Figure 16: Rainfall use efficiency and harvest index of groundnut (Arachis hypogea) as affected by organic and inorganic fertilizer application compared to farmer's practice at three locations in Upper Oueme catchment of Benin (on-farm experiment, 2001).



T0: Farmer's practice	T1F: Residual effect 10 t ha^{-1} of farmyard manure (2002)
T1M: 10 t ha^{-1}of crop residues	T2: 10 N 20 P_2O_5 (2002)

T3F: 10 N 20 P_2O_5 2002 + residual effect of 10 t ha^{-1} farmyard manure (2001)

T3M: 10 N 20 P_2O_5 +10 t ha^{-1} of crop residues (2002)

Figure 17: Rainfall use efficiency of groundnut (*Arachis hypogea*) as affected by organic and inorganic fertilizer application compared to farmer's practice at three locations in Upper Oueme catchment of Benin (on-farm experiment, 2002).

In the first year, high increase of grain, were observed in Beterou with the application of mineral fertilizer combined with crop residues (T1M) on groundnut, while in the second year, the combination of residual effect of manure (T3F) showed the best increase. Kouyaté (1997) found an increase of 40 % on the yield of groundnut pods due to the incorporation of crop residues into the soil when the author studied the effects of crops rotation, crop residues on soil productivity in Mali cropping-systems compared were: groundnut-cotton1 with 20 t ha^{-1} of farmyard manure; maize-cotton2 (20 t ha^{-1} of farmyard manure)-sorghum; groundnut-cotton1-maize-fallow1-fallow2; groundnut-cotton1-maize-cotton2 with 20 t ha^{-1} of farmyard manure-sorghum; groundnut-cotton1-maize-cotton2-sorghum; groundnut-cotton1-maize-cotton2-sorghum with the restitution of crop residues.

There is a slight increase of yield due to the application of mineral fertilizer in 2001 and the combination of residual effect manure with mineral fertilizer in 2002 at Wewe. However, there is no particular trend concerning the lowest yield. Furthermore, residual effect of manure (T1F), 10 t ha^{-1} of crop residues (T1M) and only mineral fertilizer application did not improve the yield of groundnut at Wewe (Table 16).

An increase due to crop residue application and high variability were observed with farmer's practice and mineral fertilizer application at Wewe. At Beterou the yield obtained after application of crop residues was better than after spreading manure. In general, in both years, groundnut growth was much less stimulated by organic and/or mineral fertilizer application than that of cereals.

3.1.3.2. Total biomass and RUE

The yield obtained with all the treatments were superior to those obtained with farmers' practice except for the application of crop residues at Beterou and Wewe in 2001 (Figures 15 and 16).

The combination of mineral fertilizer and organic matter showed the best increase of total biomass and RUE in both years in Beterou. Only in 2001 at Wewe, treatments did not improve total biomass and RUE in the second year, while a slight increase was observed with only the application of 10 t ha-1 of crop residues. Manure application on groundnut did not affect the total biomass and the RUE of this crop in the first year but they have been improved the residual effect of manure in the second year (Table 15).

In general, the combination of mineral and organic fertilizer or mineral fertilizer applied plus the residual effect of manure positively affected yields in 2002 with exception of Wewe, where no such effect was found.

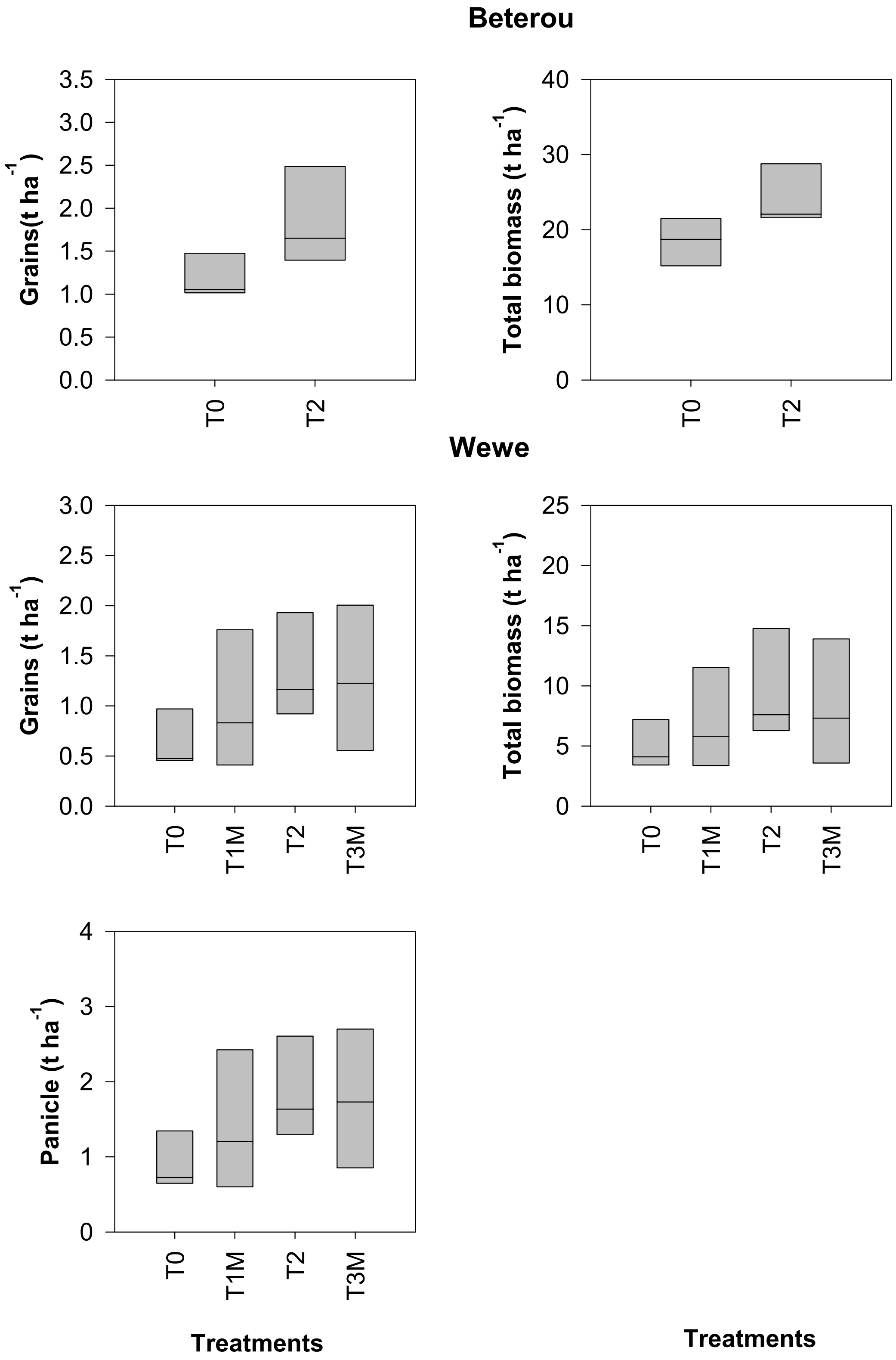
3.1.4. Sorghum

3.1.4.1. Grain, panicle and total biomass

Grain and biomass yields of sorghum did not vary much in Wewe in both years with farmers practice. In 2001, mineral fertilizer and mulch increased grain, panicle and total biomass of sorghum whereas the combination of manure (residual effect) and mineral fertilizer did not improve on panicle and total biomass yields in Dogue and similarly in Wewe in 2002.

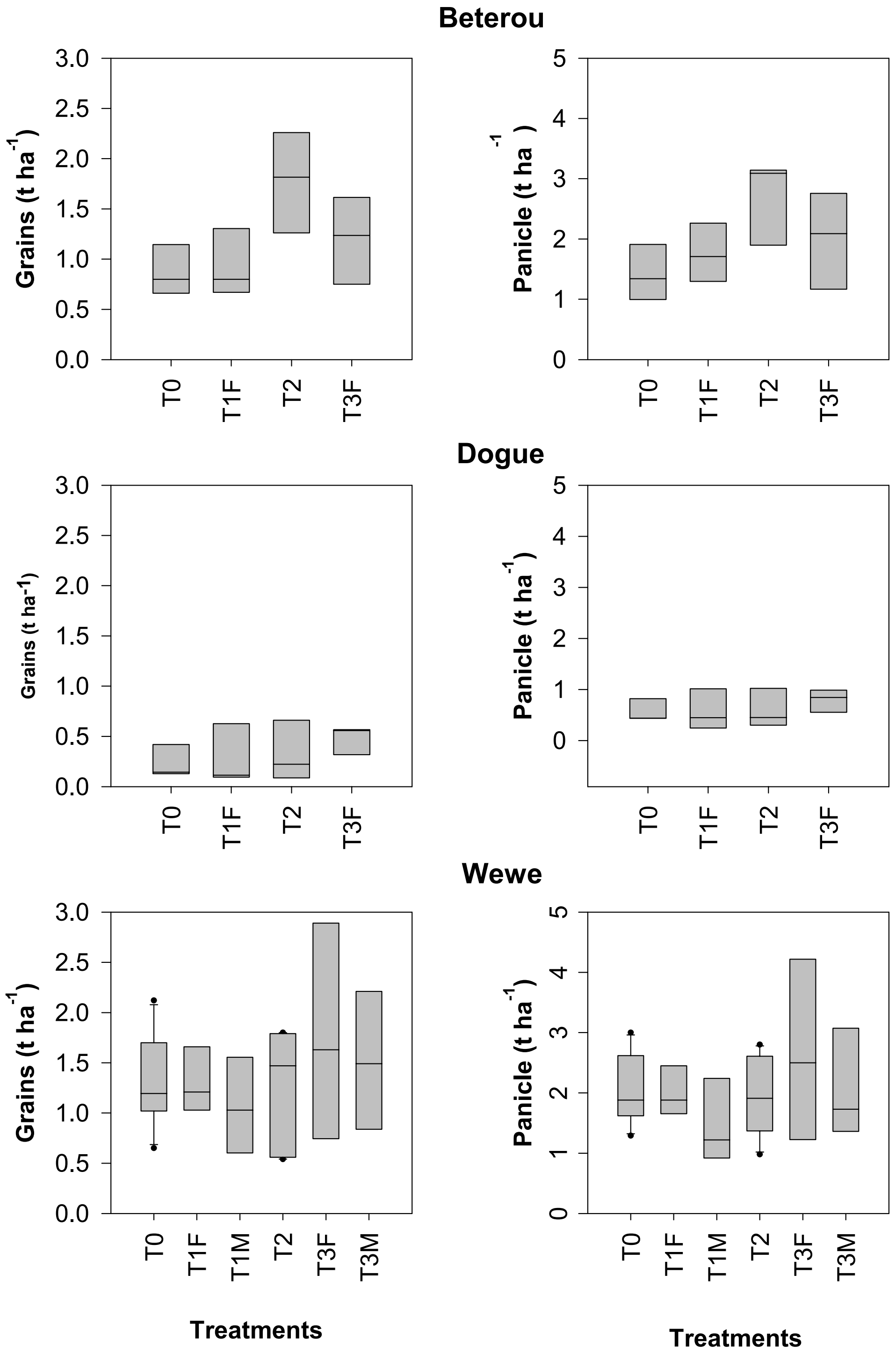
Between the three sites, there was a high variation between the treatments with respect to grain and total biomass yields (Figures 18 and 19). This can be explained by varying soil conditions. Furthermore, plant residues varied for treatments T1 (mulching) and T3 (mineral fertilizer plus mulching) which are due to the different C/N ratios of the crop residues and differences in its decomposition and possible effects on nutrient (N) availability.

In addition, farmers grow sorghum on soils which have relatively low fertility, but further differences between the sites might have played a larger influence. Nonetheless, the greatest production of sorghum grain was observed with the application of manure and mineral fertilizer, followed by mineral fertilizer alone in both years at all the sites in both years. In Wewe, the combination of manure and mineral fertilizer gave the highest production of grain compared to farmers' practice in 2001.



T0: Farmer's practice
T1M: 10 t $ha^{-1}$of crop residues
T2: 23 N 46 P_2O_5 (2001)
T3M: 23 N 46 P_2O_5 + 10 t ha^{-1} of crop residues

Figure 18: Grain, panicle and total biomass yields of sorghum as affected by organic and inorganic fertilizer application compared to farmer's practice at three locations in Upper Oueme catchment of Benin (on-farm experiment, 2001).



T0: Farmer’s practice

T1F: Residual effect of 10 t ha^{-1}of manure (2001)

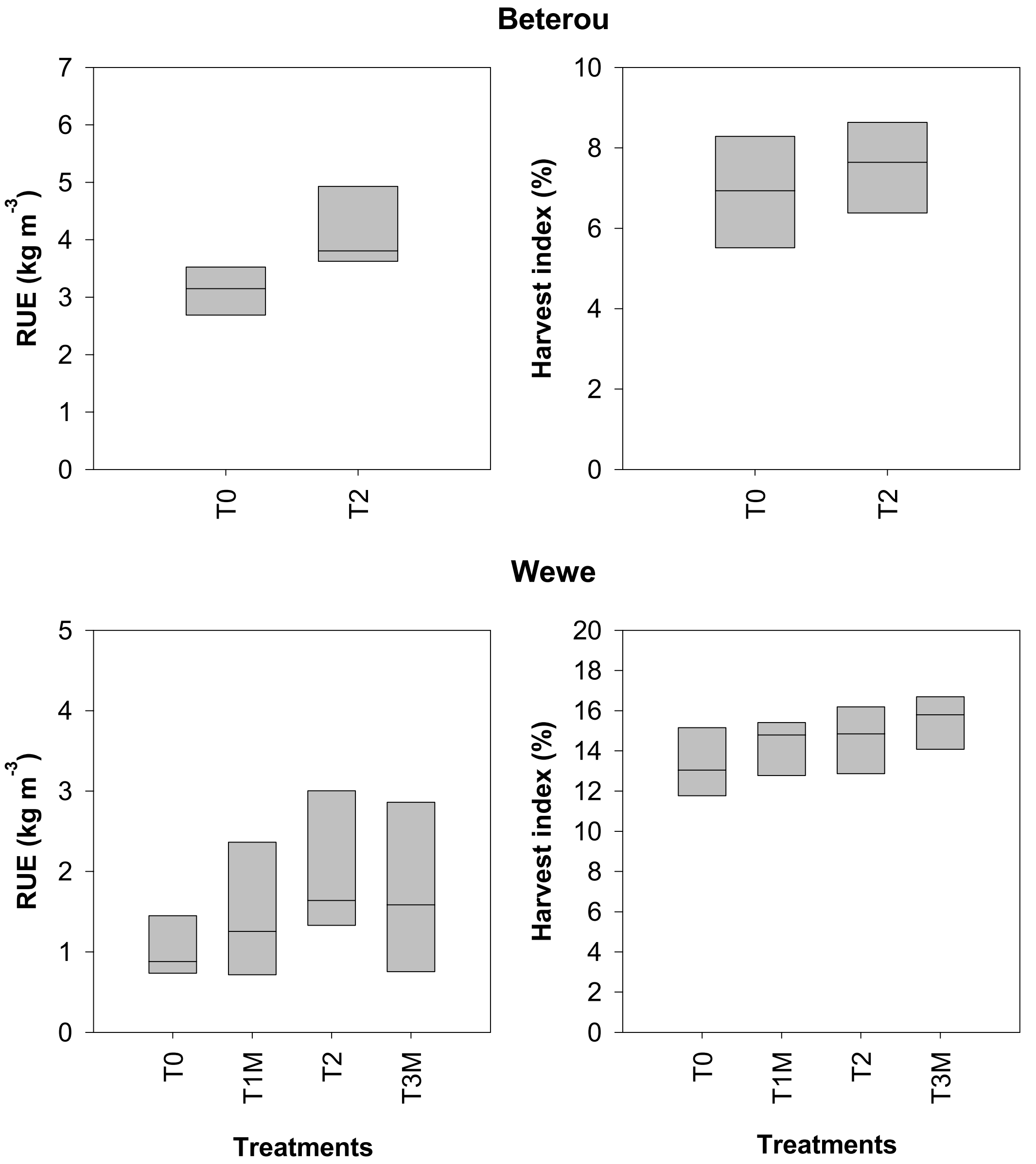
T1M: 10 t ha^{-1}of crop residues

T2: 28 N 46 P_2O_5 28 K_2O (2002)

T3F: Residual effect of 10 t ha^{-1}of manure (2001) +28 N 46 P_2O_5 28 K_2O

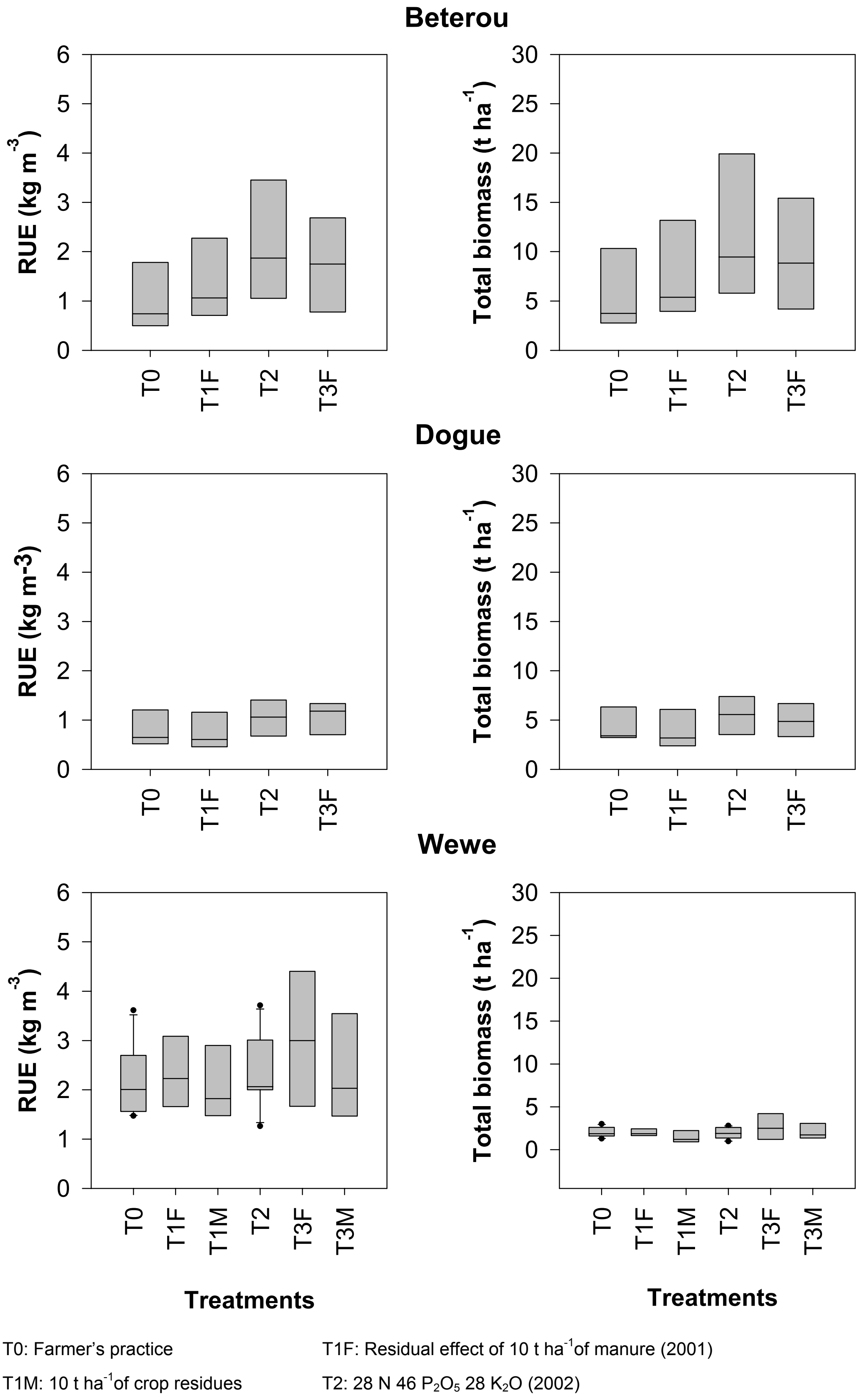
T3M: 10 t ha^{-1}of crop residues +28 N 46 P_2O_5 28 K_2O

Figure 19: Grain and panicle yields of sorghum as affected by organic and inorganic fertilizer application compared to farmer’s practice at three locations in Upper Oueme catchment of Benin (on-farm experiment, 2002).



T0: Farmer's practice	T1M: 10 t ha^{-1}of crop residues
T2: 23 N 46 P_2O_5 (2001)	T3M: 23 N 46 P_2O_5 + 10 t ha^{-1}of crop residues

Figure 20: Rainfall use efficiency and harvest index of sorghum as affected by organic and inorganic fertilizer application compared to farmer's practice at three locations in Upper Oueme catchment of Benin (on-farm experiment, 2001).



T0: Farmer's practice T1F: Residual effect of 10 t ha^{-1} of manure (2001)

T1M: 10 t ha^{-1} of crop residues T2: 28 N 46 P_2O_5 28 K_2O (2002)

T3F: Residual effect of 10 t ha^{-1} of manure (2001) +28 N 46 P_2O_5 28 K_2O

T3M: 10 t ha^{-1} of crop residues +28 N 46 P_2O_5 28 K_2O

Figure 21: Rainfall use efficiency (RUE) and total biomass of sorghum as affected by organic and inorganic fertilizer application compared to farmer's practice at three locations in Upper Oueme catchment of Benin (on-farm experiment, 2002).

Table 16: Sorghum yields, harvest index and RUE for the treatments relative (%) to farmers practice (=T0). In bold: highest and lowest values, resp. Ic= confidence interval

Treatments	Grain	Panicle	Total biomass	RUE	Harvest index
Beterou					
2001					
T1F	**127.4** *(28.5)*	- -	**121.9** *(36.9)*	**121.9** *(36.9)*	**108.0** *(13.4)*
T1M	146.2 *(12.9)*	- -	125.5 *(38.8)*	125.5 *(38.8)*	117.6 *(31.0)*
T2	152.2 *(29.5)*	- -	139.0 *(27.1)*	139.0 *(27.1)*	110.2 *(20.5)*
T3F	**174.3** *(15.4)*	- -	**156.5** *(48.4)*	**156.5** *(48.4)*	113.3 *(24.6)*
T3M	167.3 *(45.2)*	- -	132.2 *(41.4)*	132.2 *(41.4)*	**124.3** *(11.6)*
2002					
T1F	**119.7** *(36.3)*	**125.5** *(9.0)*	**137.3** *(11.1)*	**137.3** *(11.1)*	88.8 *(28.4)*
T2	**203.5** *(56.7)*	**185.0** *(52.6)*	**208.9** *(43.0)*	**208.9** *(43.0)*	**95.3** *(11.3)*
T3F	137.9 *(53.5)*	140.3 *(81.5)*	161.6 *(75.6)*	161.6 *(75.6)*	**87.0** *(15.8)*
Doguè					
T1 F	**102.7** *(54.3)*	**89.9** *(49.5)*	**85.7** *(18.3)*	**91.9** *(6.3)*	103.3 *(53.4)*
T2	115.7 *(80.9)*	96.3 *(40.1)*	**120.8** *(43.0)*	129.1 *(33.6)*	**96.2** *(76.1)*
T3 F	**242.9** *(205.6)*	**135.4** *(55.4)*	110.3 *(32.1)*	**131.7** *(49.9)*	**149.0** *(49.1)*
Wèwè					
2001					
T1 M	**167.2** *(113.4)*	**169.9** *(117.8)*	**145.1** *(64.5)*	**138.9** *(54.3)*	**106.5** *(25.0)*
T2	221.4 *(90.9)*	223.1 *(82.3)*	**196.6** *(27.7)*	**194.2** *(14.8)*	109.0 *(21.7)*
T3 M	**223.0** *(184.4)*	**223.7** *(176.0)*	175.9 *(99.1)*	167.4 *(83.4)*	**113.2** *(23.5)*
2002					
T1F	97.4 *(29.8)*	94.2 *(21.0)*	106.8 *(15.9)*	106.8 *(15.9)*	93.4 *(24.9)*
T1M	**74.5** *(33.7)*	**69.9** *(33.3)*	**102.8** *(56.9)*	**99.6** *(51.6)*	**74.5** *(9.6)*
T2	105.1 *(50.3)*	98.7 *(41.8)*	118.3 *(78.3)*	113.9 *(72.2)*	96.2 *(23.7)*
T3F	143.9 *(134.8)*	121.6 *(83.4)*	127.7 *(103.9)*	128.5 *(101.0)*	**108.4** *(11.3)*
T3M	**211.2** *(295.7)*	**167.8** *(199.9)*	**163.2** *(167.6)*	**164.1** *(164.1)*	104.4 *(56.1)*

T0: Farmer's practice

T1F: 10 t ha^{-1} of farmyard manure (2001) or its residual effect (2002)

T1M: 10 t $ha^{-1}$of crop residues

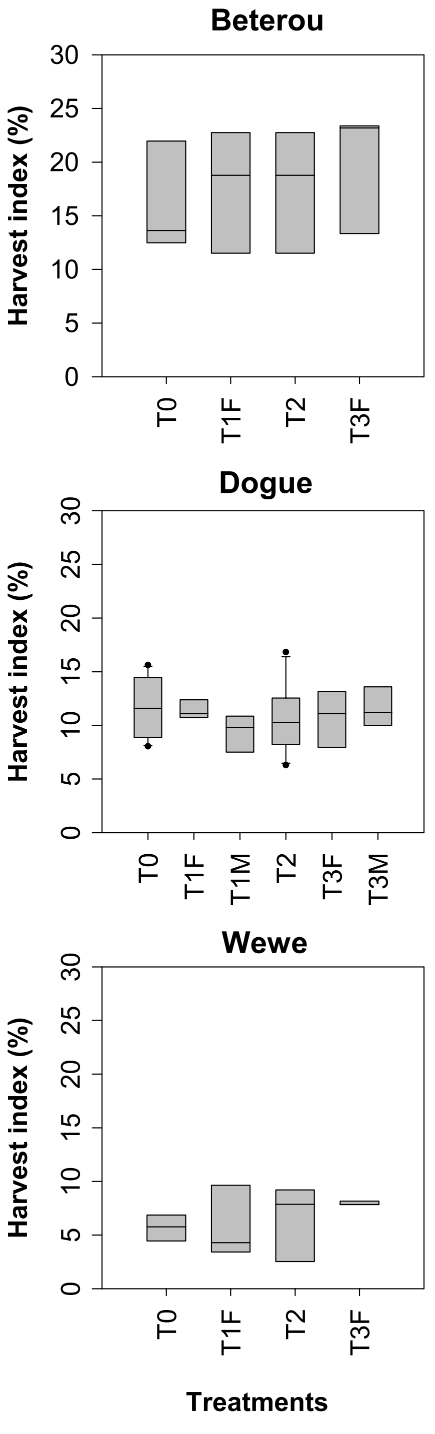
T2: 23 N 46 P_2O_5 (2001) or 28 N 46 P_2O_5 28 K_2O (2002)

T3F: 23 N 46 P_2O_5 + 10 t ha^{-1} farmyard manure (2001) or 28 N 46 P_2O_5 28 K_2O + residual effect of 10 t ha^{-1} manure (2002)

T3M: 23 N 46 P_2O_5 or 28 N 46 P_2O_5 28 K_2O +10 t $ha^{-1}$of crop residues (2001 and 2002)

Organic or mineral or both fertilizers did not affect the grain yield of sorghum in Dogue and Wewe in 2002 (Table 16), possibly due to the poor quality (low N and high C content) of the applied crop residues and used for preparing manure. Possibly more N should have been applied to overcome the temporary microbial N fixation. A Similar observation was made by Schwartz *et al.* (2002) who found that stubble-mulch tillage reduced sorghum grain yield response to organic fertilizer.

Although effects of inorganic or organic fertilizer applications were not significant due to the high variability between the individual plots, mineral fertilizer alone or in combination with farmyard manure tended to increase yield and total biomass of sorghum at three different locations of the Upper Oueme catchment (Table 16). Crop residues had no beneficial or rather a contrary effect. These results were similar to those of Kouyaté (1997) who did not find any significant yield effects after incorporation of crop residues into the soil for maize and sorghum. As pointed out above, the high C/N-ration of the applied residues may be responsible for the lack of response. The generally positive effect of fertilizer application (Table 16) is in line with reports showing that nutrient and water use efficiency in Sahelian agroecosystems may be improved through appropriate soil management practices, such as crop residue mulch, and prudential use of N and P fertilizers (Bationo *et al.*, 1988; Onken and Wendt, 1989; Geiger *et al.*, 1992; Barros and Hanks, 1993; Hafner *et al.*, 1993a).



T0: Farmer's practice T1F: Residual effect of 10 t ha^{-1}of manure (2001) T1M: 10 t ha^{-1}of crop residues

T2: 28 N 46 P_2O_5 28 K_2O (2002) T3F: Residual effect of 10 t ha^{-1}of manure (2001) +28 N 46 P_2O_5 28 K_2O

T3M: 10 t ha^{-1}of crop residues +28 N 46 P_2O_5 28 K_2O

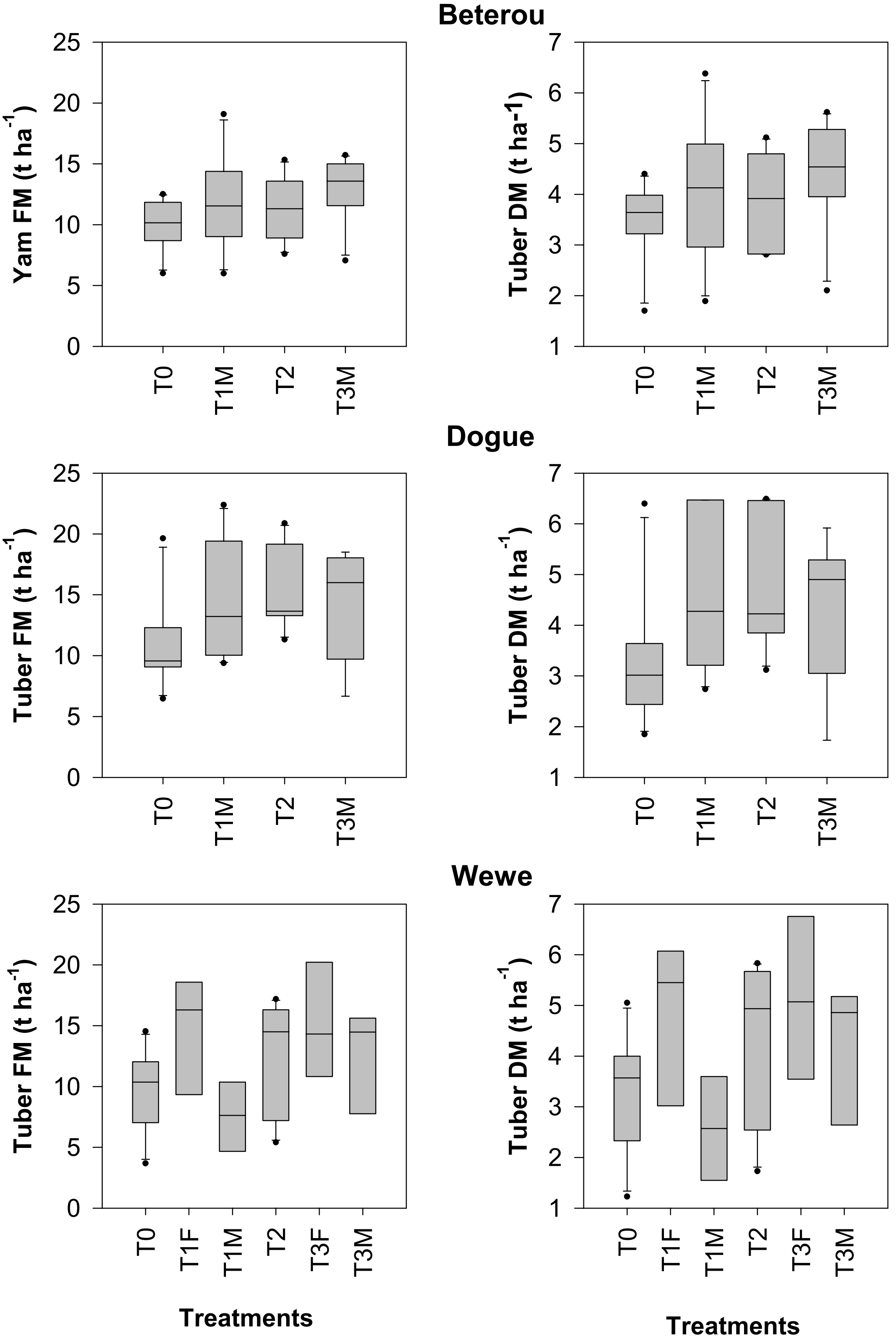
Figure 22: Harvest index of sorghum as affected by organic and inorganic fertilizer application compared to farmer's practice at three locations in Upper Oueme catchment of Benin (on-farm experiment, 2002).

3.1.5. Yam

3.1.5.1. Fresh, dry matter of tuber and total biomass of yam crop

There is an important variation between sites and within treatments for tuber yields (Figures 23 and 24) and total biomass (Figures 25 and 26) in both years. This variability could be attributed to farmers' practice or and/or N immobilization and still imbalanced and eventually too low nutrient application with organic and inorganic fertilizer.

The highest yield increase for tuber and total biomass was observed with the combination of organic matter and mineral fertilizer (Table 17). The application of manure only and its residual effect in Wewe showed in both years a remarkable effect. Similar results were reported by Kodjo *et al.* (2004) when they determined the agronomic performance of farming systems in the central Benin. The higher increase of yield was observed with the application of 10 t ha^{-1} of manure. Ogodja *et al.* (2004) pointed out that 3 t ha^{-1} of compost mixed with 50 % of bovine feces and its residual effect showed the highest yields compared to farmer's practice. Results obtained for yield (DM) were very close to those reported by Kodjo *et al.* (2004) and Ogodja *et al.* (2004) who found respectively 5 t ha^{-1} and 4.6 t ha^{-1}(DM) for the same cultivar of yams. It was observed that yams responded well to organic manure treatment in the presence of K (Djokoto and Stephens, 1961). In 2002, the same trend was observed with the residual effect of manure or two years of application of crop residues except in Beterou where a relatively low yield was obtained compared to T0.

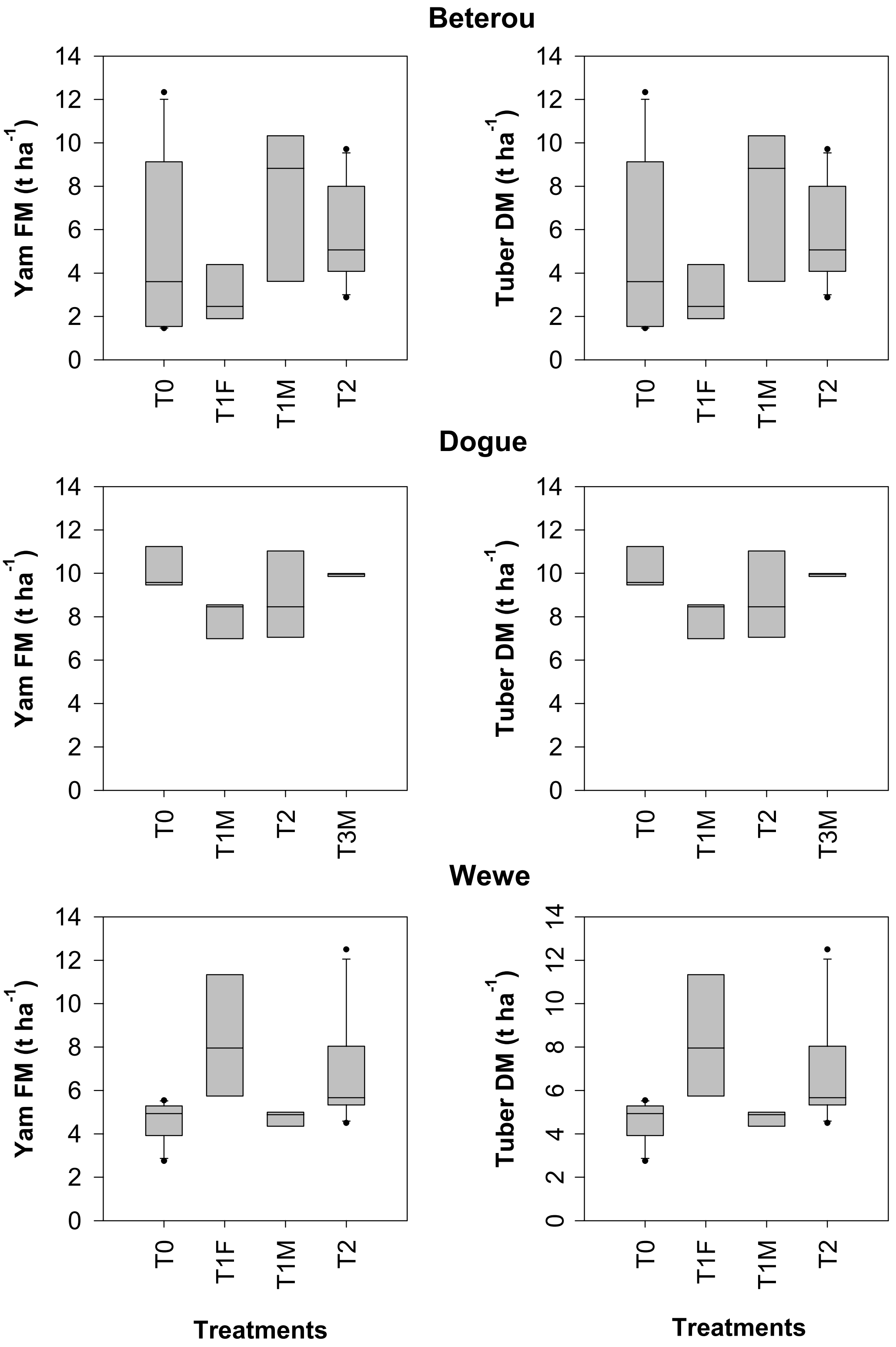


T0: Farmer's practice T1F: 10 t ha^{-1} of farmyard manure T1M: 10 t ha^{-1}of crop residues

T2: 30 N 30 P_2O_5 60 K_2O T3F: 30 N 30 P_2O_5 60 K_2O + 10 t ha^{-1} farmyard manure

T3M: 30 N 30 P_2O_5 60 K_2O + 10 t ha^{-1}of crop residues

Figure 23: Tuber (Fresh and dry matter) of yam *Dioscorea rotundata* as affected by organic and inorganic fertilizer application compared to farmer's practice at three locations in Upper Oueme catchment of Benin (on-farm experiment, 2001).



T0: Farmer's practice
T1F: Residual effect of 10 t ha^{-1} of farmyard manure (2001)
T1M: 10 t ha^{-1}of crop residues
T2: 42 N 30 P_2O_5 60 K_2O
T3F: 42 N 30 P_2O_5 60 K_2O + Residual effect of 10 t ha^{-1} of farmyard manure (2001)
T3M: 42 N 30 P_2O_5 60 K_2O + 10 t ha^{-1}of crop residues

Figure 24: Tuber (Fresh and dry matter) of yam *Dioscorea rotundata* as affected by organic and inorganic fertilizer application compared to farmer's practice at three locations in Upper Oueme catchment of Benin (on-farm experiment, 2002).

Mineral fertilizer application tended to increase tuber yields in Dogue and Wewe on 2001, but effects were inconsistent between sites, and in a number of cases, mulching or manure sometimes rather lead to a depression than to an increase in yield in all the sites (Figure 23). The latter is likely the consequence of carbon-rich material which, when incorporated into the soil, leads to a microbial N immobilization.

Nevertheless, when taking T0 as reference, the increase of tuber yields and total biomass due to the residual effect of manure, two years of mineral fertilizer, combined application of mineral fertilizer, and crop residues was beneficial (Table 17).

It appeared that mineral fertilizer tended to improve the production of yam tubers in Beterou and Wewe during the two years and only in 2001 in Dogue. This increase was less important at Beterou than Dogue and Wewe in 2001 maybe due to the short time of fallow. In the second year of the experiment, an important increase of tuber production in all sites was observed with mineral fertilizer application due probably to a cumulative effect. Howeler (1985; 2002), described several cases in which cassava tubes yields declined dramatically without nutrient application and where fertilizer application was needed to maintain productivity.

However, a depressive effect was observed in Dogue in the second year. Here, yield responses to fertilizer application were either negligible or weak. This could be attributed to the late planting date of yam in 2002, where the late onset of rainfall delayed planting and thus shortened the available vegetation period.

High variability on total biomass and RUE (Figures 25 and 26) was observed in Beterou and Wewe in both years. This could be explained by the low yield due to the short growing period caused by lower rainfall compared to the first year of experiment.

Table 17: Yam yields, harvest index and RUE for the treatments relative (%) to farmers practice (=T0) at three sites of Upper Oueme Catchment. In bold: highest and lowest values, resp. Ic= confidence interval

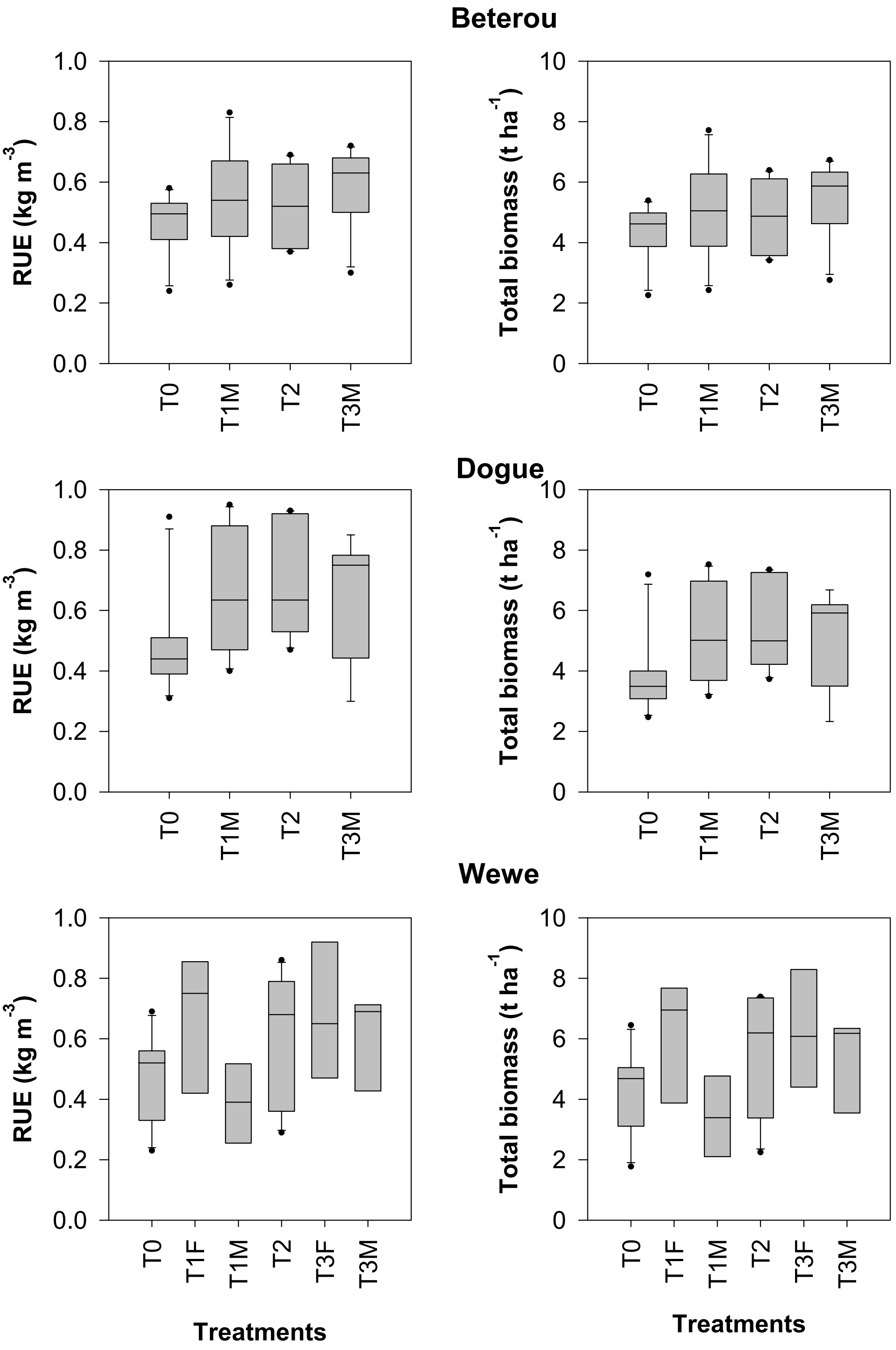
Treatments	Tuber FM	Tuber DM	Total biomass	RUE	Harvest index
Beterou					
2001					
T1M	120.0	119.5	118.0	118.0	100.6
	(26.6)	*(27.5)*	*(24.6)*	*(24.6)*	*(3.4)*
T2	118.0	119.0	117.7	117.7	100.8
	(24.4)	*(26.6)*	*(24.7)*	*(24.7)*	*(1.7)*
T3M	**129.6**	**127.5**	**125.5**	**125.5**	**101.1**
	(14.6)	*(17.5)*	*(12.2)*	*(12.2)*	*(4.7)*
2002					
T1F	125.1	143.7	141.2	137.3	93.2
	(82.4)	*(127.3)*	*(107.2)*	*(100.0)*	*(46.5)*
T1M	102.1	104.7	**93.5**	**94.8**	112.5
	(19.8)	*(36.4)*	*(10.7)*	*(8.9)*	*(48.7)*
T2	162.1	162.5	129.6	129.6	117.6
	(78.9)	*(82.2)*	*(30.7)*	*(30.7)*	*(36.2)*
T3F	**221.3**	201.8	**158.2**	**154.9**	127.9
	(179.0)	*(148.5)*	*(49.9)*	*(43.8)*	*(80.3)*
T3M	187.1	**220.7**	133.9	137.0	**135.2**
	(210.4)	*(272.8)*	*(74.6)*	*(80.2)*	*(104.3)*
Doguè					
2001					
T1M	140.7	144.2	139.5	139.5	103.3
	(41.3)	*(37.7)*	*(36.9)*	*(36.9)*	*(4.6)*
T2	**155.8**	**158.5**	**152.1**	**152.1**	**102.8**
	(51.1)	*(53.2)*	*(48.3)*	*(48.3)*	*(4.5)*
T3M	130.4	125.3	127.4	127.4	**98.2**
	(48.5)	*(43.3)*	*(42.8)*	*(42.8)*	*(1.9)*
2002					
T1M	**76.7**	**75.8**	**75.1**	**75.1**	**100.6**
T1M	*(11.5)*	*(9.4)*	*(8.5)*	*(8.5)*	*(2.7)*
T2	86.3	87.3	87.4	87.4	100.2
T2	*(17.5)*	*(17.4)*	*(19.2)*	*(19.2)*	*(2.2)*
T3M	97.7	**101.9**	**101.5**	**101.5**	100.1
T3M	*(13.0)*	*(14.7)*	*(12.8)*	*(12.8)*	*(5.4)*
Wèwè					
2001					
T1F	135.4	130.6	128.8	128.8	101.8
	(36.0)	*(37.6)*	*(38.1)*	*(38.1)*	*(2.8)*
T1M	**85.9**	**85.4**	**84.7**	**84.7**	100.7
	(14.1)	*(12.9)*	*(9.9)*	*(9.9)*	*(4.1)*
T2	131.9	132.1	127.6	127.6	103.2
	(22.4)	*(21.1)*	*(17.8)*	*(17.8)*	*(3.5)*
T3F	**149.9**	**148.1**	**141.0**	**141.0**	**105.4**
	(34.1)	*(38.2)*	*(37.2)*	*(37.2)*	*(0.8)*
T3M	137.3	136.4	130.9	130.9	104.2
	(26.7)	*(31.2)*	*(31.4)*	*(31.4)*	*(2.4)*
2002					
T1F	**176.7**	**169.6**	**150.6**	**150.6**	**113.3**
	(116.8)	*(93.4)*	*(77.1)*	*(77.1)*	*(18.1)*
T1M	**119.0**	**122.7**	**116.2**	**116.3**	**101.2**
	(49.4)	*(36.4)*	*(36.5)*	*(32.5)*	*(9.7)*
T2	159.2	160.1	144.4	144.8	108.1
	(66.0)	*(65.5)*	*(49.3)*	*(49.3)*	*(6.9)*
T3F	163.2	157.2	141.9	141.9	112.3
	(91.4)	*(64.4)*	*(62.5)*	*(62.5)*	*(13.0)*
T3M	146.6	154.1	135.8	135.4	104.0
	(91.2)	*(66.5)*	*(60.5)*	*(54.5)*	*(18.1)*

T0: Farmer's practice T1F: 10 t ha^{-1} of farmyard manure (2001) or its residual effect (2002)

T1M: 10 t ha^{-1}of crop residuesT2: 30 N 30 P_2O_5 60 K_2O (2001) or 42 N 30 P_2O_5 60 K_2O (2002)

T3F: 30 N 30 P_2O_5 60 K_2O + 10 t ha^{-1} farmyard manure (2001) or 42 N 30 P_2O_5 60 K_2O + residual effect of manure (2001)

T3M: 30 N 30 P_2O_5 60 K_2O + 10 t ha^{-1}of crop residues (2001) or 42 N 30 P_2O_5 60 K_2O + 10 t ha^{-1}of crop residues (2002)

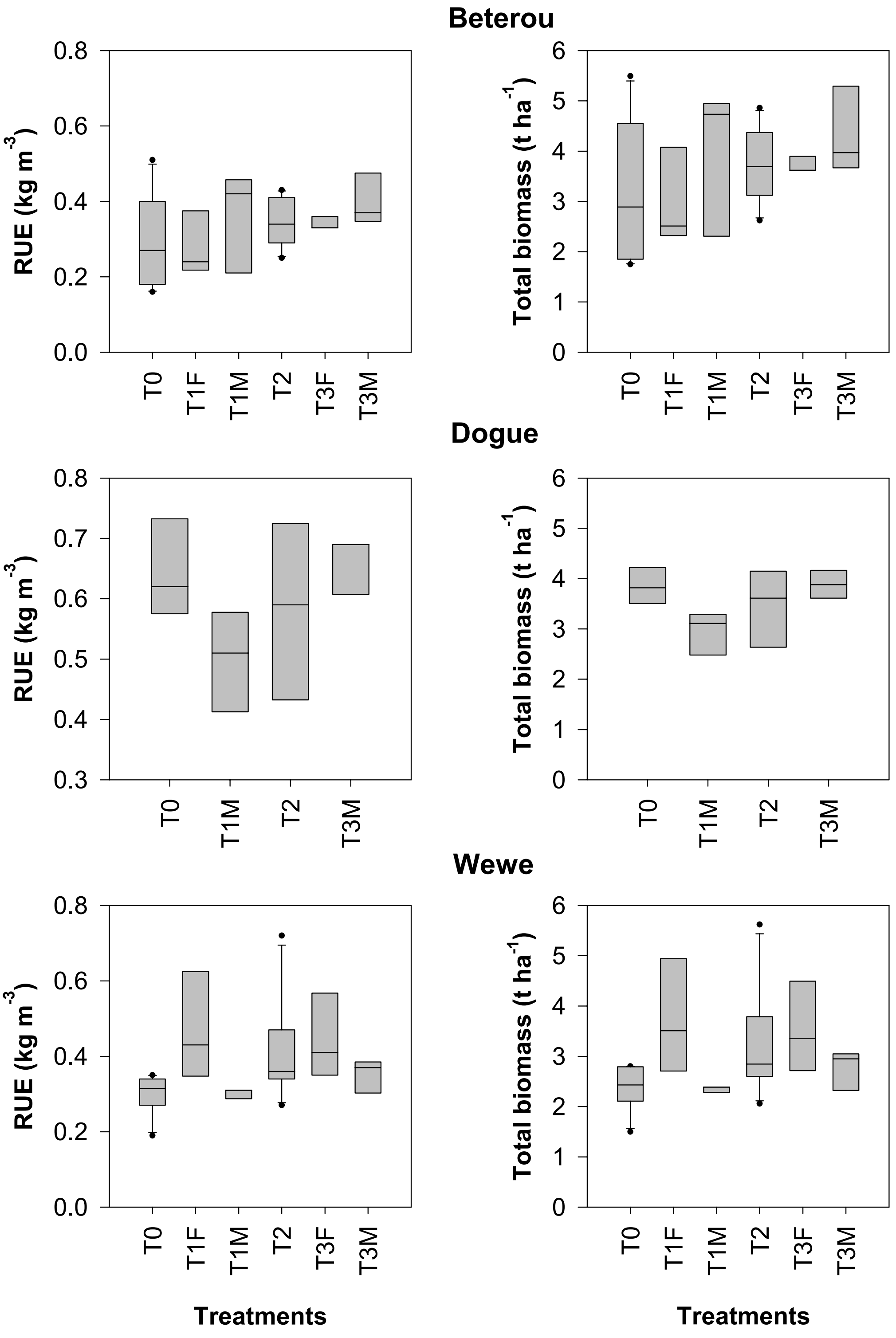


T0: Farmer's practice T1F: 10 t ha^{-1} of farmyard manure T1M: 10 t ha^{-1}of crop residues

T2: 30 N 30 P_2O_5 60 K_2O T3F: 30 N 30 P_2O_5 60 K_2O + 10 t ha^{-1} farmyard manure

T3M: 30 N 30 P_2O_5 60 K_2O + 10 t ha^{-1}of crop residues

Figure 25: Rainfall use efficiency (RUE) and total biomass of yam *Dioscorea rotundata* as affected by organic and inorganic fertilizer application compared to farmer's practice at three locations in Upper Oueme catchment of Benin (on-farm experiment, 2001).



T0: Farmer's practice

T1F: 10 t ha^{-1} of farmyard manure (2001) or its residual effect (2002)

T1M: 10 t ha^{-1}of crop residues

T2: 30 N 30 P_2O_5 60 K_2O (2001) / 42 N 30 P_2O_5 60 K_2O (2002)

T3F: 30 N 30 P_2O_5 60 K_2O + 10 t ha^{-1} farmyard manure (2001) or 42 N 30 P_2O_5 60 K_2O + residual effect of manure (2001)

T3M: 30 N 30 P_2O_5 60 K_2O + 10 t ha^{-1}of crop residues (2001) or 42 N 30 P_2O_5 60 K_2O + 10 t ha^{-1}of crop residues (2002)

Figure 26: Rainfall use efficiency (RUE) and total biomass of yam *Dioscorea rotundata* as affected by organic and inorganic fertilizer application compared to farmer's practice at three locations in Upper Oueme catchment of Benin (on-farm experiment, 2002).

3.2. Plant Nutritional Assessment

Plant nutrition is an important component in conservation agriculture, as its main objectives is to provide adequate nutrients to crops through integrated management of available soil, water and biological resources combined with external inputs such as fertilizers (Marschner, 1995). Balanced fertilization and better cultural practices are needed to obtain higher yields and to make use of the full yield potential of the crops. This led to a need for better methods for soil fertility diagnosis. When fertilizers are applied, the plant response is reflected by the tissue composition, although the relationship with yield is not necessarily direct (Sumner, 1999).

In order to assess the plant nutritional status, plant analysis must be done. Plant analysis is based on the principle that the concentration of an element or nutrient within the plant or one of its parts is an integral value of all the factors that have interacted to affect plant growth, including the availability of the element (Robert *et al.,* 1990). So, plant analysis is an important tool for diagnosing nutrient deficiencies and imbalances.

For annual crops, plant analysis plays a minor role for directly correcting nutrient supply as the response might be to late for the crop to still make use of the fertilizer application, especially for less mobile elements such as P and K. Thus, tissue analysis is mostly used for perennial (tree) crops.

Interpretation of plant analysis data has primarily followed two major approaches. The first approach is based on constructing independent nutrient indices, including only one nutrient in each index. The nutrient sufficient range (SR) is a prime example of that approach (Jones *et al.,* 1990). However, the critical value method (CVM) or the critical level method (CLM) is also used for the interpretation of plant analysis data.

If on element is found limiting, the sufficiency of others cannot really be determined until the limiting element is brought to sufficiency. Excess concentrations of essential elements can also become detrimental to growth and lead to yield (Ohki, cited by Robert *et al.,* 1990).

The second approach is based on dependant nutrient indices in which each index includes two or more nutrients. Diagnosis and Integrated System (DRIS) is the principal example of this approach (Beaufils, 1973). To diagnose nutrient deficiencies, DRIS uses a comparison of leaf tissue concentration ratios of nutrients pairs with norms developed from high-yielding populations.

This chapter provides the results of the leaf nutrient levels of all crops used during these two years of experiment and their discussion according to the critical value method (CVM), the DRIS norms established per crop, and the nutrient indices and their explanations according to Kelling and Schulte (1986). Results are presented per crop.

3.2.1. Maize Nutritional Assessment

3.2.1.1 Nutrient status assessment using Critical Value Method (CVM) for maize

The entire data for maize was separated into two sub-populations on the basis of a cut-off point yield set at 3.45 t ha^{-1} in 2001 and at 2.64 t ha^{-1} in 2002. Maize yield ranged between 3.51 and 6.21 t ha^{-1} in the high- yielding population and 0.39 up to 3.46 t ha^{-1} in the low- yielding population in the first year. It was between 2.64 t ha^{-1} and 6.25 in the high yielding sub-population and between 0.13 and 2.47 t ha^{-1} in the low yielding sub-population in the second year. This lower cut-off point observed in the second year could be explained by the lower yield of maize in this year due to not applying manure, the competition between cowpea and maize observed at the beginning of the growing period of maize, as well as the later onset of rainfall in this year. The difference between these two sub-populations of yield was highly significant ($p = 0.001$) and can be a good indicator of the precision of the DRIS norms established in these two years of experimentation.

The most important nutrients were N followed by K, Ca, P, Mg and S in the leaves of Maize in the two years of experiment (Tables 18 and 19).

Table 18: Means, coefficient of variation (CV) and variance (VAR) of nutrient contents of leaves of Maize for the low- and high-yielding sub-populations of Maize grain in 2001

Parameters	Low- yielding sub-population [n=33]			High- yielding sub-population [n=59]			Ratio of variance
	Mean	CV	VAR	Mean	CV	VAR	
Grain [t ha^{-1}]	2.48	31.3	601531.0	4.48	16.5	544843.2	1.1
Nutrients [g kg^{-1}]							
N	20.2	24.0	23.5	20.6	26.3	29.2	0.8
P	3.1	28.8	0.8	3.0	37.0	1.2	0.7
K	17.9	29.7	28.4	18.9	32.5	37.7	0.8
Ca	4.3	41.4	3.1	6.1	67.6	17.2	0.2
Mg	2.4	30.3	0.5	2.3	27.0	0.4	1.3
S	1.2	35.3	0.2	1.2	30.8	0.1	1.4
Zn [mg kg^{-1}]	20.7	31.5	42.7	19.8	36.3	51.8	0.8

Table 19: Means, coefficient of variation (CV) and variance (VAR) of nutrient contents of leaves of Maize for the low- and high-yielding sub-populations of Maize grain in 2002 in comparison to published critical levels

Parameters	Low- yielding sub-population [n=51]			High- yielding sub-population [n=34]			Ratio of variance	Critical Values (1)	Critical Values (2)
	Mean	CV	VAR	Mean	CV	VAR			
Grain [t ha-1]	1.29	57.8	558540.4	3857.4	23.9	846503.5	0.7	-	-
Nutrients [g kg^{-1}]									
N	20.4	20.4	17.3	23.5	16.3	14.6	1.2	28 - 30	26-36
P	2.6	25.9	0.5	2.9	22.9	0.5	1.0	2.3 – 3.0	2.2-4.0
K	16.7	20.1	11.3	19.1	21.6	17.1	0.7	17 - 28	18-45
Ca	3.4	23.6	0.6	3.8	15.8	0.4	1.7	-	4.3-10
Mg	2.1	27.5	0.3	1.9	26.7	0.2	1.4	1.5 – 2.5	2.7-3.4
S	1.1	22.0	0.1	1.3	18.1	0.1	1.1	1.4	2.0-2-8
Nutrients [mg kg^{-1}]									
Zn	18.2	20.7	14.1	15.3	22.1	11.4	1.2	12 - 15	20-114
Mn	29.7	39.9	140.3	37.7	56.9	460.0	0.3	15 - 20	60-130

(1) Adepetu and Adebusuyi, 1985 in (FAO 2000)

(2) (Jones *et al.* 1990a)

FAO (2000) critical values are used in this study because they are the ones used in Nigeria, a neighbour country to Benin. Nutrient sufficiency values adapted from Jones *et al.* (1990a) for ear-leaf composition of Colorado-grown

Maize from tasseling to silking stages of growth were used to comment only the Ca nutrient, due to the lack of a critical value from FAO (2000).

The leaf N and S nutrient levels in the two sub-populations for the two years were lower than the critical values published by FAO (2000). P, K and Mg contents ranged between the critical values, whereas the Mn content in 2002 was higher than this critical value. The Ca content was close to the sufficiency level in first year and inadequate in second year according to the critical value previously reported by Jones *et al.* (1990b).

To summarize, all the nutrient levels (except Mn content which was higher in 2002) were closed to the critical values reported by FAO (2000) and Jones *et al.* (1990b). So it could be concluded that multiple nutrient deficiencies could be expected according to the critical value method (CVM).

Average foliar N, P, K, Ca, Mg, S, Zn, and Mn concentrations were higher in the high-yielding sub-population than in the low-yielding sub-population. Mean of N, K, Ca, S and Mn in 2002 were significantly higher ($p < 0.01$ for N, K, Ca, S; $p < 0.05$ for P and Mn) in the high-yielding -population than in the low- yielding sub-population while the opposite trend was observed for Mg and Zn; ($p < 0.01$ for Mg; $p < 0.05$ for Zn). However, only mean Ca levels differed in 2001 highly significantly between the high- and the low-yielding sub-population.

3.2.1.2. Nutrient status assessment using Diagnosis and Integrated System (DRIS) for maize

The mean, coefficient of variation, variance of all nutrient ratios for the high- (S^2_l) and low- (S^2_h) yielding sub-populations, the coefficient of correlation between pairs of nutrients and the probability associated are shown on tables.19 and 20 for both years. The variance ratio provides an indication of the importance of a particular nutrient ratio to the yield parameter.

Twenty-one and twenty-eight ratios were used as DRIS norms in 2001 and 2002 because they showed the highest ratio (Tables 20 and 21). Mean nutrient ratios selected for DRIS norms were dissimilar between the low-and the high-yielding groups.

Table 20: Mean, coefficient of variation (CV) and variance (VAR) of ratio for pairs of nutrient of low- and high-yielding sub-populations of maize in 2001, ratio of variance and selected ratio between a pair of ratio of nutrient.

Parameters	Low- yielding sub-population [n=33]			High- yielding sub-population [n=59]			Ratio of	Selected
	Mean	CV	VAR	Mean	CV	VAR	variance	ratio
N/P	7.273	50.4	13.4	8.102	55.5	20.2	0,7	
P/N	0.159	32.3	0.0	0.149	37.0	0.0	0,9	X
N/K	1.191	28.4	0.1	1.194	40.2	0.2	0,5	
K/N	0.917	32.1	0.1	0.953	35.3	0.1	0,8	X
N/Ca	4.513	38.7	3.1	4.191	50.0	4.4	0,7	
Ca/N	0.269	63.8	0.0	0.311	58.0	0.0	0,9 ***	X
N/Mg	9.523	45.5	18.8	9.577	41.6	15.9	1,2	
Mg/N	0.124	38.8	0.0	0.118	32.5	0.0	1,6	X
N/S	17.849	40.5	52.3	18.652	42.3	62.3	0,8	
S/N	0.063	39.1	0.0	0.060	39.1	0.0	1,1	X
N/Zn	1.032	26.8	0.1	1.117	34.3	0.1	0,5	
Zn/N	1.050	31.4	0.1	0.997	33.7	0.1	1,0	X
P/K	0.179	30.2	0.0	0.160	30.8	0.0	1,2	
K/P	6.190	38.8	5.8	6.794	28.9	3.9	1,5	X
P/Ca	0.717	34.2	0.1	0.623	52.8	0.1	0,6 **	X
Ca/P	1.757	86.1	2.3	2.743	101.6	7.8	0,3 ***	
P/Mg	1.441	44.2	0.4	1.311	34.2	0.2	2,0	X
Mg/P	0.860	53.7	0.2	0.879	43.7	0.1	1,4	
P/S	2.655	34.7	0.8	2.663	48.2	1.6	0,5	
S/P	0.428	49.5	0.0	0.453	59.7	0.1	0,6	X
P/Zn	0.159	32.6	0.0	0.160	43.0	0.0	0,6	
Zn/P	7.407	55.9	17.1	7.715	53.7	17.2	1,0	X
K/Ca	3.914	30.8	1.5	3.904	48.2	3.5	0,4 ***	X
Ca/K	0.303	67.8	0.0	0.385	83.5	0.1	0,4 **	
K/Mg	8.138	36.8	9.0	8.404	29.8	6.3	1,4	
Mg/K	0.140	39.7	0.0	0.131	33.2	0.0	1,6	X
K/S	15.544	36.0	31.3	16.792	41.9	49.6	0,6	
S/K	0.072	41.0	0.0	0.067	46.9	0.0	0,9	X
K/Zn	0.892	22.1	0.0	0.999	31.6	0.1	0,4 **	
Zn/K	1.182	25.5	0.1	1.118	37.1	0.2	0,5	X
Ca/Mg	2.243	65.4	2.2	2.891	77.3	5.0	0,4	
Mg/Ca	0.522	29.9	0.0	0.459	37.8	0.0	0,8	X
Ca/S	3.978	31.7	1.6	5.284	74.3	15.4	0,1	
S/Ca	0.269	33.4	0.0	0.235	41.4	0.0	0,9	X
Ca/Zn	0.250	59.2	0.0	0.356	96.7	0.1	0,2	
Zn/Ca	4.474	29.2	1.7	4.024	52.4	4.5	0,4	X
Mg/S	2.034	36.5	0.6	2.081	39.8	0.7	0,8	
S/Mg	0.554	44.4	0.1	0.541	45.8	0.1	1,0	X
Mg/Zn	0.121	37.5	0.0	0.127	38.6	0.0	0,9	X
Zn/Mg	9.271	33.5	9.7	9.107	43.8	15.9	0,6	
S/Zn	0.063	45.7	0.0	0.066	46.3	0.0	0,9	X
Zn/S	18.103	41.6	56.6	17.710	49.7	77.6	0,7	

N, P, K, Ca, Mg, S (g kg^{-1}); Zn and Mn (mg kg^{-1})

Variances of nutrient ratios of low and high-yielding groups are significantly different at 1% (***), 5 % (**) and 10 % (*) level of probability by Levene's test.

Table 21: Mean, coefficient of variation (CV) and variance (VAR) of ratio for pairs of nutrient of low- and high-yielding sub-populations of maize in 2002, ratio of variance and selected ratio between a pair of ratio of nutrient.

Parameters	Low- yielding subpopulation [n=51]			High- yielding sub-population [n=34]			Ratio of variance	Select ratio
	Mean	CV	VAR	Mean	CV	VAR		
N/P	8.045	18.4	2.2	8.224	20.2	2.8	0.8	X
P/N	0.128	18.3	0.0	0.127	21.3	0.0	0.8	
N/K	1.257	24.8	0.1	1.255	15.8	0.0	2.5	X
K/N	0.841	23.7	0.0	0.817	16.1	0.0	2.3	
N/Ca	6.344	26.5	2.8	6.351	25.4	2.6	1.1	
Ca/N	0.170	30.1	0.0	0.169	28.9	0.0	1.1	X
N/Mg	10.499	39.1	16.9	13.666	33.5	21.0	0.8	
Mg/N	0.110	39.3	0.0	0.082	36.4	0.0	2.1 **	X
N/S	18.959	17.7	11.2	18.610	19.4	13.0	0.9	
S/N	0.055	22.1	0.0	0.056	21.7	0.0	1.0	X
N/Zn	1.157	25.7	0.1	1.591	23.4	0.1	0.6	
Zn/N	0.921	25.9	0.1	0.661	22.1	0.0	2.7 ***	X
N/Mn	0.789	42.9	0.1	0.861	60.8	0.3	0.4 **	
Mn/N	1.526	46.5	0.5	1.621	56.0	0.8	0.6 *	X
P/K	0.162	33.6	0.0	0.158	22.8	0.0	2.3	X
K/P	6.771	29.0	3.9	6.673	23.7	2.5	1.5	
P/Ca	0.806	28.4	0.1	0.789	25.6	0.0	1.3	
Ca/P	1.360	33.7	0.2	1.364	29.3	0.2	1.3	X
P/Mg	1.331	40.1	0.3	1.709	36.9	0.4	0.7	
Mg/P	0.875	40.1	0.1	0.663	34.3	0.1	2.4 *	X
P/S	2.425	23.7	0.3	2.333	25.1	0.3	1.0	
S/P	0.438	26.7	0.0	0.454	24.3	0.0	1.1	X
P/Zn	0.148	29.7	0.0	0.202	32.8	0.0	0.4	
Zn/P	7.381	30.5	5.1	5.431	30.0	2.7	1.9 *	X
P/Mn	0.102	49.1	0.0	0.111	69.1	0.0	0.4	
Mn/P	12.360	50.1	38.3	13.201	53.2	49.3	0.8 *	X
K/Ca	5.305	30.6	2.6	5.149	26.0	1.8	1.5	
Ca/K	0.216	44.8	0.0	0.211	33.4	0.0	1.9	X
K/Mg	8.724	23.6	12.6	11.137	17.2	15.9	0.8	
Mg/K	0.138	48.3	0.0	0.103	41.5	0.0	2.4 *	X
K/S	15.898	27.3	18.9	15.261	25.5	15.2	1.2	X
S/K	0.069	34.5	0.0	0.071	31.0	0.0	1.2	
K/Zn	0.965	30.6	0.1	1.312	31.4	0.2	0.5 **	
Zn/K	1.154	36.5	0.2	0.838	31.2	0.1	2.6 *	X
K/Mn	0.633	35.8	0.1	0.690	58.7	0.2	0.3 ***	
Mn/K	12.360	44.7	38.3	13.201	56.6	49.3	0.8 *	X
Ca/Mg	1.679	31.1	0.3	2.145	20.0	0.2	1.5	
Mg/Ca	0.661	36.2	0.1	0.484	19.6	0.0	6.3 ***	X
Ca/S	3.128	23.6	0.5	3.015	17.2	0.3	2.0	X
S/Ca	0.336	21.5	0.0	0.341	17.0	0.0	1.6 **	
Ca/Zn	0.192	32.2	0.0	0.264	31.0	0.0	0.6 **	
Zn/Ca	5.709	30.3	3.0	4.126	28.5	1.4	2.2 **	X
Ca/Mn	0.129	45.1	0.0	0.138	60.7	0.0	0.5	
Mn/Ca	9.178	38.9	12.8	9.663	49.0	22.4	0.6 **	X
Mg/S	2.054	41.3	0.7	1.459	24.8	0.1	5.5 ***	X
S/Mg	0.563	39.3	0.0	0.733	28.4	0.0	1.1	
Mg/Zn	0.120	29.0	0.0	0.128	41.1	0.0	0.4	
Zn/Mg	9.177	35.6	10.7	8.832	33.1	8.5	1.3	X
Mg/Mn	0.081	42.6	0.0	0.066	66.4	0.0	0.6	X
Mn/Mg	14.804	44.5	43.4	20.336	48.0	95.3	0.5 ***	
S/Zn	0.062	27.7	0.0	0.088	27.9	0.0	0.5 **	
Zn/S	17.262	29.1	25.2	12.198	27.3	11.1	2.3	X
S/Mn	0.042	39.7	0.0	0.047	68.1	0.0	0.3 *	
Mn/S	27.763	38.0	111.3	28.460	46.3	173.9	0.6	X
Zn/Mn	0.710	45.1	0.1	0.583	68.8	0.2	0.6	X
Mn/Zn	1.727	49.7	0.7	2.670	71.9	3.7	0.2 ***	

N, P, K, Ca, Mg, S (g kg^{-1}); Zn and Mn (mgkg^{-1}) Variance of nutrient ratios of low and high-yielding groups are significantly different at 1% (***), 5 % (**) and 10 % (*) level of probability by Levene's test.

The selection of nutrient of ratio as DRIS norms (i.e.: N/P or P/N) is indicated by the S^2l / S^2h ratio (Hartz *et al.* 1998). The higher the S^2l / S^2h ratio, the more limiting is the nutrient for obtaining a high yield (Payne *et al.* 1990). Although Beaufils (1973) suggests that each parameter which shows a significant difference of variance ratio between the two groups under comparison (low- and high- yielding) should be used in DRIS, other researchers have adopted the ratio which maximized the variance ratio between the low- and high- yielding group (Snyder *et al.,* 1989; Payne *et al.,* 1990; Malavolta *et al.,* 1997). The aim of this procedure is to determine the norms with the greatest precision (Caldwell *et al.* 1994). The discrimination between nutritionally healthy and unhealthy plants is maximized when the ratio of variance of low- *vs.* high-yielding groups is also maximized (Walworth *et al.* 1986). Nearly all nutrients selected as DRIS norms did not show statistical differences between mean values in the low- and high- yielding groups. Only three out of the selected DRIS norms in 2001 and seven out of them in 2002 showed statistical differences between mean values in the low- and high- yielding groups. None of the ratios selected as DRIS norms in 2001 and seven in 2002 had a variance ratio greater than two. However, two out of eight in 2002 had a ratio of variance greater than two contained micronutrient (Zn). Payne *et al.* (1990) suggest the possible importance of DRIS norms for micronutrients with high variance ratios between low- and high-yielding groups to nutritional diagnosis in bahiagrass because micronutrient fertilization requirements are not easily determined by soil testing. In the present case, the only micronutrient, which has been applied, is 1 % B in the fertilizer, and no experiment has been set up to test for micronutrient deficiencies in Benin. Thus, the DRIS norms for micronutrients with high ratio of variance found in the present study can provide more security to evaluate the micronutrient status of Maize. As pointed out by Bailey *et al.* (1997), DRIS norms (nutrient ratios) with large ratio of variance and small coefficient of variation imply that the balance between these specific pairs of nutrients could be of critical importance for crop production. Therefore, nutrient ratios with a large ratio of variance with a small coefficient of variation indicate that a high yield should be associated with a small variation around the average nutrient ratio. In this study, coefficients of variation were sometimes higher and high variability in the nutrients ratios could explain this situation. Most of the selected

nutrient ratios showed a lower coefficient of variation (CV). There is a speculation that the large ratio of variance and the small coefficient of variation found for specific ratios between nutrients probably imply that the balance between these pairs of nutrients could be important to maize production. By assessing DRIS norms for maize, Elwali *et al.* (1985) found the lowest Nutrient Balance Index in all nutritional diagnoses and (Junior, 2002) explained this result by the highest coefficient of variation observed in almost all nutrient relationships established by these authors. Most of the selected nutrient ratios showed a lower coefficient of variation (CV) than the other possible nutrient ratios for the same pair of nutrients. The same observation was made by Junior and Monnerat (2003) when they established DRIS norms for sugarcane, comparing mean yield, foliar nutrient contents and variance of nutrient ratios of low- and high-yielding groups and mean values of nutrient ratios selected as the DRIS norms of low- and high-yielding groups in Rio de Janeiro State in Brazil.
Some of the nutrient ratios selected as DRIS norms (P/Ca, K/Ca, K/Zn, Ca/N, Ca/P, Ca/K) in 2001 and (Mg/N, Mg/Ca, Mn/N, N/Mn, Zn/N, Mg/S, Zn/P, S/Zn, Mn/Zn, K/Mn, Mn/K, Mn/Mg, Mg/P, Mn/P, Mg/K, Zn/K, K/Zn, S/Ca, Zn/Ca, Ca/Zn, Mn/Ca, S/Mn) in 2002 showed significant differences between the variances in low-and high-yielding groups. However, mean nutrient ratios selected as DRIS norms were not similar in the low- and high- yielding sub-populations. When there are no differences of nutritional balance between the low-and high-yielding groups, it is to be assumed that nutritional effects are not responsible for yield differences between the groups, and that the DRIS norms developed under this situation will not produce a reliable diagnostic tool. The difference of nutritional balance between low-and high-yielding groups indicates that the DRIS norms developed in this study are reasonable.

DRIS norms (Tables 21 and 22) established in this study were compared to those found by Junior (2002). This author evaluated the confidence intervals of four DRIS norms of maize, compared maize nutritional diagnosis with four DRIS norms and evaluated the universal use of DRIS norms in maize crops. This author used for his work many DRIS norms established by several researchers.
One out of ten DRIS norm established by Sumner (1977b), 3 out of 22 established by Escano *et al.* (1981); seven and four out of 28, respectively

established by Elwali *et al*. (1985) and Dara *et al.* (1992) were similar to those found in the present work (Tables 22 and 23). Although there are significant differences between reference values established by different authors and most of DRIS norms established in Upper Oueme catchment, the latter were rather close to the reported values. This significant difference observed between the DRIS norms established for maize in this study could be explained by differences in soil conditions, climate, leaf position, and cultivar effects. Roberto dos Anjos (2002) pointed out that the universal application of these four DRIS norms established for maize by these authors should not be recommended to generally evaluate maize nutritional status. In the absence of DRIS norms locally calibrated, norms developed under one set of conditions only should be applied to another if the nutrient concentrations of high-yielding plants from these different set of conditions are similar. This was supported by Elwali and Gascho (1983; 1984) who, using a small data base (90 observations in each of the low-and high-yield sub-populations) concluded that local calibration is necessary to improve the accuracy of DRIS diagnosis, at least when based only on a small data set.

Table 22: Mean of DRIS Norms of high- yielding sub-population to reference values of different authors 2001.

Ratio	**DRIS Norms**	**Sumner**	**prob.**	**Escano *et al.***	**prob.**	**Elwali *et al.***	**prob.**	**Dara *et al.***	**prob.**
N/P	8.1	10.0	0.019	10.0	0.022	9.0	0.245	9.7	0.054
	55.5	*15.0*		*13.7*		*23.7*		*13.3*	
N/K	1.2	1.5	0.001	1.6	0.000	1.5	0.003	1.1	0.0451
	40.2	*22.0*		*15.7*		*29.2*		*20.3*	
N/Ca	4.2	5.4	0.002	7.1	0.000	6.3	0.000	5.1	0.025
	50.0	*47.0*		*19.2*		*35.6*		*26.8*	
N/Mg	9.6	10.3	0.299	13.5	0.000	14.1	0.000	9.6	0.962
	41.6	*45.0*		*21.9*		*40.8*		*26.9*	
N/S	18.7	-	-	15.2	0.000	11.9	0.000	14.7	0.008
	42.3	*-*		*8.1*		*22.6*		*23.5*	
N/Zn	1.1	-	-	0.6	0.000	1.2	0.354	1.3	0.006
	34.3	*-*		*29.5*		*37.8*		*29.2*	
K/P	6.8	-	0.876	6.7	0.061	6.1	0.016	5.9	0.030
	28.9	*-*		*25.0*		*19.5*		*32.0*	
Ca/P	2.7	1.9	0.085	1.4	0.008	1.4	0.012	1.9	0.105
	101.6	*50.0*		*26.6*		*42.3*		*32.9*	
P/Mg	1.3	1.1	0.005	1.4	0.456	1.6	0.003	1.0	0.000
	34.2	*48.0*		*22.8*		*51.6*		*32.0*	
P/S	2.7	-	-	1.6	0.000	1.4	0.000	1.5	0.000
	48.2	*-*		*18.5*		*32.0*		*25.7*	
Zn/P	7.7	-	-	15.3	0.000	8.8	0.132	-	-
	53.7	*-*		*32.2*		*47.6*		*-*	
K/Ca	3.9	3.1	0.024	4.5	0.093	4.2	0.343	4.0	0.770
	48.2	*59.0*		*18.8*		*51.5*		*33.2*	
K/Mg	8.4	7.1	0.007	8.6	0.707	9.6	0.009	7.5	0.038
	29.8	*67.0*		*24.0*		*60.6*		*43.3*	
K/S	16.8	-	-		0.000	8.8	0.000	11.6	0.000
	41.9	*-*		*15.0*		*25.4*		*29.1*	
Zn/K	1.1	-	-	2.5	0.000	1.4	0.000	1.1	0.355
	37.1	*-*		*25.2*		*48.6*		*35.2*	
Ca/Mg	2.9	1.9	0.016	2.0	0.023	2.2	0.066	1.8	0.389
	77.3	*36.0*		*25.2*		*39.1*		*38.3*	
Ca/S	5.3	-	-	2.2	0.000	2.0	0.000	3.1	0.003
	74.3	*-*		*17.1*		*45.1*		*35.7*	
Zn/Ca	4.0	-	-	10.8	0.000	5.2	0.003	3.9	0.791
	52.4	*-*		*32.6*		*56.6*		*34.6*	
Mg/S	2.1	-	-	1.2	0.000	0.8	0.000	1.4	0.000
	39.8	*-*		*22.5*		*33.1*		*33.1*	
Zn/Mg	9.1	-	-	20.5	0.000	12.1	0.000	7.3	0.012
	43.8	*-*		*32.6*		*60.7*		*41.4*	
Zn/S	17.7	-	-	23.6	0.001	10.5	0.000	31.1	0.000
	49.7	*-*		*29.5*		*38.3*		*39.6*	

( ): coefficient of variation

Prob: probability according to Student conformity test for mean

Table 23: Mean of DRIS Norms of high- yielding sub-population to reference values of different authors 2002

Ratio	**DRIS Norms**	**Sumner**	**prob.**	**Escano *et al.***	**prob.**	**Elwali *et al.***	**prob.**	**Dara *et al.***	**prob.**
N/P	8.2 *20.2*	10.0 *15.0*	0.000	10.0	0.000	9.0 *23.7*	0.008	9.7 *13.3*	0.000
N/K	1.3 *15.8*	1.5 *22.0*	0.000	1.6	0.000	1.5 *29.2*	0.000	1.1 *20.3*	0.001
N/Ca	6.4 *25.4*	5.4 *47.0*	0.002	7.1	0.015	6.3 *35.6*	0.718	5.1 *26.8*	0.000
N/Mg	13.7 *33.5*	10.3 *45.0*	0.000	13.5	0.834	14.1 *40.8*	0.601	9.6 *26.9*	0.000
N/S	18.6 *19.4*	-	-	15.2	0.000	11.9 *22.6*	0.000	14.7 *23.5*	0.000
N/Zn	1.6 *23.4*		-	0.6	0.000	1.2 *37.8*	0.000	1.3 *29.2*	0.000
K/P	6.7 *23.7*	6.7 *25.0*	0.806	6.1	0.054	5.9 *32.0*	0.009	7.6 *17.4*	0.002
Ca/P	1.4 *29.3*	1.9 *50.0*	0.000	1.4	0.806	1.4 *42.3*	0.235	1.9 *32.9*	0.000
P/Mg	1.7 *36.9*	1.1 *48.0*	0.000	1.4	0.004	1.6 *51.6*	0.191	1.0 *32.0*	0.000
P/S	2.3 *25.1*		-	1.6	0.000	1.4 *32.0*	0.000	1.5 *25.7*	0.000
Zn/P	5.4 *30.0*		-	15.3	0.000	8.8 *47.6*	0.000		-
K/Ca	5.1 *26.0*	3.1 *59.0*	0.000	4.5	0.006	4.2 *51.5*	0.000	4.0 *33.2*	0.000
K/Mg	11.1 *35.8*	7.1 *67.0*	0.000	8.6	0.001	9.6 *60.6*	0.033	7.5 *43.3*	0.000
K/S	15.3 *25.5*		-	9.7	0.000	8.8 *25.4*	0.000	11.6 *29.1*	0.000
Zn/K	0.8 *31.2*		-	2.5	0.000	1.4 *48.6*	0.000	1.1 *35.2*	0.000
Ca/Mg	2.1 *20.0*	1.9 *36.0*	0.002	2.0	0.017	2.2 *39.1*	0.941	1.8 *38.3*	0.000
Ca/S	3.0 *17.2*		-	2.2	0.000	2.0 *45.1*	0.000	3.1 *35.7*	0.581
Zn/Ca	4.1 *28.5*		-	10.8	0.000	5.2 *56.6*	0.000	3.9 *34.6*	0.330
Mg/S	1.5 *24.8*		-	1.2	0.000	0.8 *33.1*	0.000	1.4 *33.1*	0.688
Zn/Mg	8.8 *33.1*		-	20.5	0.000	12.1 *60.7*	0.000	7.3 *41.4*	0.004
Zn/S	12.2 *27.3*		-	23.6	0.000	10.5 *38.3*	0.005	11.3 *34.7*	0.110
Mn/N	1.6 *56.0*		-	0.6	0.000	1.2 *37.8*	0.481	1.3 *29.2*	0.000
Mn/P	13.2 *53.2*		-		-	14.2 *75.1*	0.431	31.1 *39.6*	0.000
Mn/K	13.2 *53.2*		-		-	2.2 *64.2*	0.000	2.5 *25.2*	0.000
Mn/Ca	9.7 *49.0*		-		-	10.5 *64.5*	0.322	10.8 *32.6*	0.000
Mn/Mg	20.3 *48.0*		-		-	24.9 *71.6*	0.011	32.3 *43.3*	0.000
Mn/S	28.5 *46.3*		-		-	15.4 *54.2*	0.000	37.9 *63.8*	0.000
Mn/Zn	2.7 *71.9*		-		-	1.7 *68.5*	0.007	4.3 *53.6*	0.000

( ): coefficient of variation Prob: probability according to Student conformity test for mean

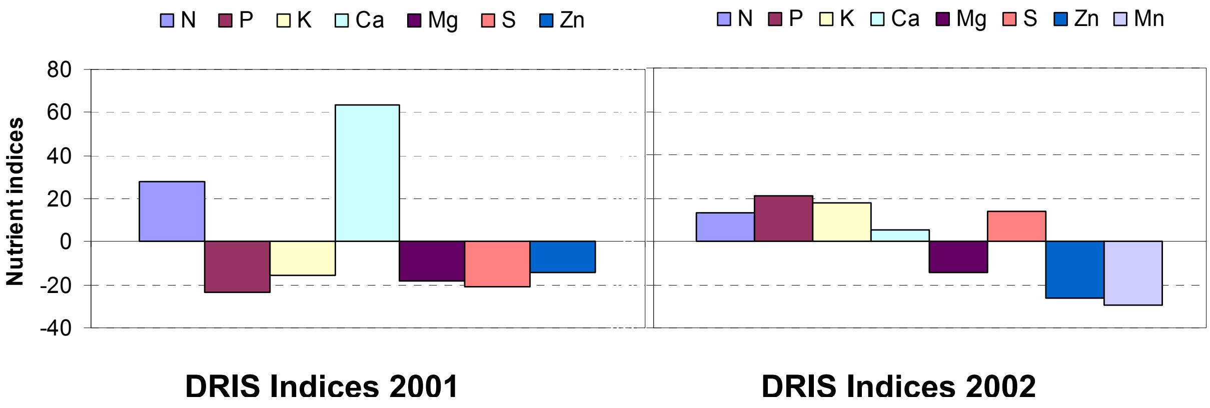


Figure 27: DRIS indices for maize in farming system in Upper Oueme catchment of Benin (on-farm experiment, 2001-2002).

Earlier studies confirmed the universal applicability of DRIS norms of several crops, regardless of variety and age of crop at sampling when the norms were established from broad data bases (Beaufils 1973; Beaufils and Sumner 1977; Sumner 1977a; Sumner 1978; Sumner 1979; Sumner 1981). For each nutrient, the DRIS reference parameters were selected as those nutrient ratios which gave the highest values for the variance ratios between the two sub-populations. In theory, the high- yielding sub-population is a group of plants genetically capable of high yields, under conditions where mineral nutrition (i.e. all the essential elements) is not limiting. Based on locations and genotype available, that group may change.

(Beaufils and Summer 1977) noted that nutrient ratio means were sometimes similar between low- and high-yielding sub-populations. So setting a cut-off value of the yield for division into two sub-populations was necessary.

The optimum ratio between two nutrients will produce a maximum yield only when both are in their respective sufficiency ranges (Soltanpour *et al.* 1995), but deficiency was observed during the two years of experiment according to CLM and after the calculation of DRIS indices. The most limiting nutrients (Figure 27) in the first year of experiment were P followed by S, K and Zn, whereas in the second year it was Mn, followed by Zn and Mg as most limiting. Phosphorous in the first year and Mn in the second year would be most limiting yield in as these indices are more negative than those of other nutrients. A similar trend was found by (Sumner, 1977b; Elwali *et al.,* 1985; Dara *et al.,* 1992). Nitrogen, and Ca level in the first year and N, P, K, Ca and S level in second year were adequate according to the DRIS indices. These results contrasted those from

CVM because N and S were deficient during the two years of experiment, Ca deficient in the second year and adequate in the first year according to this method. Phosphorous and K concentrations in the leaves were adequate according to these two approaches. According to (Kelling and Schulte, 1986), an index from -15 to +15 indicates good nutrient balance in the plant. Indices from -15 to -25 indicate possible deficiency, and indices lower than -25 are likely to be deficient. So in 2002, there is deficiency with Zn and Mn whereas in 2001 there is possible deficiency in P, K, Mg, S and Zn. The Nutritional Balance Index (NBI) is a measure of balance among fields. It is obtained by adding the values of DRIS indices irrespective of sign (Elwali and Gascho, 1984; Nick, 1998). These values were 183.8 in the first year and improved in the second year (141.2). So, the intensity of imbalances among nutrients seemed to decrease. The larger the value of the NBI, the greater was the intensity of imbalances among nutrients at the time of sampling.

According to Kelling *et al.* (1986), there is a possible deficiency in P, K, Mg and S in 2001 and only in Ca 2002 because their indices ranged between -15 and -25. All others nutrients indicates good nutrient (indices between -15 and +15) balance in plant.

In summary, mean yield and foliar nutrient concentrations are different between the low- and high-yielding groups as well as the variances of nutrient ratios. From all nutrients selected as DRIS norms 2 out of 21 in the first year and 5 out of 28 in the second year show statistically significant differences between mean values in the low- and high- yielding groups. The different nutritional balances between the low- and high-yielding groups provide some evidence that the DRIS norms developed in this study are reasonable.

Supplemental fertilization was needed according to both foliar analysis using the CNL approach and DRIS evaluation.

3.2.2. Cotton Nutritional Assessment

There were no DRIS norms previously established for cotton. So the literature found for other crops had to be used for discussing the data on cotton. The results of only one year were used because of the lack of data in the second year of the experiment. The cut-off point between high- and low-yielding sub-population was set to 0.69 t ha^{-1}.

Cotton yields have been separated into high yielding population ranged between 0.68 and 1.00 t ha^{-1}.and low-yielding sub-population ranged between 0.05 and 0.67 t ha^{-1}. The difference between these two sub-populations of yield was highly significant ($p < 0,001$) and thus can be used as a good indicator of the precision on DRIS norms established in the present work.

3.2.2.1. Nutrient status assessment using Critical Value Method (CVM) for cotton

Nutrient contents (N, P, Ca, Mg and Zn) were at the lower limit or between the critical values according to (Sabbe *et al.* 1972) for both sub-populations (Table 24). It means that most of the foliar nutrient content levels were still inadequate according to the critical level method (CVM). This also indicates that possibly the fertilizer application was not adequate to fully make use of the yield potential. The CVM method does not, however, take into account the interactions that can exist between nutrients. The high-yielding sub-population is constituted in its majority of treatments where organic matter and/or mineral fertilizers have been applied.

However, higher petiole contents of Mg 4.2 g kg^{-1} have been found by Joly (1978) in the southern Borgou and Donga departments in Benin when he worked on Mg deficiency on cotton in farmer field. Those of K ranged from 34 to 37 g kg^{-1} in the southern Borgou. Some nutrient contents found in this work are not similar to those found by Joly (1978) in North - Bénin. One can conclude that the differences may be in part attributed to differences in sampling date, age of the organ, and cultivar. This is in agreement with Braud (1987) who pointed out that nutrient contents of an organ of cotton depend on its age, its position on the plant, the type of organ (leaves, limb or petiole), and its age.

Table 24: Means, coefficient of variation (CV) and variance (VAR) of nutrient contents of leaves of cotton for the low- and high-yielding sub-populations of cotton seed and published critical levels

Parameters	Low yielding sub-population [n=37]			High yielding sub-population [n=39]			Ratio of variance	Critical Values (1)
	Mean	CV	VAR	Mean	VAR	CV		
Grain [t ha^{-1}]	0.48	35.1	27881.3	8.29	7880.6	10.7	3.5	-
Nutrients [g kg^{-1}]								
N	25.4	18.2	21.4	28.0	13.3	13.0	1.6	30 - 43
P	3.0	22.3	0.4	2.9	0.3	18.1	1.6	3 - 6.5
K	15. 8	17.6	7.7	16.4	11.1	20.3	0.7	9 - 19.5
Ca	17.2	33.3	32.8	17.0	40.4	37.4	0.8	19 - 35
Mg	2.7	31.0	0.7	2.7	0.5	25.0	1.5	3 - 7.5
S	2.1	34.7	0.5	2.2	1.0	45.8	0.5	-
Zn [mg kg^{-1}]	21.0	33.6	49.9	18.4	19.1	23.8	2.6	20 -100

(1) (Sabbe *et al.* 1972)

3.2.2.2. Nutrient status assessment using Diagnosis Regulated Integrated System (DRIS) for cotton

Although foliar average S and K concentrations were higher in the high- yielding than in the low- yielding group and those of P, Ca and Zn higher in the lower yielding sub-population than in the high- yielding group, they were not significantly different. As there is no difference of nutritional status between the low-and high-yielding groups, it is possible that the yield difference between the groups is not caused by a nutritional effect or by a nutrient not considered in the analysis; and the DRIS norms developed under this situation probably will not produce a reliable diagnosis. Nevertheless, foliar average N concentrations were higher in the high- yielding than in the low- yielding group, and this difference was significant ($p = 0.047$) proving that a higher N supply might be one reason for the higher yields of the high- yielding sub-population.

Twenty one ratios were used as DRIS norms in 2001 and 2002 because they showed the highest ratio. The choice of ratio among the pair of nutrient ratios for DRIS norms is given in the last column of the table 25.

Five out (Zn/S, Ca/S, S/Ca, Zn/Mg, and Mg/Zn) of the nutrients selected as DRIS norms had a variance ratio greater than 2. The only micronutrient showing a significant difference between the variance values in the low- and high-yielding groups was Zn (Table 25). The variance ratio provides an indication for the relative importance of a particular nutrient ratio for yield.

When comparing the mean ratio of high- and low yielding subpopulation it had been observed that these ratio in low yielding were higher than those of high yielding sub-population which the exception of the ratio K/P.

A high coefficient of variation was observed with the pair of nutrient in which Ca was associated.

In the present case, the ratios of variance were low and could explain the low yield. A nutritional imbalance has been observed according to the established DRIS indices. The most limiting nutrients were S followed by Ca, Zn and K (Figure 28). This means that the amount of K and S supplied with the fertilizer could not probably satisfy the crop requirement.

Table 25: Mean, coefficient of variation (CV) and variance (VAR) of ratio for pairs of nutrient of low- and high-yielding sub-populations of cotton, ratio of variance and selected ratio between a pair of ratio of nutrient.

Parameters	Low- yielding sub-population [n=37]			High- yielding sub-population [n=39]			Ratio of	Selected
	Mean	CV	VAR	Mean	CV	VAR	variance	ratio
N/P	8.754	22.0	3.7	9.719	22.2	4.7	0.8	
P/N	0.120	22.3	0.0	0.108	22.8	0.0	1.2	X
N/K	1.679	18.5	0.1	1.657	16.6	0.1	1.3	
K/N	0.616	18.6	0.0	0.617	14.5	0.0	1.6	X
N/Ca	2.137	104.5	5.0	3.048	88.7	7.3	0.7	X
Ca/N	0.684	33.9	0.1	0.554	52.5	0.1	0.6	
N/Mg	10.311	34.1	12.4	11.105	32.2	12.7	1.0	X
Mg/N	0.106	26.6	0.0	0.100	35.5	0.0	0.6	
N/S	13.540	46.6	39.8	17.756	68.0	145.7	0.3 *	
S/N	0.084	29.8	0.0	0.078	48.1	0.0	0.4	X
N/Zn	1.270	32.4	0.2	1.499	25.9	0.2	1.1	
Zn/N	0.875	35.1	0.1	0.721	32.1	0.1	1.8	X
P/K	0.189	18.7	0.0	0.182	28.7	0.0	0.5	
K/P	5.515	21.5	1.4	5.890	25.7	2.3	0.6	X
P/Ca	0.227	87.3	0.0	0.256	103.1	0.1	0.6	
Ca/P	5.932	35.2	4.4	6.110	38.8	5.6	0.8	X
P/Mg	1.189	35.9	0.2	1.127	31.7	0.1	1.4	X
Mg/P	0.920	25.7	0.1	0.955	24.2	0.1	1.0	
P/S	1.569	42.1	0.4	1.956	77.2	2.3	0.2 *	
S/P	0.718	30.5	0.0	0.759	47.9	0.1	0.4	X
P/Zn	0.148	27.3	0.0	0.161	22.3	0.0	1.3	
Zn/P	7.221	27.2	3.9	6.477	20.1	1.7	2.3	X
K/Ca	1.301	105.6	1.9	1.489	103.3	2.4	0.8	X
Ca/K	1.116	36.3	0.2	1.106	47.7	0.3	0.6	
K/Mg	6.496	38.0	6.1	6.571	36.7	5.8	1.0	X
Mg/K	0.172	30.8	0.0	0.172	35.3	0.0	0.8	
K/S	8.350	51.2	18.3	11.414	77.0	77.2	0.2 *	
S/K	0.141	33.8	0.0	0.132	49.8	0.0	0.5	X
K/Zn	0.813	31.5	0.1	0.932	26.2	0.1	1.1	
Zn/K	1.358	32.5	0.2	1.159	30.5	0.1	1.6	X
Ca/Mg	6.489	32.6	4.5	6.153	32.4	4.0	1.1	X
Mg/Ca	0.182	56.6	0.0	0.197	59.9	0.0	0.8	
Ca/S	8.128	34.4	7.8	6.747	21.6	2.1	3.7	
S/Ca	0.142	45.8	0.0	0.155	21.7	0.0	3.7	X
Ca/Zn	0.831	32.2	0.1	0.930	39.6	0.1	0.5	
Zn/Ca	1.490	69.3	1.1	1.449	77.2	1.3	0.9	X
Mg/S	1.325	28.1	0.1	1.489	38.6	0.3	0.4	
S/Mg	0.816	29.1	0.1	0.759	33.5	0.1	0.9	X
S/Zn	0.102	34.7	0.0	0.107	39.5	0.0	0.7	X
Zn/S	10.979	32.2	12.5	11.320	50.1	32.2	0.4	
Zn/Mg	8.305	35.1	8.5	6.955	16.4	1.3	6.6 **	X
Mg/Zn	0.132	27.2	0.0	0.147	16.3	0.0	2.3 **	

N, P, K, Ca, Mg, S (g kg^{-1}); Zn and Mn (mgkg^{-1})

Variance of nutrient ratios of low and high-yielding groups are significantly different at 1% (***), 5 % (**) and 10 % (*) level of probability by Levene's test.

The negative indices observed with these nutrients support identification of some deficiencies as observed in the leaves according to the CVM.

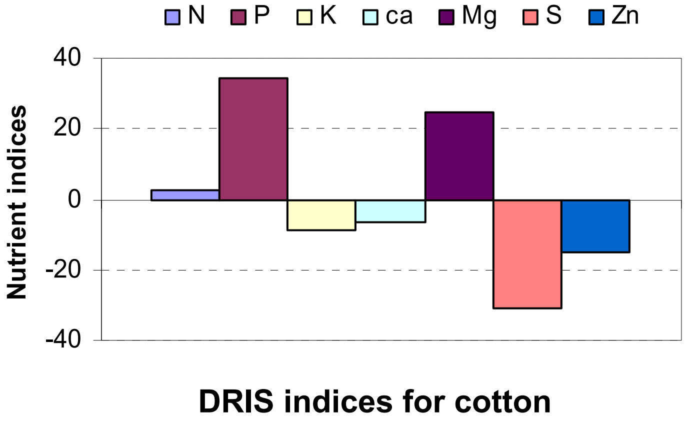


Figure 28: DRIS indices for cotton in farming system in Upper Oueme catchment of Benin (on-farm experiment, 2001).

There is a good nutrient balance for N, K, Ca and Mg according to (Kelling and Schulte,1986) because the DRIS indices of these nutrients are between -15 and +15. This approach which took into account the interaction between nutrients did not show similar result with the CVM. According to the values set by these authors, a slight deficiency was observed with Zn whereas S showed a strong deficiency. So, the S content in the leaves could be limiting yield.

These norms, provisionally established for cotton in this work, could possibly be used as a basis for a calibration of the fertilization programs of cotton, which should subsequently be validated by farmers and organizations involved in this production.

3.2.3. Groundnut Nutritional Assessment

The cut-off point between these two sub-populations was 0.92 t ha^{-1} in 2001 and 1.49 t ha^{-1} in 2002. The yield of groundnut have been divided into high-yielding sub-population ranged from 0.93 and 1.86 t ha^{-1} in the high- yielding sub-population, and in the low- yielding sub-population from 0.35 to 0.92 t ha^{-1} in the first year. In 2002, it was from 1.51 up to 2.21 t ha^{-1} in the low- yielding, and between 0.26 and 1.48 t ha^{-1} in the high- yield sub-population. The difference between these two sub-populations for yield was highly significant (p = 0.001) in both years.

3.2.3.1. Nutrient status assessment using Critical Value Method (CVM) for groundnut

The average foliar N contents in the first year and K, Ca, S concentrations in both years were higher in the high-yielding sub-population than in the low-yielding sub-population, with the means being significantly higher ($p < 0.01$). So, higher nutrient contents were observed in the high- yielding sub-population. Only the Mg content was significantly higher in the low- yielding sub-population ($p = 0.006$) in the first year.

Leaf N, P and K nutrient levels in our experiments were lower in both years, or at least at the lower limit of the critical levels published by Kang (1980) (Tables 26 and 27). Ca, Mg, Zn, and Mn contents ranked between the critical levels. In summary, all macronutrient levels (N, P and K) seemed to be inadequate. So it could be concluded that a deficiency in macronutrients was observed in the leaves of groundnut at the flowering period of growth according to the critical value method (CVM) during both years of the experiment.

Table 26: Means, coefficient of variation (CV) and variance (VAR) of nutrient contents of leaves of groundnut for the low- and high-yielding sub-populations of grain of groundnut in 2001

Parameters	Low- yielding sub-population [n=31			High- yielding sub-population [n=9]			Ratio of variance
	Mean	CV	VAR	Mean	CV	VAR	
Grain [t ha^{-1}]	0.64	28.4	33187.0	1.36	23.7	77328.0	0.4
Nutrients [g kg^{-1}]							
N	28.8	19.7	32.2	35.7	3.6	0.8	39.8
P	2.2	14.0	0.1	2.0	16.2	0.1	1.0
K	20.6	23.1	22.7	22.6	12.1	8.5	2.7
Ca	11.6	54.0	39.3	18.1	9.4	1.9	20.2
Mg	7.8	74.7	33.7	4.4	13.6	0.3	115.0
S	1.1	27.9	0.1	1.5	6.8	0.0	9.1
Zn[mg kg^{-1}]	27.6	34.6	90.9	24.0	26.8	44.9	2.0

Table 27: Means, coefficient of variation (CV) and variance (VAR) of nutrient contents of leaves of groundnut for the low- and high-yielding sub-populations of grain of groundnut in 2002 and published critical levels

Parameters	Low- yielding sub-population [n=28]			High- yielding sub-population [n=24]			Ratio of variance	Critical Values (1)
	Mean	CV	VAR	Mean	CV	VAR		
Grain [t ha^{-1}]	0.96	36.4	123267.4	1.80	9.3	27863.1	4.4	
Nutrients [g kg^{-1}]								
N	33.6	15.2	26.0	35.3	6.1	4.7	5.5	35 - 45
P	2.1	26.9	0.3	2.0	9.9	0.0	8.8	2.5 - 5
K	20.2	23.4	22.4	25.1	22.8	32.9	0.7	20 - 30
Ca	15.1	36.2	29.9	18.0	10.8	3.8	7.9	12.5 - 20
Mg	4.0	29.7	1.4	3.9	15.3	0.3	4.1	3 - 8
S	1.3	19.7	0.1	1.5	13.4	0.0	1.6	-
Nutrients [mg kg^{-1}]								
Zn	28.3	32.5	84.5	27.3	25.3	47.7	1.8	20 - 50
Mn	122.2	67.2	6752.2	116.8	47.7	3105.0	2.2	50 - 350

(1) (Kang 1980)

3.2.3.2. Nutrient status assessment using Diagnosis Regulated Integrated System (DRIS) for groundnut

The choice of a ratio among the pair of nutrient ratios for DRIS norms was given in the last column of tables 26 and 27. Some pairs of ratios with a high variance (Mg/N, P/Ca, Mg/P, K/Ca, Mg/K, Mg/Ca, Zn/Ca, Mg/S and Mg/Zn) in the first year and (P/N, N/Ca, N/S, P/Ca, P/Mg, P/S, P/Mn and S/Ca) in the second year were observed due to the low variance found for the high-yielding sub-population. This situation may be due either to the low number of observations found in the high- yielding sub-population after the separation of population into sub-populations, or to the high variability found in the ratios of nutrient content of the low- sub-population. However, low coefficients of variation were observed with high pairs of ratios of variance in the high-yielding sub-population whereas it was high in the low-yielding sub-population (Tables 28 and 29). According to Bailey *et al.* (1997), DRIS norms with a large ratio of variance and small coefficient of variation imply that the balance between these specific pairs of nutrients could be of critical importance for crop production. Therefore, nutrient ratios with a large ratio of variance and small coefficient of variation indicate that the high yields should be associated to a small variation around the average nutrient ratio. Nine out of the twenty one in the first year and eighteen out off the twenty eight nutrient ratios selected as DRIS norms showed statistically significant differences between variance values in the low- and high- yielding groups (Tables 28 and 29). Eighteen in the first year and 23 in the second year of the selected ratios showed variance ratios above 2.

The most limiting nutrient was Mg and P in the 2001 and P followed by Mg and N in 2002 (Figure.29). It means that the supply of these nutrients through organic or mineral fertilizers in both years was inadequate. Therefore, although K was not applied during both years of experiment, this element seemed not to be among the factors limiting groundnut productivity in the project area. A rather good nutrient balance was observed for all other nutrients during the two years of the experiment.

The indices of Ca in 2001 and Zn in 2002 were very close to zero indicating that these nutrients were adequately supplied. According to CVs set by Kelling and Schulte (1986), there was no deficiency in both years.

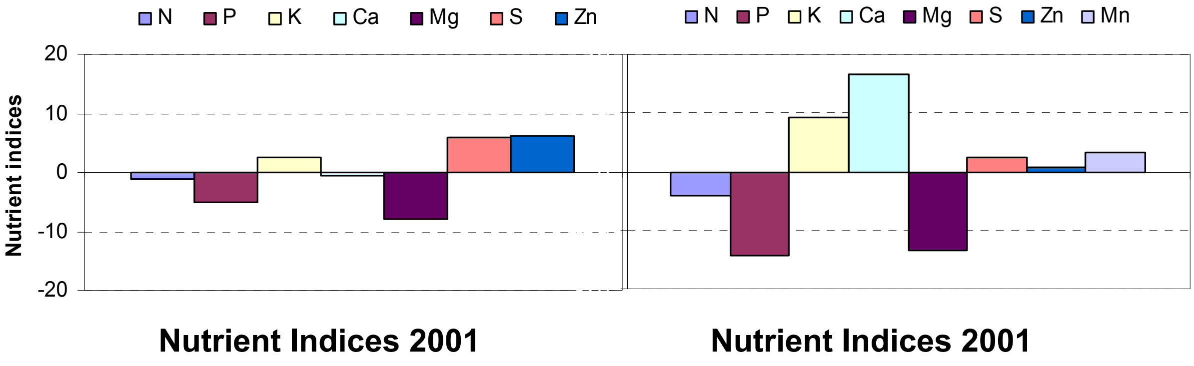


Figure 29: DRIS indices for groundnut in farming system in Upper Oueme catchment of Benin (on-farm experiment, 2001-2002).

The Nutritional Balance Index (NBI) was 29.4 in the first year and increased in the second year (64.0). So, the intensity of imbalances among nutrients seemed to be slightly higher in the second year. This could be due to either the different amount of ratios and nutrients considered in both years, and thus the imbalance could have been lower than suggested by the mere figure

Table 28: Mean, coefficient of variation (CV) and variance (VAR) of ratio for pairs of nutrient of low- and high-yielding sub-populations of groundnut in 2001, ratio of variance and selected ratio between a pair of ratio of nutrient.

Parameters	**Low- yielding sub-population [n=31]**			**High- yielding sub-population [n=9]**			**Ratio**	**Selected**
	Mean	**CV**	**VAR**	**Mean**	**CV**	**VAR**	**Variance**	**Ratio**
N/P	13.947	19.2	7.2	11.404	96.1	120.1	0.1	
P/N	0.074	19.3	0.0	0.049	11.9	0.0	6.0	X
N/K	1.502	22.6	0.1	0.950	95.2	0.8	0.1	
K/N	0.695	20.2	0.0	0.587	6.3	0.0	14.2 **	X
N/Ca	4.665	92.7	18.7	1.185	95.7	1.3	14.5	
Ca/N	0.369	50.7	0.0	0.472	9.1	0.0	19.0 *	X
N/Mg	5.954	54.2	10.4	4.889	96.1	22.1	0.5	
Mg/N	0.294	87.7	0.1	0.115	11.1	0.0	409.7	X
N/S	26.620	21.8	33.7	23.585	8.9	4.4	7.7	X
S/N	0.039	18.6	0.0	0.043	9.0	0.0	3.6	
N/Zn	1.191	37.2	0.2	1.614	26.2	0.2	1.1	X
Zn/N	0.910	25.2	0.1	0.674	38.9	0.1	0.8	
P/K	0.110	26.4	0.0	0.089	14.7	0.0	5.0	X
K/P	9.583	22.3	4.6	11.440	14.7	2.8	1.6	
P/Ca	0.394	112.8	0.2	0.110	8.4	0.0	2280.0 *	X
Ca/P	5.506	59.5	10.7	9.142	8.8	0.7	16.5 ***	
P/Mg	0.417	54.0	0.1	0.454	12.1	0.0	16.8 ***	
Mg/P	3.674	73.4	7.3	2.227	11.0	0.1	121.1 **	X
P/S	1.957	30.9	0.4	1.160	13.7	0.0	14.4	X
S/P	0.550	24.3	0.0	0.728	50.9	0.1	0.1	
P/Zn	0.090	45.1	0.0	0.086	18.2	0.0	6.7	X
Zn/P	13.027	41.2	28.8	12.104	26.0	9.9	2.9	
K/Ca	3.297	96.2	10.1	1.250	10.6	0.0	570.9 *	X
Ca/K	0.564	57.5	0.1	0.808	10.8	0.0	13.7 ***	
K/Mg	4.010	53.5	4.6	5.191	18.3	0.9	5.2 **	
Mg/K	0.423	86.3	0.1	0.198	17.3	0.0	114.0 *	X
K/S	18.253	32.3	34.8	13.801	7.5	1.1	32.8	X
S/K	0.060	28.6	0.0	0.061	49.5	0.0	0.3	
K/Zn	0.808	28.5	0.1	0.988	22.1	0.0	1.1	
Zn/K	1.353	33.4	0.2	1.089	36.8	0.2	1.3	X
Ca/Mg	2.674	65.3	3.1	4.132	10.1	0.2	17.4 **	
Mg/Ca	2.404	153.3	13.6	0.244	9.3	0.0	26268.5 *	X
Ca/S	8.894	48.2	18.3	11.093	8.6	0.9	20.2 **	
S/Ca	0.181	95.6	0.0	0.076	49.7	0.0	21.2	X
Ca/Zn	0.429	67.1	0.1	0.785	17.9	0.0	4.2	
Zn/Ca	3.962	85.1	11.4	1.328	26.1	0.1	94.6 *	X
Mg/S	8.580	103.6	79.0	2.700	11.4	0.1	830.5	X
S/Mg	0.245	58.9	0.0	0.312	50.3	0.0	0.8 *	
Mg/Zn	0.355	95.7	0.1	0.191	19.3	0.0	84.8 *	X
Zn/Mg	5.440	57.9	9.9	5.470	25.8	2.0	5.0 **	
S/Zn	0.048	48.1	0.0	0.058	58.4	0.0	0.5	
Zn/S	23.971	35.7	73.2	16.048	43.5	48.8	1.5	X

N, P, K, Ca, Mg, S (g kg^{-1}); Zn and Mn (mgkg^{-1})

Variance of nutrient ratios of low and high-yielding groups are significantly different at 1% (***), 5 % (**) and 10 % (*) level of probability by Levene's test.

Table 29: Mean, coefficient of variation (CV) and variance (VAR) of ratio for pairs of nutrient of low- and high-yielding sub-populations of groundnut 2002, ratio of variance and selected ratio between a pair of ratio of nutrient.

Parameters	Low- yielding sub-population [n=28]			High- yielding sub-population [n=24]			Ratio of variance	Selected ratio
	Mean	CV	VAR	Mean	CV	VAR		
N/P	16.930	27.8	22.1	18.042	10.3	3.5	6.4 **	
P/N	0.067	44.8	0.0	0.056	10.5	0.0	25.6 **	X
N/K	1.738	24.9	0.2	1.502	28.5	0.2	1	X
K/N	0.616	27.8	0.0	0.715	25.7	0.0	0.9	
N/Ca	2.994	77.5	5.4	1.990	12.5	0.1	86.5 **	X
Ca/N	0.438	33.4	0.0	0.510	11.9	0.0	5.8 **	
N/Mg	9.080	28.9	6.9	9.265	14.6	1.8	3.7 *	
Mg/N	0.118	26.0	0.0	0.110	14.3	0.0	3.8 **	X
N/S	27.940	56.2	246.7	23.125	12.9	8.9	27.6	X
S/N	0.040	20.9	0.0	0.044	13.1	0.0	2.1	
N/Zn	1.298	29.7	0.1	1.402	30.7	0.2	0.8	
Zn/N	0.849	33.8	0.1	0.776	28.3	0.0	1.7	X
N/Mn	0.457	78.2	0.1	0.366	44.7	0.0	4.8 *	X
Mn/N	3.585	64.8	5.4	3.378	48.0	2.6	2.1	
P/K	0.114	45.6	0.0	0.082	27.3	0.0	5.4 **	X
K/P	10.330	38.3	15.6	12.971	24.8	10.3	1.5	
P/Ca	0.263	142.5	0.1	0.110	16.0	0.0	450.2 **	X
Ca/P	7.883	41.3	10.6	9.298	15.6	2.1	5.1 **	
P/Mg	0.663	82.5	0.3	0.516	14.9	0.0	50.8 *	X
Mg/P	2.054	36.3	0.6	1.981	14.9	0.1	6.4 **	
P/S	2.023	122.3	6.1	1.286	11.3	0.0	288.5	X
S/P	0.667	29.6	0.0	0.787	11.1	0.0	5.1 **	
P/Zn	0.089	65.4	0.0	0.077	28.6	0.0	7.1 *	X
Zn/P	14.466	41.1	35.3	14.081	27.8	15.4	2.3 **	
P/Mn	0.037	126.6	0.0	0.020	40.3	0.0	33.9 **	X
Mn/P	67.212	79.8	2878.6	59.235	44.9	707.3	4.1 **	
K/Ca	1.811	78.7	2.0	1.428	29.6	0.2	11.4	X
Ca/K	0.751	39.6	0.1	0.764	30.3	0.1	1.6	
K/Mg	5.484	33.3	3.3	6.748	31.7	4.6	0.7	
Mg/K	0.202	32.7	0.0	0.164	34.4	0.0	1.4	X
K/S	17.082	63.8	118.9	16.165	19.7	10.1	11.7	X
S/K	0.068	28.8	0.0	0.065	23.1	0.0	1.7	
K/Zn	0.754	21.4	0.0	0.943	19.0	0.0	0.8	
Zn/K	1.392	23.4	0.1	1.098	19.1	0.0	2.4	X
K/Mn	0.262	75.1	0.0	0.256	45.2	0.0	2.9	
Mn/K	5.846	62.6	13.4	4.683	41.0	3.7	3.6 *	X
Ca/Mg	3.647	27.9	1.0	4.757	17.5	0.7	1.5	
Mg/Ca	0.306	41.0	0.0	0.216	17.5	0.0	10.9 **	X
Ca/S	11.476	32.0	13.5	11.819	18.7	4.9	2.8	
S/Ca	0.119	96.4	0.0	0.088	20.7	0.0	40.1	X
Ca/Zn	0.544	40.9	0.0	0.712	32.8	0.1	0.9	
Zn/Ca	2.306	58.2	1.8	1.550	32.0	0.2	7.3 *	X
Ca/Mn	0.161	59.6	0.0	0.192	46.2	0.0	1.2	
Mn/Ca	5.846	62.6	13.4	4.683	41.0	3.7	3.6 *	X
Mg/S	3.204	41.2	1.7	2.542	18.8	0.2	7.6 *	X
S/Mg	0.360	43.7	0.0	0.406	17.7	0.0	4.8	
Mg/Zn	0.148	30.7	0.0	0.151	30.4	0.0	1	X
Zn/Mg	7.331	26.1	3.7	7.220	29.8	4.6	0.8	
Mg/Mn	0.048	61.2	0.0	0.039	39.9	0.0	3.5 *	X
Mn/Mg	30.246	65.2	389.0	30.033	42.8	165.6	2.3	
S/Zn	0.051	36.6	0.0	0.060	25.2	0.0	1.5	
Zn/S	23.110	53.7	154.0	17.532	22.5	15.5	9.9 *	X
S/Mn	0.018	100.6	0.0	0.015	36.7	0.0	10.8 *	X
Mn/S	93.518	61.4	3295.1	74.685	39.3	860.3	3.8 ***	
Zn/Mn	0.345	64.8	0.0	0.269	41.4	0.0	4.0 **	
Mn/Zn	4.319	68.3	8.7	4.228	33.7	2.0	4.3 *	X

N, P, K, Ca, Mg, S (g kg^{-1}); Zn and Mn (mgkg^{-1})

Variance of nutrient ratios of low and high-yielding groups are significantly different at 1% (***), 5 % (**) and 10 % (*) level of probability by Levene's test.

3.3.4. Sorghum Nutritional Assessment

DRIS norms have so far not been developed for sorghum and thus cannot be compared to literature data.

The cut-off point between the high- and low-yielding plant sub-populations was set to 1.61 t ha^{-1} in 2001 and 1.22 t ha^{-1} in 2002. The grain yield of sorghum ranked in the high-yielding sub-population between 1.63 and 3.42 t·ha^{-1} , and in the low-yielding sub-population between 0.30 and 1.59 t·ha^{-1} in 2001, and between 1.28 t ha^{-1} and 2.45 t $ha^{-1}$for the high-yielding, and 0.04 and 1.21 t ha^{-1} for the low-yielding sub-population in 2002.

3.3.4.1. Nutrient status assessment using Critical Value Method (CVM) for sorghum

Critical levels of nutrients reported by Kang (1980) and FAO (2000) are similar, and will accordingly be compared to the own data below.

The mean contents of the samples were similar for both years of the experiment. Leaf N, P, K, Ca and Mg levels for the two years were close to or even below the deficiency limit published by Kang (1980). The micronutrients Zn or Mn ranged between the critical values reported by FAO (2000) and Kang (1980). In summary, all nutrient levels except the micronutrients could be considered as inadequate (Tables 30 and 31). So it could be concluded that according to the critical value method (CVM), a deficiency in macronutrients was observed in sorghum at the flowering period for both years of the experiment.

Average foliar N and K concentrations were significantly higher in the low-yielding sub-population ($p = 0.006$ for N and $p = 0.000$ for K) in 2001, while Ca and Mg were significantly lower in the low-yielding sub-population ($p = 0.000$ for Ca and $p = 0.036$ for Mg) in the same year (Table 30).

Furthermore, foliar average Ca nutrient concentration in the leaves were higher in the low-yielding group than in the high-yielding sub-population and S lower in the low-yielding group than in the high-yielding group at significance levels of $p = 0.000$ for Ca and $p = 0.023$ for S in 2002 (Table 31).

Table 30: Mean, coefficient of variation (CV), variance (VAR) and ratio of variance of nutrient contents of sorghum leaves for the low- and high-yielding sub-populations of sorghum grain in 2001

Parameters	Low-yielding sub-population [n=26]			High-yielding sub-population [n=19]			Ratio of variance
	Mean	CV	VAR	Mean	CV	VAR	
Grain [t ha^{-1}]	9.14	46.5	180750.0	2.20	26.8	348474.5	0.5
Nutrients [g kg^{-1}]							
N	17.0	16.8	8.1	16.3	18.6	9.2	0.9
P	2.8	21.0	0.4	2.6	31.7	0.7	0.5
K	12.3	21.0	6.7	10.8	16.9	3.3	2.0
Ca	3.4	21.5	0.5	3.9	18.5	0.5	1.0
Mg	2.3	15.5	0.1	2.5	15.5	0.1	0.9
S	0.8	39.6	0.1	0.7	70.8	0.2	0.4
Zn [mg kg^{-1}]	22.0	14.4	10.0	21.7	12.4	7.3	1.4

Table 31: Mean, coefficient of variation (CV), variance (VAR) and ratio of variance of nutrient contents of sorghum leaves for the low- and high-yielding sub-populations of sorghum grain in 2002 and published critical levels.

Parameters	Low-yielding sub-population [n=37]			High-yielding sub-population [n=19]			Ratio of variance	Critical levels (1)	Critical Levels (2)
	Mean	CV	VAR	Mean	CV	VAR			
Grain [t ha^{-1}]	0.63	52.0	107698.2	1.84	25.8	226665.2	0.5	-	
Nutrients [g kg^{-1}]									
N	16.6	19.0	9.9	17.2	9.9	2.9	3.4	32 - 44	33 - 40
P	2.4	22.6	0.3	2.6	15.4	0.2	1.8	2 - 6	2 - 3.5
K	12.6	21.1	7.1	13.0	17.9	5.4	1.3	15	14 -17
Ca	4.6	20.5	0.9	3.7	17.5	0.4	2.1	-	3 - 6
Mg	2.9	21.3	0.4	2.7	22.4	0.4	1.0	3.5 - 5	2 - 5
S	0.9	21.4	0.0	1.0	26.6	0.1	0.6	-	-
Nutrients [mg kg^{-1}]									
Zn	24.2	17.0	17.1	24.3	16.7	16.4	1.0	7 - 10	15 - 30
Mn	57.5	41.3	564.0	53.6	43.3	538.3	1.0	40 - 60	8 - 190

(1) (FAO 2000)

(2) (Kang 1980)

3.3.4.2. Nutrient status assessment using Diagnosis Regulated Integrated System (DRIS) for sorghum

Among the variance ratios used as DRIS norms, there were 21 and 28 ratios respectively in 2001 in 2002 which were highly significant between sub-populations. The choice of ratio among the pairs of nutrient ratios for DRIS norms is given in the last column of tables 32 and 33.

Some of the nutrient ratios selected as DRIS norms (K/N, N/Zn, Zn/N, Mg/P, K/Ca and Zn/Ca) in 2001 and (N/P, Ca/N, Mg/N, Ca/P, Mg/P, P/S, Zn/P, Ca/K, Mg/K, Zn/K, Ca/S, Mg/S, Mg/Mn and Zn/S) in 2002 showed significant differences between their mean values in low-and high-yielding groups. When there were no differences of nutritional balance between the low-and high-yielding groups, it is likely that the yield differences between the groups were not caused by a nutritional effect; and the DRIS norms developed under this situation probably will not produce a reliable diagnosis. From the selected ratios of variance of the DRIS norms, only three in the first year, and 17 in the second year were greater than 2.

The most limiting nutrients were N, P, K, and (slightly) Zn in the first year and Mg followed by Mn and Ca in the second year. It means that there was an inadequate supply of N, P and K in the first year (Figure 30). The deficiency observed with N and K was in agreement with those of CVM where inadequate concentrations of N, P and K in the leaves of sorghum were found. The deficiency observed in the first year can be related to the low available nutrient levels in the soil, and as the amount of the mineral of fertilizer and low nutrient levels in the applied organic matter probably prevented higher yields, Otherwise, one would have expected a more pronounced difference between the low and the high yielding (mostly fertilized) sub-population.

In the northern Benin, sorghum is cultivated before fallowing or on poor soil. So the soil is depleted in nutrients before growing sorghum. However, when interpreted according to Kelling and Schulte (1986), a possible deficiency was observed only with Mg in 2001. Otherwise, a good balance was found for all other nutrients. It might as well indicate that the nutrients most limiting yield have not been addressed in our DRIS evaluation and thus cannot be reflected by this method.

Table 32: Mean, coefficient of variation (CV) and variance of ratio (VAR) for pairs of nutrient of low- and high-yielding sub-populations of sorghum in 2001, ratio of variance and selected ratios.

Parameters	Low- yielding sub-population [n=14]			High- yielding sub-population [n=26]			Ratio of Variance	Select ratio
	Mean	CV	VAR	Mean	CV	VAR		
N/P	6.217	22.5	2.0	6.592	22.1	2.1	0.9	X
P/N	0.172	34.4	0.0	0.166	44.0	0.0	0.7	
N/K	1.402	11.5	0.0	1.540	23.9	0.1	0.2 ***	
K/N	0.722	11.5	0.0	0.684	23.2	0.0	0.3 ***	X
N/Ca	5.417	33.2	3.2	4.406	33.8	2.2	1.5	
Ca/N	0.208	37.8	0.0	0.251	32.6	0.0	0.9	X
N/Mg	7.656	23.7	3.3	6.834	28.1	3.7	0.9	X
Mg/N	0.139	28.9	0.0	0.157	29.4	0.0	0.8	
N/S	23.817	31.6	56.6	21.048	28.7	36.4	1.6	X
S/N	0.046	32.7	0.0	0.051	28.8	0.0	1.1	
N/Zn	0.777	12.9	0.0	0.757	20.5	0.0	0.4 *	X
Zn/N	1.308	13.0	0.0	1.374	20.7	0.1	0.4 *	
P/K	0.242	36.4	0.0	0.247	33.0	0.0	1.2	X
K/P	4.501	26.3	1.4	4.445	31.0	1.9	0.7	
P/Ca	0.878	27.9	0.1	0.684	30.1	0.0	1.4	X
Ca/P	1.220	26.1	0.1	1.580	28.0	0.2	0.5	
P/Mg	1.246	16.0	0.0	1.069	26.6	0.1	0.5	X
Mg/P	0.822	15.6	0.0	0.998	26.3	0.1	0.2 **	
P/S	4.035	44.0	3.2	3.702	54.6	4.1	0.8	X
S/P	0.288	36.0	0.0	0.326	37.5	0.0	0.7	
P/Zn	0.132	30.9	0.0	0.120	27.5	0.0	1.5	X
Zn/P	8.018	20.3	2.6	8.826	23.8	4.4	0.6	
K/Ca	3.923	34.7	1.9	2.884	27.3	0.6	3.0 *	X
Ca/K	0.294	41.8	0.0	0.369	24.3	0.0	1.9	
K/Mg	5.569	28.6	2.5	4.522	24.8	1.3	2	X
Mg/K	0.197	33.5	0.0	0.234	24.2	0.0	1.4	
K/S	17.450	31.9	31.0	14.896	45.5	45.9	0.7	X
S/K	0.064	35.3	0.0	0.081	42.8	0.0	0.4	
K/Zn	0.562	17.8	0.0	0.500	15.3	0.0	1.7	X
Zn/K	1.835	17.5	0.1	2.040	14.4	0.1	1.2	
Ca/Mg	1.487	21.0	0.1	1.586	13.2	0.0	2.2	
Mg/Ca	0.708	25.8	0.0	0.640	12.4	0.0	5.3	X
Ca/S	5.038	57.1	8.3	5.363	51.6	7.6	1.1	
S/Ca	0.271	58.7	0.0	0.244	55.5	0.0	1.4	X
Ca/Zn	0.157	31.8	0.0	0.180	18.4	0.0	2.3	
Zn/Ca	6.913	28.5	3.9	5.733	18.6	1.1	3.4 *	X
Mg/S	3.277	47.1	2.4	3.305	48.1	2.5	0.9	X
S/Mg	0.359	36.2	0.0	0.379	50.2	0.0	0.5	
Mg/Zn	0.107	25.3	0.0	0.114	18.8	0.0	1.6	
Zn/Mg	9.888	22.6	5.0	9.023	18.4	2.8	1.8	X
S/Zn	0.036	38.5	0.0	0.039	41.5	0.0	0.7	
Zn/S	31.750	39.7	158.6	29.554	38.4	128.5	1.2	X

N, P, K, Ca, Mg, S (g kg^{-1}); Zn and Mn (mgkg^{-1}) Variance of nutrient ratios of low and high-yielding groups are significantly different at 1% (***), 5 % (**) and 10 % (*) level of probability by Levene's test.

Table 33: Mean, coefficient of variation (CV) and variance (VAR) of ratio for pairs of nutrient of low- and high-yielding sub-populations of sorghum in 2002, ratio of variance and selected ratios.

Parameters	Low- yielding sub-population [n=37]			High- yielding sub-population [n=19]			Ratio of	Select
	Mean	CV	VAR	Mean	CV	VAR	variance	Ratio
N/P	7.156	26.3	3.6	6.613	10.5	0.5	7.4 ***	X
P/N	0.149	24.6	0.0	0.153	10.7	0.0	5.0 ***	
N/K	1.367	27.9	0.1	1.358	17.3	0.1	2.6	X
K/N	0.777	22.8	0.0	0.754	14.6	0.0	2.6	
N/Ca	3.855	34.2	1.7	4.774	21.9	1.1	1.6	
Ca/N	0.291	36.3	0.0	0.220	24.8	0.0	3.7 **	X
N/Mg	6.048	34.1	4.3	6.521	21.5	2.0	2.2 *	
Mg/N	0.185	35.3	0.0	0.160	20.0	0.0	4.2 **	X
N/S	17.893	20.1	13.0	16.506	9.4	2.4	5.4	X
S/N	0.058	18.9	0.0	0.061	9.6	0.0	3.5	
N/Zn	0.700	22.0	0.0	0.721	14.9	0.0	2.1	
Zn/N	1.506	25.5	0.1	1.415	14.5	0.0	3.5	X
N/Mn	0.332	39.3	0.0	0.383	43.6	0.0	0.6	
Mn/N	3.605	47.0	2.9	3.186	48.9	2.4	1.2	X
P/K	0.197	26.4	0.0	0.207	17.8	0.0	2	
K/P	5.406	25.9	2.0	4.975	17.0	0.7	2.7	X
P/Ca	0.565	39.4	0.0	0.732	24.6	0.0	1.5	
Ca/P	2.043	38.5	0.6	1.469	33.4	0.2	2.6 **	X
P/Mg	0.870	32.0	0.1	0.986	18.2	0.0	2.4 **	
Mg/P	1.287	37.2	0.2	1.045	17.4	0.0	6.9 **	X
P/S	2.595	21.5	0.3	2.538	14.1	0.1	2.4 *	X
S/P	0.404	22.8	0.0	0.402	15.6	0.0	2.2	
P/Zn	0.102	28.2	0.0	0.110	19.1	0.0	1.9	
Zn/P	10.580	30.0	10.1	9.360	17.5	2.7	3.8 **	X
P/Mn	0.005	52.3	0.0	0.006	46.2	0.0	0.9	
Mn/P	26.408	60.1	252.1	21.426	53.1	129.4	1.9	X
K/Ca	2.947	38.3	1.3	3.644	29.7	1.2	1.1	
Ca/K	0.388	35.2	0.0	0.304	38.4	0.0	1.4 *	X
K/Mg	4.525	32.4	2.2	4.871	21.8	1.1	1.9	
Mg/K	0.242	28.6	0.0	0.215	21.3	0.0	2.3 *	X
K/S	13.713	24.3	11.1	12.714	15.5	3.9	2.9 **	
S/K	0.078	30.2	0.0	0.081	16.6	0.0	3.1	X
K/Zn	0.525	18.7	0.0	0.536	12.1	0.0	2.3 *	
Zn/K	1.975	20.3	0.2	1.892	12.0	0.1	3.1 *	X
K/Mn	0.253	40.6	0.0	0.284	42.7	0.0	0.7	
Mn/K	4.810	49.6	5.7	4.232	45.2	3.7	1.6	X
Ca/Mg	1.609	22.2	0.1	1.419	29.8	0.2	0.7	
Mg/Ca	0.654	23.9	0.0	0.752	23.4	0.0	0.8	X
Ca/S	5.104	36.1	3.4	3.573	21.9	0.6	5.5 **	X
S/Ca	0.218	31.5	0.0	0.291	19.3	0.0	1.5	
Ca/Zn	0.195	27.1	0.0	0.159	30.1	0.0	1.2	X
Zn/Ca	5.560	30.1	2.8	6.760	26.0	3.1	0.9	
Ca/Mn	0.089	38.8	0.0	0.082	44.7	0.0	0.9	X
Mn/Ca	12.680	34.9	19.6	14.755	45.4	44.9	0.4 *	
Mg/S	3.225	33.2	1.1	2.694	21.2	0.3	3.5 *	X
S/Mg	0.340	29.6	0.0	0.387	21.3	0.0	1.5	
Mg/Zn	0.123	23.8	0.0	0.115	23.2	0.0	1.2	X
Zn/Mg	8.618	24.7	4.5	9.168	22.5	4.2	1.1	
Mg/Mn	0.057	36.0	0.0	0.061	49.7	0.0	0.4 *	X
Mn/Mg	19.804	33.2	43.1	20.610	49.4	103.7	0.4 *	
S/Zn	0.040	29.8	0.0	0.043	14.9	0.0	3.5	
Zn/S	26.670	27.0	52.0	23.698	14.9	12.5	4.1 **	X
S/Mn	0.019	53.4	0.0	0.022	41.0	0.0	1.3	
Mn/S	63.981	46.4	880.5	53.047	42.7	512.6	1.7	X
Zn/Mn	0.472	31.2	0.0	0.540	47.0	0.1	0.3 ***	
Mn/Zn	2.392	42.2	1.0	2.268	45.5	1.1	1	X

N, P, K, Ca, Mg, S (g kg^{-1}); Zn and Mn (mgkg^{-1}) Variance of nutrient ratios of low and high-yielding groups are significantly different at 1% (***), 5 % (**) and 10 % (*) level of probability by Levene’s test.

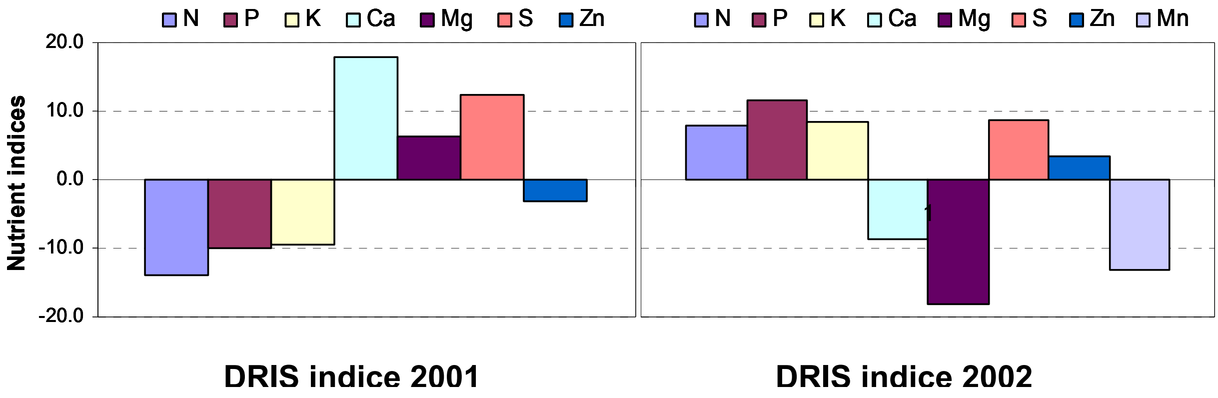


Figure 30: DRIS indices for sorghum in farming system in Upper Oueme catchment of Benin (on-farm experiment, 2001-2002).

In the second year of experiment, there was an accumulation of N, P, and K in the leaves due to the combined effect of previous organic matter and those of 2002, mineral fertilizer and the mixed mineral and organic fertilizers applied in 2001 and 2002. The plots did not change in the second year, only the crop was changed. For example, there were 5 out of 14 of observations with farmer's practice, with 9 out of 14 organic matter application, mineral fertilizer alone or in combination with OM in the low yielding sub-population, while there were 5 out of 26 observations with farmer's practice, 9 out of14 where only organic matter application, mineral fertilizer, or the combination of both were represented in the high- yielding sub-population in 2001. In 2002, the low-yielding sub-population was composed by 10 out of 37 plots with farmer's practice, and 27 out of 37 with application of either organic matter, mineral fertilizer, or the combination of both, whereas for the high- yielding sub-population the corresponding ratios were 4/19 observations with farmer's practice, and 15 out of 19 with organic matter, mineral fertilizer, or the combination of both.

The Nutritional Balance Index (NBI) was 73.4 in the first year and was not substantially changed (80.2) for the second year.

3.2.5. Yam Nutritional Assessment

DRIS norms for yam have not yet been developed. We thus separated the entire data set into two sub-populations on the basis of a cut-off yield set at 4.50 t ha^{-1} in the first year and 4.29 t ha^{-1} in the second year.

The dry matter tuber yields of the high- yielding sub-population ranged between 4.57 and 7.32 t ha^{-1}, whereas it was 1.21 up to 4.45 t ha^{-1} for the low- yielding one in the first year. In the second year, values ranged between 0.45 t ha^{-1} and 4.17 t ha^{-1} for the low- yielding sub-population and between 4.50 t ha^{-1} and 12.50 t ha^{-1} for the high- yielding sub-population.

3.2.5.1. Nutrient status assessment using Critical Value Method (CVM) for yam

N and P were higher concentrated in the low- yielding group than in the high-yielding subpopulation, whereas K, Ca, Mg, S, and Zn were higher in the high-yielding group in the first year (Tables 34 and 35).

Foliar average K, Ca, and S concentrations were higher in the high- yielding group than in the low-yielding sub-population in 2002. Only the means of these nutrients in 2002 were significantly higher (p = 0.025 for K, p = 0.000 for Ca) in the high-yielding sub-population than in the low- yielding sub-population.

Table 34: Mean, coefficient of variation (CV), variance (VAR) and ratio of variance of nutrient contents of leaves of yam for the low and high yielding sub-populations of tuber of yam in 2001

Parameters	**Low- yielding subpopulation [n=31]**			**High- yielding subpopulation [n=24]**			**Ratio of variance**
	Mean	**CV**	**VAR**	**Mean**	**CV**	**VAR**	
Tuber [t ha^{-1}]	2.96	32.3	913363.7	5.55	13.0	523479.6	1.7
Nutrients [g kg^{-1}]							
N	22.4	42.2	89.3	20.6	49.7	104.9	0.9
P	2.0	31.7	0.4	1.9	24.3	0.2	1.9
K	17.6	26.9	22.5	17.8	24.9	19.7	1.1
Ca	14.2	38.2	29.5	15.3	31.3	22.9	1.3
Mg	4.1	43.6	3.2	4.6	29.0	1.8	1.8
S	1.2	61.9	0.5	1.3	74.6	1.0	0.5
Zn [mg kg^{-1}]	21.2	17.8	14.3	22.7	31.0	49.8	0.3

Table 35: Mean, coefficient of variation (CV), variance (VAR) and ratio of variance of nutrient contents of leaves of yam for the low and high yielding sub-populations of tuber of yam in 2002 and published critical levels.

Parameters	Low- yielding subpopulation [n=48]			High- yielding subpopulation [n=24]			Ratio of variance
	Mean	CV	VAR	Mean	CV	VAR	
Tuber [t ha^{-1}]	2.32	45.1	1097884.1	6.5	36.2	5482437.6	0.2
Nutrients [g kg^{-1}]							
N	24.7	18.7	21.4	23.8	9.9	5.6	3.8
P	1.8	17.4	0.1	1.9	27.5	0.3	0.3
K	19.6	17.0	11.1	22.3	23.2	26.7	0.4
Ca	13.7	18.8	6.6	16.8	18.3	9.4	0.7
Mg	3.6	23.4	0.7	3.8	21.3	0.6	1.1
S	1.5	21.3	0.1	1.5	18.4	0.1	1.4
Nutrients [g kg^{-1}]							
Zn	26.3	28.6	56.8	26.8	18.4	24.4	2.3
Mn	201.0	52.1	10980.6	295.9	45.6	18241.0	0.6

3.2.5.2. Nutrient status assessment using Diagnosis Regulated Integrated System (DRIS) for yam

Twenty one ratios were used as DRIS norms in the 2001 and 28 in 2002 which showed the highest ratios. These norms established were used for the calculation of nutrient indices. The choice of a ratio among the pair of nutriments ratio for DRIS norms is given in the last column of each table (36. and 37).

Some of the nutrient ratios selected as DRIS norms (N/Mg, P/K, P/S, K/Mg and Mg/Ca) in 2001 and (S/N, N/Zn, N/Mn, K/P, S/P, P/Mn, Zn/K, Mg/Ca, Zn/Ca, Ca/Mn, Mg/Mn, and S/Mn) in 2002 showed significant differences between the means of the low- and high-yielding groups.

Ten out of the 21 in the first year and 9 out of 28 the second year of selected ratios as DRIS norms had a ratio greater than two. Therefore, 11 out of 21 of the selected ratios in 2001 and 19 out of 28 in 2002 were lower than two.

Table 36: Mean, coefficient of variation (CV) and variance (VAR) of ratio f pairs of nutrient of low- and high-yielding sub-populations of yam in 2001, ratio of variance and selected ratio between a pair of ratio of nutrient.

Parameters	Low- yielding sub-population [n=31]			High- yielding sub-population [n=24]			Ratio of variance	Selected ratio
	Mean	CV	VAR	Mean	CV	VAR		
N/P	14.052	36.1	25.7	14.213	27.3	15.1	1.7	X
P/N	0.080	33.8	0.0	0.076	31.1	0.0	1.3	
N/K	1.540	35.1	0.3	1.554	36.1	0.3	0.9	
K/N	0.730	35.8	0.1	0.731	37.1	0.1	0.9	X
N/Ca	2.660	84.2	5.0	1.833	47.9	0.8	6.5	X
Ca/N	0.538	41.7	0.1	0.626	31.3	0.0	1.3	
N/Mg	8.144	59.2	23.3	6.226	42.2	6.9	3.4 *	X
Mg/N	0.165	56.3	0.0	0.182	33.4	0.0	2.3	
N/S	20.591	51.3	111.5	16.726	36.3	36.8	3	X
S/N	0.059	42.5	0.0	0.071	54.2	0.0	0.4	
N/Zn	1.288	27.8	0.1	1.219	38.3	0.2	0.6	X
Zn/N	0.859	23.0	0.0	0.918	34.9	0.1	0.4 *	
P/K	0.121	34.9	0.0	0.114	26.9	0.0	1.9 **	X
K/P	9.319	35.6	11.0	9.502	29.6	7.9	1.4	
P/Ca	0.224	121.4	0.1	0.145	48.9	0.0	14.6	X
Ca/P	7.964	44.9	12.8	8.431	42.0	12.5	1	
P/Mg	0.674	89.6	0.4	0.474	46.7	0.0	7.5	X
Mg/P	2.305	53.3	1.5	2.493	36.7	0.8	1.8	
P/S	1.771	82.3	2.1	1.211	38.0	0.2	10.0 *	X
S/P	0.805	42.2	0.1	0.908	28.6	0.1	1.7	
P/Zn	0.100	43.8	0.0	0.089	26.0	0.0	3.5	X
Zn/P	11.593	32.9	14.5	11.998	27.6	11.0	1.3	
K/Ca	1.694	79.3	1.8	1.373	54.2	0.6	3.3	X
Ca/K	0.912	58.2	0.3	0.969	56.4	0.3	0.9	
K/Mg	5.508	60.2	11.0	4.476	51.0	5.2	2.1 *	X
Mg/K	0.268	63.5	0.0	0.286	51.1	0.0	1.4	
K/S	14.173	48.0	46.4	11.714	47.0	30.4	1.5	X
S/K	0.088	47.8	0.0	0.104	43.8	0.0	0.9	
K/Zn	0.856	31.7	0.1	0.831	33.0	0.1	1	X
Zn/K	1.291	32.3	0.2	1.364	41.5	0.3	0.5	
Ca/Mg	3.609	32.5	1.4	3.362	17.2	0.3	4.1 **	
Mg/Ca	0.310	36.9	0.0	0.305	16.0	0.0	5.5 **	X
Ca/S	9.449	36.8	12.1	10.602	34.7	13.6	0.9	X
S/Ca	0.119	34.0	0.0	0.121	76.2	0.0	0.2	
Ca/Zn	0.665	34.8	0.1	0.720	39.4	0.1	0.7	
Zn/Ca	1.789	65.2	1.4	1.713	53.6	0.8	1.6	X
Mg/S	2.887	35.8	1.1	3.063	36.5	1.3	0.9	X
S/Mg	0.388	34.0	0.0	0.408	66.2	0.1	0.2	
Mg/Zn	0.194	43.7	0.0	0.213	33.2	0.0	1.4	X
Zn/Mg	5.997	47.7	8.2	5.486	45.3	6.2	1.3	
S/Zn	0.069	35.6	0.0	0.073	29.9	0.0	1.3	X
Zn/S	16.666	44.9	56.1	14.998	50.8	58.2	1	

N, P, K, Ca, Mg, S (g kg^{-1}); Zn and Mn (mgkg^{-1}) Variance of nutrient ratios of low and high-yielding groups are significantly different at 1% (***), 5 % (**) and 10 % (*) level of probability by Levene's test.

Table 37: Mean, coefficient of variation (CV) and variance (VAR) of ratio, for pairs of nutrient of low- and high-yielding sub-populations of yam in 2002, ratio of variance and selected ratio between a pair of ratio of nutrient.

Parameters	Low- yielding sub-population [n=48]			High- yielding sub-population [n=24]			Ratio of variance	Selected ratio
	Mean	CV	VAR	Mean	CV	VAR		
N/P	14.356	24.2	12.0	13.115	23.7	9.6	1.2	X
P/N	0.074	25.0	0.0	0.081	25.3	0.0	0.8	
N/K	1.294	25.2	0.1	1.132	28.7	0.1	1	X
K/N	0.818	23.9	0.0	0.948	26.3	0.1	0.6	
N/Ca	1.867	27.6	0.3	1.486	30.6	0.2	1.3	X
Ca/N	0.570	23.5	0.0	0.710	19.7	0.0	0.9	
N/Mg	7.516	43.0	10.5	6.646	27.6	3.4	3.1	X
Mg/N	0.150	30.6	0.0	0.159	21.6	0.0	1.8	
N/S	16.872	25.4	18.4	17.159	45.1	59.9	0.3	
S/N	0.063	27.8	0.0	0.063	16.5	0.0	2.9 ***	X
N/Zn	1.045	41.9	0.2	0.919	20.5	0.0	5.4 ***	X
Zn/N	1.117	36.6	0.2	1.136	21.7	0.1	2.7 ***	
N/Mn	0.154	47.6	0.0	0.096	41.4	0.0	3.4 ***	X
Mn/N	8.240	48.4	15.9	12.321	42.0	26.8	0.6	
P/K	0.092	19.2	0.0	0.090	35.4	0.0	0.3 **	
K/P	11.295	19.1	4.7	12.232	28.8	12.4	0.4 ***	X
P/Ca	0.133	24.3	0.0	0.116	25.1	0.0	1.2	X
Ca/P	7.945	24.4	3.7	9.129	25.2	5.3	0.7	
P/Mg	0.525	30.3	0.0	0.535	35.6	0.0	0.7	X
Mg/P	2.060	27.1	0.3	2.095	34.3	0.5	0.6	
P/S	1.192	20.4	0.1	1.372	46.1	0.4	0.1 **	
S/P	0.869	18.4	0.0	0.821	30.3	0.1	0.4 *	X
P/Zn	0.071	26.3	0.0	0.072	22.2	0.0	1.4	
Zn/P	14.960	26.5	15.7	14.530	22.4	10.6	1.5	X
P/Mn	0.011	48.3	0.0	0.008	45.5	0.0	2.3 *	X
Mn/P	116.037	55.4	4136.7	162.782	52.0	7166.5	0.6	
K/Ca	1.488	26.3	0.2	1.373	29.3	0.2	0.9	X
Ca/K	0.721	27.7	0.0	0.787	28.5	0.1	0.8	
K/Mg	5.870	34.1	4.0	6.261	36.2	5.1	0.8	
Mg/K	0.187	31.2	0.0	0.179	32.4	0.0	1	X
K/S	13.392	25.8	12.0	16.336	54.2	78.3	0.2	
S/K	0.079	24.1	0.0	0.071	33.4	0.0	0.6	X
K/Zn	0.811	34.8	0.1	0.847	24.2	0.0	1.9	
Zn/K	1.377	32.8	0.2	1.245	23.1	0.1	2.5 **	X
K/Mn	0.123	50.4	0.0	0.094	56.1	0.0	1.4	X
Mn/K	10.394	50.4	27.4	14.445	59.0	72.6	0.4 **	
Ca/Mg	3.990	23.4	0.9	4.554	18.9	0.7	1.2	
Mg/Ca	0.263	21.6	0.0	0.227	19.8	0.0	1.6 **	X
Ca/S	9.372	26.8	6.3	12.333	55.7	47.2	0.1	
S/Ca	0.115	29.0	0.0	0.093	36.6	0.0	1	X
Ca/Zn	0.579	43.8	0.1	0.644	25.8	0.0	2.3	
Zn/Ca	2.014	36.8	0.5	1.650	24.9	0.2	3.3 **	X
Ca/Mn	0.088	54.1	0.0	0.067	40.7	0.0	3.1 ***	X
Mn/Ca	15.529	61.7	91.8	17.874	46.0	67.7	1.4	
Mg/S	2.413	26.6	0.4	2.764	57.9	2.6	0.2	
S/Mg	0.450	32.9	0.0	0.417	31.9	0.0	1.2	X
Mg/Zn	0.146	38.0	0.0	0.146	31.8	0.0	1.4	X
Zn/Mg	7.716	32.8	6.4	7.502	30.4	5.2	1.2	
Mg/Mn	0.022	47.8	0.0	0.014	34.0	0.0	4.6 ***	X
Mn/Mg	60.295	69.4	1752.6	77.016	33.4	662.5	2.6	
S/Zn	0.062	31.2	0.0	0.057	24.3	0.0	1.9	X
Zn/S	17.750	31.8	31.9	19.013	36.0	46.7	0.7	
S/Mn	0.009	41.0	0.0	0.006	46.7	0.0	1.8 *	X
Mn/S	132.819	51.2	4622.0	216.955	71.9	24314.2	0.2 *	
Zn/Mn	0.162	51.4	0.0	0.113	55.2	0.0	1.8	X
Mn/Zn	8.156	64.2	27.4	11.684	55.1	41.5	0.7	

N, P, K, Ca, Mg, S (g kg^{-1}); Zn and Mn ($mgkg^{-1}$) Variance of nutrient ratios of low and high-yielding groups are significantly different at 1% (***), 5 % (**) and 10 % (*) level of probability by Levene's test.

Nitrogen, followed by K, P, and Mg were identified as the most limiting nutrients in 2001 whereas S followed by N was identified as most limiting in 2002 (Figure 31). This means that although yam stood after fallow, organic and mineral fertilizer applied in the first year were inadequate to adequately cover the supply with these elements. Therefore, the nutrient imbalance observed in 2001 was less pronounced compared to that of 2002. Thus, a significant contribution of fallow could be found. In the second year, P and K were close to the limit of critical level, which still calls for a further optimization of mineral and organic fertilizer application rates. However, S in 2001 and Mn in 2002 were indicated as excessive, and Ca was high in relation to the other nutrients in both years.

So two years of mineral and organic fertilizer's application were not sufficient to improve soil fertility because of the deficiency observed during this period of experiment and the soil status did not improved. Sulfur and Zn which were not limiting in 2001 became inadequate in 2002. This could be explained by the fact that in the first cropping year most of the plots were installed after fallow. Soil was likely still of higher fertility, whereas in the second cropping year, S seemed to become inadequate.

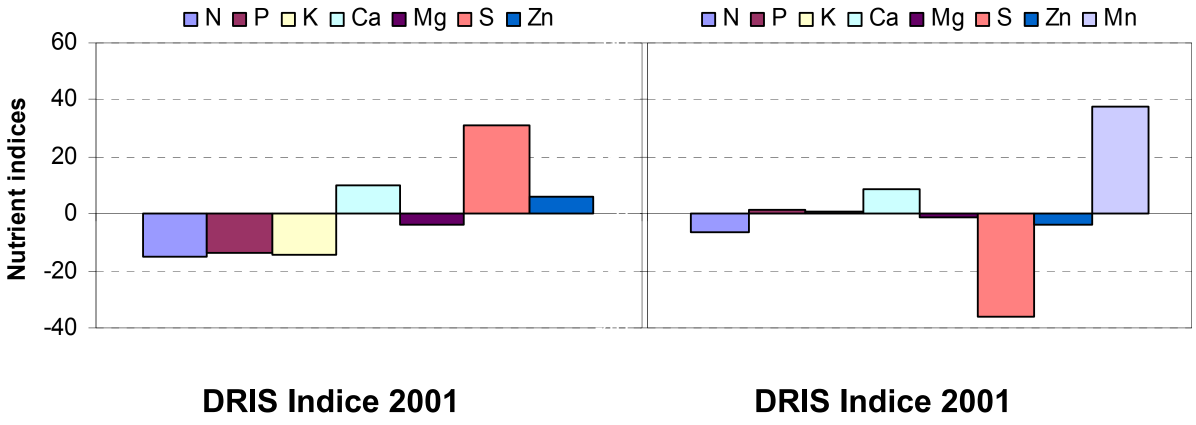


Figure 31: DRIS indices for yam in farming system in Upper Oueme catchment of Benin (on-farm experiment, 2001-2002).

In the absence of locally calibrated DRIS norms, norms developed under one set of conditions only should be applied to another if the nutrient concentrations of high-yielding plants from these different set of conditions are similar.

Sulfur was identified as deficient as well according to the data provided by Kelling and Schulte (1986). All other nutrients were adequately balanced.

The Nutritional Balance Index (NBI) was similar in both years.

3.3. Assessment of simplified nutrient balance

This chapter describes and discusses the outcome of partial nutrient balances assessed for each crop in this study.

3.3.1. Nutrient balance of cotton

Nutrient contents in the grain and lint of cotton at harvest in both low- and high-yielding sub-populations during the first year (Annex 8) of the experiment were almost similar and close to those reported by Stoorvogel and Smaling (1990), Duivenbooden (1992), NAS (1994) and Linnemann (1996) who found 1.5 - 40.5 g N, 2.9 - 6.5 g P and 8.2 - 13.1 g K per kg of cotton lint (grain and fiber).

Amounts of 6.0 - 17.8 g N, 0.9 - 2.7 g P and 0.7 - 26.8 g per kg of straw have been reported by Stoorvogel and Smaling (1990), Duivenbooden (1992), NAS (1994) and Linnemann (1996). These data are different from those obtained in the leaves and stem for both low and high yielding subpopulations in our experiment, as these authors considered stem and leaves together. Before harvest, however, there is a loss of leaves from cotton. So, in the present study, leaves and stem of this crop were sampled at harvest. As most leaves of cotton drop until harvest, however, sampling at an early stage of maturity may lead to an overestimation of nutrient removal.

Mean N concentration leaves was higher in the high yielding than in the low-yielding sub-population.

Nitrogen and P export (Table 38) by harvested products and crop residues of cotton were higher in the high yielding subpopulation than in low yielding subpopulation, and higher in crop residues than in the harvested product.

The lowest nutrient removal was observed with farmer’s practice followed by treatments with organic matter or/and fertilizer application for both low and high yielding subpopulations. So organic or/and mineral fertilizer increased the nutrient removal in both high and low yielding subpopulations due to an enhanced productivity.

Slightly negative N and K balances were observed with farmer’s practice, with the combination of organic and mineral fertilizer in the high yielding subpopulation whereas only a slight K deficit was observed in the low yielding subpopulation (Table 38) when only organic matter was supplied.

Positive N and K balances were found with the other treatments in the low yielding subpopulation.

Positive P balances were observed with all the treatments in both high and low yielding subpopulations. The combination of organic and mineral fertilizer showed the most positive balances followed by the application of organic matter.

Compared with nutrient balances obtained by a 12 years average (1987-1999), and those of 2000, N was more positive while the amount of P was similar. Potassium balance was slightly altered and became negative when a high production was expected.

In Benin’s farming systems, farmers usually do not use all mineral fertilizer received for cotton from the extension service. About 25 % of this mineral fertilizer is generally used for others crops, mostly maize. This may explain as well as the slightly negative N balance observed for cotton. The official recommended fertilizer rate could cover this crop’s requirements.

Complementary N and K fertilizer would be needed to compensate for nutrient removal and losses without considering input by deposition and output by leaching and erosion with actual farmer’s practice. The mineral fertilizer application recommended by extension service (150 kg $N_{14}P_{23}K_{14}S_5B_1$ and 50 kg Urea) is not sufficient whether high yielding cotton was expected.

In the Upper Oueme Catchment, slightly negative N balances (-4.1 kg N ha^{-1}) were observed in 1999 with an average yield of 0.56 t ha^{-1} and -5.2 kg N ha^{-1} in 2000 with 0.73 kg ha^{-1}. Phosphorous balances were slightly positive for farmer’s practice throughout; whereas K balances were slightly negative for the high-yielding sub population.

Table 38: Nutrient (N, P, K) balances of farming systems for low and high yielding subpopulations of cotton in Upper Oueme catchment of Benin (on-farm experiment, 2001).

Cotton	**In 1.1**	**In 1.2**	**In 2**	**In 4**	**Σ In**	**Out 1**	**Out 2**	**Σ Out**	***Balance***
N									
Low yielding subpopulation									
Treatments									
T0	0.0	0.0	44.0	0.0	44.0	13.2	18.9	32.1	***11.9***
T1	33.9	46.7	0.0	0.0	80.5	11.4	19.8	31.2	***49.3***
T2	0.0	0.0	51.0	0.0	51.0	17.0	22.1	39.1	***11.9***
T3	33.9	46.7	51.0	0.0	131.5	14.0	27.5	41.5	***90.1***
High yielding subpopulation									
T0	0.0	0.0	44.0	0.0	44.0	20.5	25.9	46.4	***-2.4***
T1	27.9	100.2	0.0	0.0	128.1	20.6	23.4	44.0	***84.1***
T2	0.0	0.0	51.0	0.0	51.0	19.0	32.6	51.7	***-0.7***
T3	27.9	100.2	51.0	0.0	179.1	23.3	27.7	51.0	***128.1***
P									
Treatments									
Low yielding subpopulation									
T0	0.0	0.0	15.0	0.0	15.0	2.1	1.4	3.5	***11.5***
T1	17.2	9.6	0.0	0.0	26.7	2.0	1.6	3.6	***23.1***
T2	0.0	0.0	20.0	0.0	20.0	2.3	1.6	3.9	***16.1***
T3	17.2	9.6	20.0	0.0	46.7	2.1	1.8	3.9	***42.9***
High yielding subpopulation									
T0	0.0	0.0	15.0	0.0	15.0	3.7	2.1	5.8	***9.2***
T1	12.2	19.9	0.0	0.0	32.1	3.5	2.2	5.7	***26.4***
T2	0.0	0.0	20.0	0.0	20.0	3.8	2.4	6.2	***13.8***
T3	12.2	19.9	20.0	0.0	52.1	3.8	2.4	6.2	***45.8***
K									
Low yielding subpopulation									
Treatments									
T0	0.0	0.0	17.5	0.0	17.5	8.2	10.6	18.8	***-1.3***
T1	60.0	39.3	0.0	0.0	99.3	7.9	11.6	19.5	***79.8***
T2	0.0	0.0	23.3	0.0	23.3	9.3	12.2	21.5	***1.8***
T3	60.0	39.3	23.3	0.0	122.6	8.5	12.8	21.3	***101.3***
High yielding subpopulation									
T0	0.0	0.0	17.5	0.0	17.5	13.1	15.3	28.4	***-10.9***
T1	45.1	98.4	0.0	0.0	143.5	12.4	15.8	28.1	***115.4***
T2	0.0	0.0	23.3	0.0	23.3	13.5	18.6	32.0	***-8.7***
T3	45.1	98.4	23.3	0.0	166.9	14.1	17.2	31.3	***135.6***

T0: Farmer's practice T1: 10 t ha^{-1} of crop residues or of farmyard manure (2001)
T2: 51 N 46 P_2O_5 28 K_2O T3: 51 N 46 P_2O_5 28 K_2O + 10 t ha^{-1} of crop residues or farmyard manure (2001)

In 1: input of crop residues; In 12: input of farmyard manure; In2: input of mineral fertilizer; ∑In: sum inputs; Ou1: output of harvest product; Out 2: output of crop residues (leaves, stems) ∑Out: sum outputs

3.3.2. Nutrient balances for maize

Mean nutrient contents in the grain cob and stem at harvest during the two years of experiment in both low- and high- yielding sub-populations were similar to those reported by Stoorvogel and Smaling (1990), Duivenbooden (1992), NAS (1994) and Linnemann (1996). These authors found 8.8 - 26.7 g N kg^{-1}, 1.6 - 4.4 g P kg^{-1} and 2.5 - 5.7 g K kg^{-1} in the grain, and 4.5 - 12.4 g N kg^{-1}, 0.2 - 1.4 g P kg^{-1} and 8.0 -16.4 g K kg^{-1} in the maize straw. Those of cob and stems are alike. Major differences have not been observed between treatments (Appendix 9).

Considering that nutrient concentrations were similar, the amounts of nutrients removed by the high yielding subpopulation were logically higher than those by low yielding subpopulation (Table 39).

Negative N, P, and K balances were observed with farmer's practice in both low and high yielding subpopulations. A negative K balance was obtained even with mineral fertilizer application in both groups.

During the two years of the experiment, nutrient outputs were higher than input and a negative nutrient balance was observed. This balance became less negative in the second year of the experiment (Appendix 14). The positive nutrient balance was observed with the combination of organic and mineral fertilizers in both years.

On the average, a positive nutrient balance was obtained when applying organic matter in the first year, showing that the amount of nutrients supplied by mulching or manure was theoretically high enough to compensate for the losses of the first year. The output of N and P in the second year resulted already in a negative balance in the high yielding subpopulation, i.e. the amount of organic matter supplied during the first year was not high enough to compensate for nutrient removal over two years (not considering the availability of the nutrients). Even though the soils in the project area are considered as high in K, continued depletion without compensating for nutrient outputs according to the farmers practice will result on the long run in deficient levels even for K.

Treatment T2 resulted in a negative balance with N, P and K for the high yielding subpopulation in the first year whereas for the low yielding subpopulation, only the K balance was still negative (Table 38).

Returning crop residues to the field makes the balance less negative which may be a way to both improve organic matter substitution for the soils.

The combination of mineral fertilizer and organic matter resulted in a positive balance during the two years of experiment for all nutrients, i.e. total supply of nutrients was higher than the average nutrient removal.

The yield was higher in 2001 and 2002 compared to that of 1999 and 2000.

The higher productivity is raised, the more attention has to be paid to compensate for all nutrients which will export with the products and residues.

The nutrient balance assessed in the present study was more negative (table 2) compared to previous results from 1999 where a deficit of 27 kg N ha^{-1}, 6.3 kg P ha and 13,7 kg K ha^{-1} was observed, with those reported by Dagbenonbakin *et al.* (2002) who found a negative balance of -28.5 kg N ha^{-1}, 32.9 kg P ha^{-1} and -7.5 kg K ha^{-1}, whereas Stoorvogel and Smaling (1990) found for Benin a negative nutrient balance of -12 N kg ha^{-1} -3.9 kg P ha^{-1} and -4.2 kg K ha^{-1} for 1983 and had predicted -17 kg N ha^{-1}, -4.3 kg P ha^{-1} and -7.5 kg K ha^{-1} for 2000. Compared with the data of Dagbenonbakin *et al*. (2002), the nutrient balance became more negative in 2001 but less so in 2002 due to the lower yield level in this year. The values for removal by harvested products and crop residues found in the present study were higher than those reported earlier (Dagbenonbakin et al. 2002). The amount of nutrients added as organic matter and mineral fertilizer in this experiment were lower than overall nutrient output by harvest products and crop residues. This could probably explain the higher negative nutrient balance obtained with maize in the present study taking into account farmer’s practice.

Organic matter in the first year constituted the major contribution, but did not fully compensate for P output by the high yielding sub-population. Furthermore, 30 kg N ha^{-1} in 2001 and 25 kg N ha^{-1} in 2002 were applied at sowing date and a second application of 30 kg N ha^{-1} and 50 kg N ha^{-1}, 45 days after sowing respectively in 2001 and 2002. The type of fractionation which could probably minimize the loss of nutrients through soil erosion and leaching may positively affect the nutrient balance. Several studies show that large amounts of applied

N can be either lost or may accumulate in the subsoil. About 40 to 50 % of the mineralized N may be lost under high rainfall conditions in West Africa (Mueller-Harvey *et al.,* 1985; Van der Kruijs *et al.,* 1988). In a sandy soil in Niger, large parts of N added to the soil with 13 t ha^{-1} of manure were leached to depths below 1.5 m, indicating that smaller, more frequent applications may be a more effective way of using manure (Brouwer and Powell, 1995).

Organic matter supplied in this experiment compensated for a larger proportion of nutrient outputs. Furthermore it should be considered that bio-availability of N in this organic matter is rather low, whereas N excess supplied by mineral fertilizer may be leached out during the rainy season in West Africa, and considerable amount of N way accumulate in the subsoil (Mueller-Harvey *et al*. 1985; Van der Kruijs *et al,*. 1988). Split application of N may help to minimize N losses (Brouwer and Powell, 1995).

The amount of P calculated to compensate for the deficit in farmer’s practice (12 kg P ha^{-1}) is similar to the level reported by Jama et *al.* (1997) who found that broadcast application of 10 kg P ha^{-1} as triple superphosphate (TSP) to maize on acid soils in western Kenya gave a significant residual benefit in the season following the P application. P fertilization at the tested rates of 10 and 30 kg P ha^{-1} was economically attractive for maize (Bekunda *et al.* 1997). Several authors reported crop responses to small or moderate amounts of P fertilizers and residual benefit in the season following P application (Le Mare 1959, 1974; Boswinkle 1961) for similar conditions.

Furthermore, the combination of mineral and organic fertilizer gave mostly the best yield.

Table 39: Average nutrient (N, P, K) balances of farming systems for low and high yielding subpopulations of maize in Upper Oueme catchment of Benin (on-farm experiment, 2001 and 2002).

Maize	In 1.1	In 1.2	In 2	In 4	Σ In	Out 1	Out 2	Σ Out	Balance
N									
Low- yielding sub-population									
Treatments									
T0	0.0	0.0	0.0	0.0	0.0	26.9	2.0	28.9	**-28.9**
T1	22.7	39.9	0.0	0.0	62.6	29.4	2.0	31.3	**31.3**
T2	0.0	0.0	66.3	0.0	66.3	34.7	2.4	37.1	**29.2**
T3	22.9	49.9	66.3	0.0	139.1	26.8	2.9	29.7	**109.3**
High- yielding sub-population									
T0	0.0	0.0	0.0	0.0	0.0	55.5	3.5	59.0	**-59.0**
T1	18.3	64.5	0.0	0.0	82.8	55.2	3.4	58.6	**24.2**
T2	0.0	0.0	66.3	0.0	66.3	75.2	3.7	78.8	**-12.5**
T3	20.6	45.9	66.3	0.0	132.8	73.7	4.0	77.6	**55.2**
P									
Treatments									
Low- yielding sub-population									
T0	0.0	0.0	0.0	0.0	0.0	7.4	0.4	7.8	**-7.8**
T1	10.2	6.1	0.0	0.0	16.3	8.1	0.3	8.4	**7.9**
T2	0.0	0.0	17.4	0.0	17.4	9.1	0.6	9.6	**7.8**
T3	11.7	7.5	17.4	0.0	36.6	8.1	0.6	8.7	**27.9**
High- yielding sub-population									
T0	0.0	0.0	0.0	0.0	0.0	11.7	0.5	12.2	**-12.2**
T1	4.2	10.4	0.0	0.0	14.6	15.2	0.7	15.9	**-1.3**
T2	0.0	0.0	17.4	0.0	17.4	18.8	0.6	19.4	**-2.0**
T3	6.7	7.1	17.4	0.0	31.3	18.6	0.6	19.2	**12.0**
K									
Treatments									
Low- yielding sub-population									
T0	0.0	0.0	0.0	0.0	0.0	9.7	3.0	12.6	**-12.6**
T1	37.1	45.0	0.0	0.0	82.1	10.9	3.0	13.8	**68.3**
T2	0.0	0.0	10.0	0.0	10.0	11.5	3.7	15.3	**-5.3**
T3	39.3	55.6	10.0	0.0	104.9	9.9	4.3	14.1	**90.8**
High- yielding sub-population									
T0	0.0	0.0	0.0	0.0	0.0	18.1	5.0	23.0	**-23.0**
T1	28.9	98.2	0.0	0.0	127.1	18.9	5.0	23.9	**103.2**
T2	0.0	0.0	10.0	0.0	10.0	25.7	5.8	31.5	**-21.5**
T3	31.8	61.4	10.0	0.0	103.2	24.8	5.9	30.7	**72.5**

T0: Farmer's practice T1: 10 t ha^{-1} of crop residues or farmyard manure (2001) or residual effect of manure (2002)
T2: 60 N 40 P_2O_5 (2001) or 75 N 40 P_2O_5 24 K_2O (2002) T3: 60 N 40 P_2O_5 with 10 t ha^{-1} of crop residues or farmyard manure (2001) or 75 N 40 P_2O_5 24 K_2O +10 t ha^{-1} of crop residues or residual effect of manure (2002)
In 1: input of crop residues; In 12: input of farmyard manure; In2: input of mineral fertilizer; ∑In: sum inputs;
Ou1 1: output of harvest product; Out 2: output of crop residues (leaves, stems) ∑Out: sum outputs

4.3.3. Nutrient balance of groundnut

Nutrient contents in grain, husk and stem (Appendix 10) for both high- and low-yielding sub-populations during the two years of experiment were similar to those of Stoorvogel and Smaling (1990), Duivenbooden (1992), NAS (1994) and Linnemann (1996), who reported 39.1- 57.6 g N kg^{-1}, 2.2 -7.8 g P kg^{-1} and 6.0 - 8.1 g K kg^{-1} for in grain, 7.5 - 13.4 g N kg^{-1}, 0.4 -0.7g P kg^{-1} and 4.0 - 9.0 g K kg^{-1} for pod and 11.9 - 27.4 g N kg^{-1} , 0.5 - 2.6 g P kg^{-1} and 3.4 - 26.3 g K kg^{-1} for straw of groundnut. Nutrient removal by the harvest products was about doubled in the high yielding subpopulation due to its higher productivity. Even though groundnut as a leguminous plant adds nitrogen, the output is generally higher, and the higher the yields, the higher the nutrient depletion. There was no particular trend for the application of organic (T1) or mineral fertilizers (T2).

The proportion of N derived from nitrogen fixation when calculated using sorghum as reference crop were 53.5 % for T0, 50.8 % for T1, 33.3 % for T2 and 30 % for T3. These values, when related to farmer’s practice, are very close to the values reported by Munyinda *et al.* (1988); Tisdale *et al.* (1985); Wetselaar and Ganry 1982 cited by Smaling *et al.* (1993) and Stoorvogel e*t al*. (1990), who assumed that about 60 % of the total nitrogen requirement of groundnut is supplied through biological nitrogen fixation. When calculating with cotton, maize and yam as reference crop, values differed wider from literature data. Thus, the percentages on the basis of sorghum were used for the calculation of nitrogen derived from symbiotic fixation.

Despite the high N content as input from symbiotic fixation, compensation by organic matter application and 10 kg N ha^{-1} applied at sowing date of groundnut, N balances were negative (Table 40). Taking into consideration only farmer’s practice (T0), balances were all negative. The balance deficit in this present study (for the years 2000 and 2001) was even bigger than in the study from Dagbenonbakin *et al.* (2000). During the two years of experiment, no K was applied and thus an average annual negative balance was obtained except where organic matter was applied in the first year in the low- yielding sub-population. The potassium content in crop residues by far exceeded that in the harvested product.

Table 40: Average nutrient (N, P, K) balances of farming systems for low and high yielding subpopulations of groundnut in Upper Oueme catchment of Benin (on-farm experiment, average of 2001-2002).

Groundnut	In 1.1	In 1.2	In 2	In 4	Σ In	Out 1	Out 2	Σ Out	Balance
N									
Low- yielding sub-population									
Treatments									
T0	0.0	0.0	0.0	34.3	34.3	30.0	37.8	67.8	**-33.5**
T1	28.9	49.9	0.0	36.4	115.2	32.5	37.2	69.7	**45.6**
T2	0.0	0.0	10.0	23.7	33.7	29.5	28.6	58.1	**-24.4**
T3	28.0	49.9	10.0	20.6	108.5	31.4	25.0	56.4	**52.1**
High- yielding sub-population									
T0	0.0	0.0	0.0	54.7	54.7	63.2	55.2	118.4	**-63.7**
T1	19.8	0.0	0.0	40.7	60.6	55.0	38.3	93.3	**-32.7**
T2	8.9	0.0	10.0	33.9	52.7	60.5	32.0	92.5	**-39.8**
T3	39.9	0.0	10.0	40.5	90.4	63.7	41.8	105.5	**-15.1**
P									
Low- yielding sub-population									
Treatments									
T0	0.0	0.0	0.0	0.0	0.0	2.7	3.2	5.9	**-5.9**
T1	8.1	7.6	0.0	0.0	15.7	3.1	2.8	5.8	**9.9**
T2	0.0	0.0	13.0	0.0	13.0	2.9	2.8	5.7	**7.4**
T3	7.0	7.6	13.0	0.0	27.6	2.9	2.6	5.5	**22.1**
High- yielding sub-population									
T0	0.0	0.0	0.0	0.0	0.0	5.2	5.4	10.6	**-10.6**
T1	5.8	0.0	0.0	0.0	5.8	4.8	3.4	8.3	**-2.5**
T2	3.4	0.0	13.0	0.0	16.4	5.4	2.9	8.3	**8.1**
T3	12.1	0.0	13.0	0.0	25.2	5.6	3.0	8.6	**16.6**
K									
Low- yielding sub-population									
Treatments									
T0	0.0	0.0	0.0	0.0	0.0	6.3	40.6	46.9	**-46.9**
T1	45.5	55.4	0.0	0.0	100.9	7.3	41.3	48.6	**52.4**
T2	0.0	0.0	0.0	0.0	0.0	6.5	33.0	39.5	**-39.5**
T3	48.5	55.4	0.0	0.0	103.9	6.7	31.8	38.5	**65.4**
High- yielding sub-population									
T0	0.0	0.0	0.0	0.0	0.0	12.5	59.3	71.8	**-71.8**
T1	13.5	0.0	0.0	0.0	13.5	11.4	48.0	59.4	**-45.9**
T2	13.8	0.0	0.0	0.0	13.8	12.1	47.4	59.4	**-45.7**
T3	44.6	0.0	0.0	0.0	44.6	12.7	48.7	61.5	**-16.9**

T0: Farmer's practice T2: 10 N 40 P_2O_5 (2001) or 10 N 20 P_2O_5 (2002) T1: 10 t ha^{-1} of crop residues or farmyard manure (2001) or 10 t ha^{-1} of crop residues or its residual effect (2002) T3: 10 N 40 P_2O_5 with 10 t ha^{-1} of crop residues or farmyard manure (2001) or 10 N 20 P_2O_5 + 10 t ha^{-1} crop residues or residual effect of manure (2002)

In 1: input of crop residues; In 12: input of farmyard manure; In2: input of mineral fertilizer; In 4: N derived from symbiotic fixation ∑In: sum inputs; Ou1 1: output of harvest product; Out 2: output of crop residues (leaves, stems) ∑Out: sum outputs

Negative balances were observed with P and K in both high and low-yielding subpopulations during the two years of experiment with farmer's practice, while the nutrient balance was positive for treatment T1 (organic fertilizer). The application of organic matter alone even to over compensated P removal. For K, however, K output was just balanced in the low- but not the high- yielding sub-population resulting in a negative K balance in the latter (-25.6 kg K ha^{-1}).

It has to be considered that the high yielding sub-population usually includes mostly the treatments with fertilizer application, whereas farmers practice (T0) is more represented in the low yielding sub-population. Thus, balances for low-yielding subpopulations in our experiments were largely negative.

Large amounts of N are exported from the field through the biomass which is used for animal feeding. This adds to the negative balance as long as dung is not returned to the field. The amount of mineral fertilizer applied during the two years of experiment did not fully cover the plant requirements. As most of the groundnut biomass is exported either as grain or for animal feeding, and even though part of the exported N is derived from biological nitrogen fixation, groundnut under farmers practice contributes significantly to soil mining even for N, in Bénin.

Nutrient balance for groundnut could either be improved when crop residues are left in the field, but as the dried foliage is a valuable feed for animals, dung should be returned to the field or else mineral fertilizer would be needed to compensate for the negative nutrient balance. Most of the values obtained in this study are close to those reported by Stoorvogel *et al.* (1990) who found for Bénin -20 kg N ha^{-1}, -2 kg P ha^{-1} and -8.5 kg K ha^{-1} for 1983 and predicted -29 kg N ha^{-1}, 4 kg P ha^{-1} and 8 kg K ha^{-1} for 2000. Where the present data differed from these values, this may largely be explained by slightly differing yields.

The annual amount of P needed to compensate deficits is 11 kg P ha^{-1} in the high yielding subpopulation. This amount of P is close to the 14.3 kg P ha^{-1}, which is recommended as optimal rate of phosphorous for groundnut production by Dagbenonbakin (1985) for southern Benin.

3.3.4. Nutrient balance of Yam

Nutrient contents (Appendix 11) were higher in the high- than in the low-yielding subpopulation.

Nutrient removal was higher in the high compared to the low- yielding subpopulation (Table 41), and K followed by N were the nutrients found in the highest concentration in yams (on a w/w basis).

Negative nutrient N, P and K balances were observed with farmer's practice in both low and high yielding subpopulations, and in the treatments with organic fertilizer and mineral fertilizer for the high yielding subpopulation, indicating that the amount of nutrients supplied with the treatments T1 and T2 did not fully compensate nutrient removal at high yields.

A negative annual nutrient balance of -42.2 kg N ha^{-1}, -7.4 kg P ha^{-1} and -58.1 kg K ha^{-1} was found when calculating the average of results from 12 years in the project area (Dagbenonbakin *et al.* 2005, own unpublished results). Taking the data of the 2002000, this nutrient balance was more negative for P and slightly lower for N and K. Data for nutrient balances of yam are very scarce. However, this trend was similar with that found by Carsky *et al.* (2005) who reported for cassava in southern Benin a slightly negative N and P balance in plots with 60 kg ha^{-1} N as urea, 16 kg ha^{-1} P as triple super phosphate (TSP) and 138 kg ha^{-1} K as muriate of potash (MOP) in the first year, but positive after 3 years while the K balance was positive throughout the period.

Table 41: Average nutrient (N, P, K) balances of farming systems for low and high yielding subpopulations of yam in Upper Oueme catchment of Benin (on-farm experiment, 2001 and 2002).

Yam	In 1.1	In 1.2	In 2	In 4	Σ In	Out 1	Out 2	Σ Out	Balance
N									
Low- yielding sub-population									
Treatments									
T0	0.0	0.0	0.0	0.0	0.0	19.7	0.8	20.5	**-20.5**
T1	19.5	13.3	0.0	0.0	32.8	21.6	0.9	22.5	**10.3**
T2	0.0	0.0	36.0	0.0	36.0	21.9	1.1	23.0	**13.0**
T3	22.9	0.0	33.5	0.0	56.4	26.5	1.2	27.7	**28.7**
High- yielding sub-population									
T0	0.0	0.0	0.0	0.0	0.0	23.5	1.4	24.9	**-24.9**
T1	15.5	20.1	0.0	0.0	35.6	29.3	1.2	30.5	**5.1**
T2	0.0	0.0	36.0	0.0	36.0	35.0	1.1	36.1	**-0.1**
T3	14.0	22.7	36.0	0.0	72.7	31.5	1.2	32.7	**40.1**
P									
Low- yielding sub-population									
Treatments									
T0	0.0	0.0	0.0	0.0	0.0	3.4	0.1	3.5	**-3.5**
T1	10.7	1.9	0.0	0.0	12.6	4.0	0.1	4.1	**8.5**
T2	0.0	0.0	13.0	0.0	13.0	4.4	0.1	4.5	**8.5**
T3	12.2	0.0	12.0	0.0	24.2	4.3	0.1	4.5	**19.7**
High- yielding sub-population									
T0	0.0	0.0	0.0	0.0	0.0	3.7	0.2	3.9	**-3.9**
T1	8.2	3.1	0.0	0.0	11.3	5.1	0.2	5.2	**6.1**
T2	0.0	0.0	13.0	0.0	13.0	5.6	0.1	5.7	**7.3**
T3	7.2	3.3	13.0	0.0	23.5	6.5	0.2	6.7	**16.9**
K									
Low- yielding sub-population									
Treatments									
T0	0.0	0.0	0.0	0.0	0.0	24.4	1.3	25.7	**-25.7**
T1	36.9	12.8	0.0	0.0	49.7	30.1	1.3	31.4	**18.3**
T2	0.0	0.0	50.0	0.0	50.0	34.8	1.5	36.3	**13.7**
T3	38.9	0.0	45.8	0.0	84.7	36.3	1.7	38.1	**46.6**
High- yielding sub-population									
T0	0.0	0.0	0.0	0.0	0.0	33.4	1.5	34.9	**-34.9**
T1	26.6	26.9	0.0	0.0	53.4	41.2	1.5	42.7	**10.7**
T2	0.0	0.0	50.0	0.0	50.0	39.8	1.3	41.0	**9.0**
T3	24.3	22.0	50.0	0.0	96.3	55.1	1.8	56.9	**39.4**

T0: Farmer's practice T2: 30 N 30 P_2O_5 60 K_2O
T1: 10 t ha^{-1} of crop residues or farmyard manure (2001) or its residual effect (2002)
T3: 30 N 30 P_2O_5 60 K_2O + 10 t ha^{-1} of crop residues or farmyard manure (2001) or 42 N 30 P_2O_5 60 K_2O + of crop residues or residual effect of manure (2001)

In 1: input of crop residues; In 12: input of farmyard manure; In2: input of mineral fertilizer; ∑In: sum inputs; Ou1: output of harvest product; Out 2: output of crop residues (leaves, stems) ∑Out: sum outputs

Normally yam is grown just after fallow and no fertilizer is applied to this crop. The negative nutrient balance observed with yam could be explained by the high removal of nutrients through the harvested tuber (Table 41). This nutrient balance was more negative in the second year where the vegetative period and the amount of rainfall were similar during the two years of experiment. Thus, the vegetation period for yam was shorter in the second year due to a bad distribution of rainfall. As result, yields and amounts of crop residues were below averages in 2001 and thus do not represent long-term average values.
Nitrogen, P and K balances were negative with farmer’s practice, whereas only a slightly negative N balance was obtained for T2.

3.3.5. Nutrient balance of sorghum

Mean concentrations of grain, panicle spike and stem (Appendix 12) in the first year of experiment were close to those of Stoorvogel and Smaling (1990); Duivenbooden (1992), NAS (1994) and Linnemann (1996) who reported 10.9-31.4 g N kg^{-1}, 1.3 – 3.84 g P kg^{-1} and 2.5 - 5.0 g K kg^{-1} in the grain and 2.5 – 11.8 g N kg^{-1}, 0.2 – 2.1 g P kg^{-1} and 3.1 - 20.7 g K kg^{-1} in the straw.

Nutrient removal by harvest products were higher in the high yielding subpopulation compared to the low yielding subpopulation. Crop residues exported more K than grain while the N and P outputs are higher with grain than with straw.

The nutrient balance for farmers practice was negative throughout as farmers usually do not apply fertilizer to sorghum. N and K supplied as mineral fertilizer and organic matter did not suffice to fully compensate for the nutrient output in the high yielding subpopulation which means that higher amounts of fertilizers than those supplied in our experiments would be required to sustain high yields. It has to be highlighted as well that the simplified balance does not consider output by erosion, leaching and de-nitrification. True fertilizer requirements would thus be rather higher than lower as the balance calculated in the present work.

Table 42: Average nutrient (N, P, K) balances of farming systems for low and high yielding subpopulations of sorghum in Upper Oueme catchment of Benin (on-farm experiment, 2001 and 2002).

Sorghum	In 1.1	In 1.2	In 2	In 4	Σ In	Out 1	Out 2	Σ Out	*Balance*
N									
Low- yielding sub-population									
Treatments									
T0	0.0	0.0	0.0	0.0	0.0	13.9	10.7	24.6	**-24.6**
T1	35.7	11.4	0.0	0.0	47.1	14.9	11.3	26.3	**20.8**
T2	0.0	0.0	25.5	0.0	25.5	17.6	10.3	27.9	**-2.4**
T3	40.3	0.0	25.5	0.0	65.8	12.2	9.1	21.2	**44.6**
High- yielding sub-population									
T0	0.0	0.0	0.0	0.0	0.0	18.7	16.9	35.7	**-35.7**
T1	9.2	53.0	0.0	0.0	62.2	32.0	19.5	51.5	**10.7**
T2	0.3	0.0	19.9	0.0	20.2	32.9	22.5	55.4	**-35.2**
T3	17.4	39.8	25.5	0.0	82.6	35.7	20.9	56.6	**26.0**
P									
Low- yielding sub-population									
Treatments									
T0	0.0	0.0	0.0	0.0	0.0	3.0	2.3	5.2	**-5.2**
T1	10.9	1.6	0.0	0.0	12.5	3.3	1.9	5.1	**7.4**
T2	0.0	0.0	20.0	0.0	20.0	3.8	2.2	5.9	**14.1**
T3	11.0	0.0	20.0	0.0	31.0	2.3	1.6	3.8	**27.2**
High- yielding sub-population									
T0	0.0	0.0	0.0	0.0	0.0	11.2	12.5	23.7	**-23.7**
T1	8.4	7.8	0.0	0.0	16.2	7.4	4.7	12.1	**4.2**
T2	0.0	0.0	16.0	0.0	16.0	7.5	5.4	12.8	**3.2**
T3	9.2	5.8	20.0	0.0	34.9	8.9	5.2	14.1	**20.8**
K									
Treatments									
Low- yielding sub-population									
T0	0.0	0.0	0.0	0.0	0.0	4.8	27.6	32.4	**-32.4**
T1	58.3	11.0	0.0	0.0	69.3	5.3	30.3	35.5	**33.8**
T2	0.0	0.0	11.7	0.0	11.7	6.1	28.8	34.9	**-23.3**
T3	65.7	0.0	11.7	0.0	77.3	3.8	25.9	29.6	**47.7**
High- yielding sub-population									
T0	0.0	0.0	0.0	0.0	0.0	12.2	24.0	36.3	**-36.3**
T1	18.5	50.8	0.0	0.0	69.4	12.6	61.0	73.6	**-4.3**
T2	0.4	0.0	7.0	0.0	7.4	14.0	73.2	87.2	**-79.8**
T3	28.6	38.5	11.7	0.0	78.8	13.1	68.0	81.1	**-2.3**

T0: Farmer's practice T2: 23 N 46 P_2O_5 (2001) or 28 N 46 P_2O_5 28 K_2O (2002) T1: 10 t ha^{-1} of crop residues or farmyard manure (2001) or 10 t ha^{-1} of crop residues or residual effect of manure (2002) T3: 23 N 46 P_2O_5 + 10 t ha^{-1} of crop residues or farmyard manure (2001) or 28 N 46 P_2O_5 28 K_2O + 10 t ha^{-1} of crop residues or residual effect manure (2002)

In 1: input of crop residues; In 12: input of farmyard manure; In2: input of mineral fertilizer; ∑In: sum inputs;

Ou1 1: output of harvest product; Out 2: output of crop residues (leaves, stems) ∑Out: sum outputs

The amount of organic matter supplied in the present experiment already compensated for all nutrient output in both high and low yielding subpopulations. As a relatively large proportion of sorghum stem is not exported from the framer’s field (about 60%), and as it constitutes the majority of the biomass, nutrient losses are rather easily compensated. Nutrient balance calculated on the basis of a 12 years average until 1999 were -16.7 kg N ha^{-1}, -3.2 kg P ha^{-1} and -7.3 kg K ha^{-1}compared to -23.2 kg N ha^{-1}, -14.4 kg P ha^{-1} and -21.4 kg K ha^{-1} in 2000. N and K balances from our data are higher than those found by Stoorvogel *et al.* (1990) who reported for Bénin -10 kg N ha^{-1}, -3.9 kg P ha^{-1} and -5 kg K ha^{-1} for 1983 and predicted -11 kg N ha^{-1}, 4.8 kg P ha^{-1} and -5.8 kg K ha^{-1} for 2000 considering farmer’s practice. However during the two years of field experiment, only the values of P balance in the low-yielding sub-population were close to those reported by Stoorvogel *et al.* (1990). The difference between N and K balances from our compared to literature data can be explained by the differences of exporting sorghum stem. The potassium content in crop residues by far exceeds that by grain. If residues are left in the field, K losses can be reduced considerably. There is a positive impact on the nutrient balance whether crop residues or farmyard manure and or mineral fertilizer were applied to sorghum.

Nutrient balances assessed in this study were likewise negative for farmers practice in both years (Table 42). The nutrient removal by grain and crop residues, and the losses of nutrients by leaching and soil erosion, will progressively deplete the soil of nutrients if adequate nutrient amounts are not returned to the field.

With respect to nutrient management, the balances show that the application of nutrients as crop residues or manure and mineral fertilizer are important components at the input side. The nutrient output largely derives from harvest product and crop residues. The strategies to compensate the nutrient gap are to increase the recycling of residues, to increase the application of manure, and/or introduce fertilizers or a combination of all three.

4. General discussion and conclusions

4.1. General discussion

This chapter starts with a discussion on the effect of fertilizer on crop productivity and water use efficiency of maize. It is followed by the identification of nutrients which limit productivity on the basis of plant analysis (CVM and DRIS-Evaluation) and the assessment of simplified nutrient balances for the prediction of long term trend of nutrients availability.

Fallowing is one of the important cultural practices on all three test sites of our experiments according to the diagnosis on soil fertility management executed at the beginning of experiment. Mineral fertilizer application is the most important practice in Beterou because the agricultural development in this zone has largely been determined by cotton cultivation. Good institutional infrastructure, accessible credit facilities and a guaranteed price for their produce have encouraged many farmers to cultivate this crop.

Farmers in Wewe and Dogue do not use mineral fertilizer for crops as very few farmers cultivate cotton in these localities. Furthermore, the advantages of crop residues, farmyard manure and mineral fertilizers are known by farmers of all these localities according to an informal interview with them but they do not apply theses practices, as the labour needed for a proper management of crop residues, preparation and application of manure, and the high cost of mineral fertilizers discourage the adaptation of better farming practices according to the farmers of these localities.

4.1.1. Effect of fertilizer application on crop productivity and water use efficiency

In this study, farmer’s practice represented the treatment without organic and mineral fertilizer input with exception of cotton, where mineral fertilizer was applied at the rate, recommended by the extension service. In the first years, many plots of yam were installed just after of fallow. But according to Mulindabigwi (2005), farmers in Upper Oueme Catchment distinguish four types of fallow: short duration fallow, seasonal fallow, average fallow and long duration fallows. Maize fields of only two farmers involved in our experiment followed long duration fallows. As plots with farmer's practice (T0) were predominantly found in the low yielding- subpopulations and as fertilizer application in most cases lead to an enhanced yield, fallow periods in most cases were likely not sufficient to support high crop yields. However, farmer's practice, the type of crop residues used as mulch and to prepare farmyard manure significantly affected the productivity. Therefore, there was a considerable variability between treatments and within each treatment for almost all crops studied in this work. Especially straw with a high C/N ratio decreased productivity when mulched, at least in the year of its application due to a decreased N availability to the crop. The RUE or WUE of the respective data largely coincides with the results obtained for yield and total biomass production.

The relatively high variability observed with crops in this study could be attributed to sites conditions, farmer's practice and especially a rather late sowing or planting date in 2002.

Furthermore, Djokoto and Stephens (1961), Kodjo *et al* (2004) and Ogodja *et al.* (2004) pointed out that manure and its residual effect affected the yield of yams. In this study, organic and/or mineral fertilizer or both fertilizers influenced the productivity and the efficiency of available water of crops at all three localities and water use efficiency of maize in Dogue in 2002. Similar results were observed by Jones *et al.* (1969); Nyakatawa and Reddy (2000); Ji and Unger (2001); Dagbenonbakin *et al.* (2002, 2003) and (Turner (2004). Mineral fertilizer or combination with organic matter showed the best increase yield of cotton compared to farmer's practice (where mineral fertilizer application is already common practice). Similar results with CRA-CF, (2002) were observed in Beterou while it contrasted to those of Wewe and Dogue probably due to poorer soil conditions and inadequate management practice by farmers of the latter sites.

In both years, a positive influence of mineral fertilizer and/or its combination with organic matter was observed on yield and total biomass of groundnut in Beterou and Wewe.

Only mineral fertilizer improved the production of grain, panicle and the total biomass of sorghum, whereas organic residues seemed to be without major effect. Growing cowpea in order to supply the N content of the cereal crops in the second year of the experiment did not improve yield very much because of the high competition (for water and eventually through shading) between the plants at the beginning of the experiment. This situation affected yield and could be one of the causes for the high variability observed in the second year. However, the plots with the highest sorghum productivity received mineral and/or farmyard manure.

The application of organic and/or mineral or both fertilizers affected the parameters studied on yam. The increase of tuber yield due to manure application as well as a positive residual effect has been observed in Wewe, similar to the results obtained by Kodjo *et al.* (2004) and Ogodja *et al.* (2004).

It appears that although inorganic fertilizer is a key factor for a productive agriculture (Gamini *et al.* 2003), mineral fertilizer- based systems alone cannot solve the problem of declining soil fertility and loss of productivity in the research area. However, if fertilizers are not to be used on a much wider scale in Upper Oueme Catchment, it is not due to a lack of knowledge of the importance of fertilizers in plant nutrition, but due to economic constraints such as high prices, low income of farmers, and accessibility of fertilizers for other crops except cotton. In Benin, the most available commercial fertilizer is the NPKSB 14-23-14-5-1 compound fertilizer. Its use is meant for cotton production. There are fertilizers for other crops but there are no published results on the experiment using these formulas of fertilizers in the project area. Thus we used in our experiments mostly the fertilizer for cotton as basis, and complementary other single fertilizers were added in other to obtain the recommended rates according to INRAB (1995). Therefore, it is also necessary to find out more about the conditions under which applications of mineral fertilizers can give economic return; this in turn depends on the fertilizer cost, the yield increase obtained, and the local retail price of the crop. Since fertilizers have normally to be paid for in cash, their use is often associated with a more commercial approach to agriculture than the predominating subsistence agriculture in most parts of West Africa. The subsistence farmers are not able to invest money in fertilizers even if they want, and may have to be supported by loans or subsidies, particularly in the early stages of their introduction.

4.1.2. Plant nutritional assessment

To find out the most limiting nutrients for a higher productivity in the Upper Oueme catchment, we used both critical values as well as DRIS evaluation, which are as well backed up by data already published for soil fertility (Junge 2004). The difficulty lies in finding standard values which can be used under the local conditions. Therefore, to this end, for DRIS evaluation a separation into low and high yielding- sub-populations is required, for critical values or sufficiency range approaches a high yielding standard population is required as well. The criterion to select the standard population must be specific to establish adequate norms. There are many ways to cut off the population into high- and low- yielding sub-populations. Arbitrary values were used to separate the population (Beaufils, 1973; Elwali *et al.,* 1984, 1985; Hallmark *et al.,* 1985, 1986, 1987; Payne *et al.,* 1990; Shumway *et al.,* 1994; Soltanpour *et al.,* 1995). It can be subdivided into two equal parts or into the lower 75% for the low yielding sub-population, and the top 25% for the high yielding sub-population. Analyzing the entire data base per crop, it has been judicious to set the yield population of each crop into high and low yielding subpopulations using the mean + interval of confidence as criteria for the cut-off yield. Statistical analysis showed a significant difference between these two subpopulations for each crop confirming the accuracy of this subdivision.

According to FAO (2000), Zn and Mn were well in the sufficiency range for maize in both years, but were the most limiting nutrients for maize production according to DRIS. Also Jones *et al.* (1990) diagnosed Mn as a deficient nutrient in the project area (Table 43), which was in agreement with the DRIS evaluation for the second year for maize. Nitrogen was insufficient for maize according to CVM, but was not limiting maize production in both years according to DRIS.

Nitrogen and P were deficient in groundnut according to Kang (1980) and DRIS while K was close to the critical level and almost at the optimum according to DRIS evaluation in both two years (Table 43).

Nitrogen, P and K were identified as the nutrients which were mostly limiting the production of sorghum according to our DRIS evaluation and Kang (1980) in the

second year, while from these three nutrients, only P was classified to be at the critical level according to FAO (2000) in the first year.
It appeared that N, P, K, Mg and S were deficient in maize, groundnut and sorghum trials of this thesis, only for maize P was sufficient in the second year according to Jones (1990). However, P and K were at the critical range for cotton, while N and Ca were classified as deficient nutrients according to Sabbe *et al.* (1972).

DRIS norms established for maize showed highly significant differences with those reported by Sumner (1977b); Escano *et al.* (1981), Elwali *et al*. (1985) and Dara *et al.* *(*1992). Soil conditions, climate, leaf position, management practices, and genetic factors could explain highly significant differences observed between these norms. This was supported by dos Anjos (2002) who reported that universal DRIS norms established for maize should not be applied to evaluate the maize nutritional status. In the absence of DRIS norms which have been locally calibrated, norms developed under one set of conditions only should be applied to other conditions if the nutrient concentrations of high-yielding plants from these different set of conditions are similar. This was supported by Escano *et al.* (1981*)* cited by Kelling et al. (1986) who found that the use of published DRIS norms may not be as accurate in making diagnoses as are locally calibrated critical values. However, according to the previous author when DRIS norms were established by local data, the percentage of accuracy was 2 to 8 % better with DRIS than with the best locally calibrated critical concentrations. Deficiencies were diagnosed in the first year for P, K, Mg and S in maize, only for N with yam, S and Zn with cotton (Table 44) according to Kelling *et al.* (1986). The same author reported that the use of the DRIS indices shows that the results are often taken too dogmatically, but the ranged proposed by himself appears just again an approach to over-interpret these indices. In interpreting the DRIS indices, based on Colorado norms for example a value of -7 or lower was used to indicate nutrient deficiency (Soltanpour *et al.*,1995). This means that the values used for interpreting DRIS indices depend on the environmental conditions. It has to be stated as well that even the so-called high- yielding sub-population was not able to make full use of the yield potential, and the fertilizer treatments used in this experiments were probably not yet near the optimum with respect to its composition, nutrient ratio and application rate.

Table 43: Grouping of nutrient contents in the leaves according to CVM from literature data of the crops sampled for nutrient assessment

Crops	*Year*	*Range*	*N*	*P*	*K*	*Ca*	*Mg*	*S*	*Zn*	*Mn*	*Nutrient ranking* (1)
Low											
Maize	*2001*	*D*	*FJ*				*J*	*FJ*			
		C		*FJ*	*FJ*	*F*	*F*		*J*		*F: N=S<P=K=Ca=Mg<Zn* *J: N=Mg=S<P=K=Zn*
		S							*F*		
	2002	*D*	*FJ*		*J*	*J*	*J*	*FJ*	*J*	*J*	
		C		*FJ*	*F*		*F*				*F: N=S<P=K=Mg<Zn=Mn* *J: N=K=Ca=Mg=S=Zn=Mn<P*
		S							*F*	*F*	
Groundnut	*2001*	*D*	*K*	*K*		*K*					
		C			*K*		*K*		*K*		*N=P=Ca<K=Mg=Zn*
		S									
	2002	*D*	*K*	*K*							
		C			*K*	*K*	*K*	-	*K*	*K*	*N=P<K=Ca=Mg=Zn=Mn*
		S									
Sorghum	*2001*	*D*	*FK*		*FK*		*F*				
		C		*FK*		*K*	*K*		*K*		*F: N=K=Mg<P<Zn* *K: N=K<P=Ca=Mg=Zn*
		S							*F*		
	2002	*D*	*FK*		*FK*		*F*				
		C		*FK*		*K*	*K*		*K*	*FK*	*F: N=K=Mg<P=Mn<Zn* *K N=K<P=Ca=Mg=Zn=Mn*
		S							*F*		
Cotton	*2001*	*D*	*S*			*S*					
		C		*S*	*S*		*S*		*S*		*N=Ca<P=K=Mg=Zn*
		S									
High											
Maize	*2001*	*D*	*FJ*				*J*	*FJ*			
		C		*FJ*	*FJ*	*J*	*F*		*J*		*F: N=S<P=K=Mg<Zn* *J: N=Mg=S<P=K=Ca=Zn*
		S							*F*		
	2002	*D*	*FJ*				*J*	*FJ*	*J*	*J*	
		C		*FJ*	*FJ*	*J*	*F*		*F*		*F: N=S<P=K=Mg=Zn* *J: N=Mg=S=Zn=Mn<P=K=Ca*
		S								*F*	
Groundnut	*2001*	*D*		*K*							*P<N=K=Ca=Mg=Zn*
		C	*K*		*K*	*K*	*K*		*K*		
		S									
	2002	*D*		*K*							
		C	*K*		*K*	*K*	*K*	-	*K*	*K*	
		S									
Sorghum	*2001*	*D*	*FK*		*FK*		*F*		*K*		
		C		*FK*		*K*	*K*				*F: N=K=Mg<P<Zn* *K: N=K=Zn<P=Ca=Mg*
		S							*F*		
	2002	*D*	*FK*		*FK*		*F*				
		C		*FK*		*K*	*K*		*K*	*FK*	*F: N=K=Mg<P=Mn<Zn* *K: N=K<P=Ca=Mg=Zn=Mn*
		S							*F*		
Cotton	*2002*	*D*	*S*			*S*					
		C		*S*	*S*		*S*	-	*S*		*N=Ca<P=K=Mg=Zn*
		S									

D: Deficiency C: Critical S: Sufficient

Interpretation of nutrient content according to:

F: FAO (2000) S: Sabbe *et al.* (1972) Jones *et al.* (1990) K: Kang (1980)

(1): Ranking of nutrient from deficiency to sufficiency according to CVM derived from literature data

Differences in DRIS norms established for maize in this thesis compared to literature data could as well be due to the fact, that there are still nutrient constraints for high yields in the selected “high- yielding” sub-population.

In the second year, Mg, Zn, and Mn seemed to be limiting in maize, Mg and S respectively for sorghum and yam. Zinc deficiency was observed similar to those reported by Sillanpää (1990) who pointed out that zinc deficiency is the most commonly occurring micronutrient deficiency problem, limiting crop growth in many tropical countries.

Most of the imbalances reflected by DRIS indices were likely caused by relatively insufficient levels of some nutrients rather than by excessive ones of the other nutrients. The relative deficiencies of P, K, Mg, and S observed with maize in 2001 were the consequence of the relative high level of N and Ca. This is because of the inherent symmetry in the DRIS formula for calculation of the indices or indices that sum to zero according to Elwali *et al.* (1984), Rathfon *et al.* (1984). The groundnut was the crop which did not show any deficiency according to Kelling *et al.* (1986) while none of the nutrients was sufficient according to the CVM (Table 43). In this study, the nutritional balance index (NBI) for the nutrients indicated significant imbalances among nutrients due to the different treatments. There are three possible reasons for this observation: both the fertilizer application had a higher and consistent impact on nutrient balances or possibly another factor i.e. water, was the really limiting factor in 2002 or the competition observed at the beginning between cereal and cowpea.

Table 44: N, P, K, Ca, Mg, S, Zn and Mn Indices, Nutrient Balance Index and Order of Nutrient Requirement Diagnosis and Recommended Integrated System Norms for all crops in 2001 and 2002

Crops	DRIS Indices								NBI	Order of Nutrient Requirement
	N	P	K	Ca	Mg	S	Zn	Mn		
2001										
Maize	0.28	-0.24	-0.15	0.64	-0.18	-0.21	-0.14	-	1.84	P < S < Mg < K < Zn < N <Ca
Cotton	0.03	0.34	-0.09	-0.06	0.25	-0.31	-0.15	-	1.23	S < Zn <K < Ca < N < Mg < P
Peanut	-0.01	-0.05	0.03	-0.01	-0.08	0.06	0.06	-	0.29	Mg < P < N < Ca < K < S < Zn
Sorghum	-0.14	-0.10	-0.09	0.18	0.06	0.12	-0.03	-	0.73	N < P < K < Zn < Mg < S < Ca
Yam	-0.15	-0.14	-0.14	0.10	-0.04	0.31	0.06	-	0.94	N < K < P < Mg < Zn < Ca < S
2002										
Maize	0.13	0.21	0.18	0.05	-0.15	0.14	-0.26	-0.30	1.41	Mn < Zn < Mg < Ca < N < S < K < P
Peanut	-0.04	-0.14	0.09	0.17	-0.13	0.02	0.01	0.03	0.64	P < Mg < N < Zn < S < Mn < K < Ca
Sorghum	0.08	0.11	0.09	-0.09	-0.18	0.09	0.03	-0.13	0.80	Mg < Mn < Ca < Zn < N < K < S < P
Yam	-0.07	0.01	0.00	0.09	-0.01	-0.36	-0.04	0.37	0.95	S < N < Zn < Mg < K < P < Ca < Mn

N, P, K, Ca, Mg, S (g/kg) Zn and Mn (mg kg-1)

NBI: Nutrient Balance Index

4.1.3. Assessment of simplified nutrient balances

Sub-populations constituted for DRIS were used for calculating the nutrient balance per crop. Farmyard manure, its residual effect, and the application of crop residues were considered as organic matter treatment. Nutrient balance assessed in this study did not take into account the input by atmospheric deposition, which is difficult to estimate, the export by leaching and soil erosion as respective data were not collected on a field basis (a more comprehensive assessment of erosion losses has been made by Junge (2004). So in this study a partial nutrient balance has been assessed, which reflected the reality in the farmers' field in the Upper Oueme Catchment.

Mean of nutrient contents in different part of the crops were similar to those reported by many authors Duivenbooden (1992), Stoorvogel and Smaling (1990), Linnemann (1996) and NAS (1994).

Farmers in general used to apply mineral fertilizer on cotton even though the rate recommended by INRAB was frequently not respected. Thus, farmers practice leads to slight deficits for N and K. To guarantee a sustainable cotton production would require higher fertilizer inputs.

Actual farmers' practices in maize, sorghum, groundnut and yam cropping systems lead to the depletion in soil nutrient levels, as there is almost no return of nutrients to the fields.

At the end of the experiment, soil chemical characteristics (Table 45) were not improved. N and P were low ($N < 0.1$ %, $P< 8$ mg kg^{-1}), K contents low ($K< 0.15$) to intermediate ($0.15 < K <0.30$ cmol kg^{-1}), and organic matter contents likewise low.

In summary, the soil fertility of all tested sites in the Upper Oueme Catchment is always low.

Table 45: Soil chemical properties at the end of experiment (2002)

Treatments	N	P	K	OM	C/N	pH	N	P	K	OM	C/N	pH
	Low- yielding sub- population						High- yielding sub- population					
Maize												
T0	0.067	2.3	0.16	1.35	12.4	6.2	0.079	-	0.14	1.73	12.8	-
	(0.021)	*(1.6)*	*(0.08)*	*(0.59)*	*0.9*	*0.3*	*(0.032)*	-	*(0.04)*	*(0.73)*	*(1.4)*	-
T1	0.068	**2.5**	**0.16**	1.51	**12.8**	6.2	0.074	-	0.15	1.67	13.1	-
	(0.016)	*(1.9)*	*(0.05)*	*(0.41)*	*(0.6)*	*(0.2)*	*(0.014)*	-	*(0.05)*	*(0.36)*	*(1.5)*	-
T2	**0.071**	2.2	**0.17**	**1.56**	12.7	**6.0**	0.061	-	0.15	1.36	12.9	-
	(0.015)	*(2.0)*	*(0.02)*	*(0.43)*	*(1.2)*	*(0.2)*	*(0.015)*	-	*(0.05)*	*(0.34)*	*(0.9)*	-
T3	**0.063**	**1.9**	0.17	**1.31**	**12.0**	**6.2**	0.066	7.3	0.16	1.46	12.8	6.1
	(0.017)	*(1.0)*	*(0.06)*	*(0.40)*	*(1.1)*	*(0.2)*	*(0.014)*	*(2.8)*	*(0.05)*	*(0.41)*	*(1.4)*	*(0.1)*
Yam												
T0	0.065	3.6	**0.15**	**1.42**	12.7	**6.4**	0.060	-	0.14	1.26	12.2	-
	(0.017)	*(2.0)*	*(0.05)*	*(0.40)*	*(1.1)*	*(0.3)*	*(0.016)*	-	*(0.12)*	*(0.30)*	*(0.7)*	-
T1	**0.063**	**3.1**	0.18	1.46	**13.3**	**6.5**	0.072	-	0.14	1.53	12.4	-
	(0.014)	*(2.6)*	*(0.06)*	*(0.44)*	*(1.8)*	*(0.2)*	*(0.016)*	-	*(0.06)*	*(0.40)*	*(1.0)*	-
T2	0.066	4.6	0.16	1.53	13.2	6.4	0.064	4.1	0.15	1.35	12.1	6.3
	(0.018)	*(1.9)*	*(0.04)*	*(0.50)*	*(1.4)*	*(0.3)*	*(0.016)*	-	*(0.04)*	*(0.40)*	*(0.9)*	-
T3	**0.074**	**7.1**	**0.26**	**1.61**	**12.6**	6.4	0.066	-	0.12	1.35	12.1	-
	(0.024)	*(5.3)*	*(0.19)*	*(0.58)*	*(1.8)*	*(0.2)*	*(0.013)*	-	*(0.08)*	*(0.24)*	*(1.3)*	-
Sorghum												
T0	0.056	5.1	0.14	1.17	12.1	6.6	0.058	-	0.14	1.27	12.5	-
	(0.008)	*(1.4)*	*(0.03)*	*(0.18)*	*(0.7)*	*(0.2)*	*(0.013)*	-	*(0.08)*	*(0.35)*	*(1.1)*	-
T1	0.062	4.1	0.19	1.27	11.9	6.5	0.060	-	0.12	1.36	13.0	-
	(0.015)	*(1.9)*	*(0.08)*	*(0.36)*	*(1.3)*	*(0.3)*	*(0.012)*	-	*(0.02)*	*(0.35)*	*(1.4)*	-
T2	0.061	5.2	0.22	1.28	12.2	6.6	0.062	-	0.11	1.43	13.4	-
	(0.015)	*(1.0)*	*(0.16)*	*(0.30)*	*(1.1)*	*(0.3)*	*(0.011)*	-	*(0.04)*	*(0.21)*	*(1.1)*	-
T3	0.064	4.8	0.15	1.32	12.0	6.6	0.059	-	0.17	1.34	13.1	-
	(0.017)	*(2.5)*	*(0.05)*	*(0.36)*	*(0.7)*	*(0.2)*	*(0.013)*	-	*(0.04)*	*(0.32)*	*(1.4)*	-
Groundnut												
T0	0.062	-	0.14	1.27	11.8	6.4	0.054	-	0.19	1.16	12.4	-
	(0.014)	-	*(0.04)*	*(0.32)*	*(1.0)*	-	*(0.008)*	-	*(0.11)*	*(0.19)*	*(0.8)*	-
T1	0.060	-	0.19	1.30	12.5	6.5	0.057	-	0.19	1.17	12.0	-
	(0.008)	-	*(0.11)*	*(0.26)*	*(0.9)*	-	*(0.011)*	-	*(0.04)*	*(0.23)*	*(1.0)*	-
T2	0.055	-	0.15	1.17	12.1	6.5	0.062	-	0.25	1.39	12.9	-
	(0.012)	-	*(0.05)*	*(0.40)*	*(1.7)*	-	*(0.017)*	-	*(0.16)*	*(0.38)*	*(0.7)*	-
T3	0.056	-	0.16	1.19	12.2	6.4	0.067	-	0.17	1.50	13.0	-
	(0.005)	-	*(0.05)*	*(0.22)*	*(1.2)*	-	*(0.021)*	-	*(0.04)*	*(0.54)*	*(0.9)*	-

( ) Standard deviation N and OM: in %

P: in mg kg^{-1} K: in cmol kg^{-1}

As farmers usually do not apply fertilizer to food crops, after a cropping sequence without almost any fertilizer (besides for cotton), present farmer's practice will lead inevitably to a depletion of available nutrients. When calculating the for a typical yam-cotton-maize-groundnut-sorghum rotation

(Table 46), during the five years of this rotation, the nutrient balances become increasingly negative. The deficit of N for the high productivity population needs to be annually compensated (Table 45). If about 40 and 50 % of the mineralized N may be lost under high rainfall conditions in West Africa (Muller Harvey *et al.* 1981), and due to the important amount of nitrogen exported by harvest product and the crop residues, it is obvious to take into account this amount of nutrient lost in the fertilizer program.

In this study, K appeared to be second most limiting the production of all crops used for the experiment. Even although most soils of the experiment derived from micaceous minerals, which are rich in potassium, this nutrient depleted within the time and will be needed in order to supply crop demand. The amount of this nutrient released per year apparently did not supply crop this demand. The rate of K application needed to be reviewed on PLINTHOSOLS, Ferric LUVISOLS, ACRISOLS and LIXISOLS as this nutrient was one of the most limiting crop production according to DRIS-evaluation, and for K, partial nutrient balances where negative throughout (Table 44).

Even though P is annually exported in lesser amounts by the harvested product and crop residues, care should be taken to compensate for nutrient export from the field.

According to Sanchez *et al.* (1997), annual nutrient losses in Africa are equivalent to 7.9 million tons of NPK, 6 times the annual fertilizer consumption. Lal (2001) reported that depletion of soil organic matter in tropic regions can be as high as 70 per cent within a cultivation period of 10 years. Soil organic matter is a key factor in maintaining long-term soil fertility, as it is the reservoir of metabolic energy, which drives soil biological processes involved in nutrient availability.

Soil organic matter has also a profound influence on soil chemical (cation exchange capacity, buffering of soil pH, chelation of metals, etc.) and physical (stabilization of soil structure, water retention, etc.) properties (Sumner, 1999). Agricultural production cannot be replenished, and if appropriate agricultural practices are not implemented to maintain soil organic matter. This could help for the rational use of the scarce water resources in the Upper Oueme Catchment.

Table 46: Average nutrients (N, P, K) balance of farming system as affected by low and high yielding subpopulations of yam-cotton-maize-groundnut-sorghum rotation in Upper Oueme catchment of Benin

	In 1.1	In 1.2	In 2	In 4	Σ In	Out 1	Out 2	Σ Out	Balance
N									
Low- yielding sub-population									
Treatments									
T0	0.0	0.0	44.0	34.3	78.3	103.7	70.2	174.0	-95.7
T1	140.8	161.1	0.0	36.4	338.3	109.7	71.2	180.9	157.3
T2	0.0	0.0	188.8	23.7	212.5	120.6	64.5	185.1	27.4
T3	148.0	146.4	186.3	20.6	501.3	110.9	65.7	176.6	324.8
High- yielding sub-population									
T0	0.0	0.0	44.0	54.7	98.7	181.5	103.0	284.4	-185.7
T1	90.8	237.8	0.0	40.7	369.3	192.1	85.8	278.0	91.4
T2	9.1	0.0	183.2	33.9	226.2	222.6	91.8	314.5	-88.2
T3	119.9	208.5	188.8	40.5	557.7	227.9	95.5	323.4	234.2
P									
Low- yielding sub-population									
Treatments									
T0	0.0	0.0	15.0	0.0	15.0	18.6	7.3	25.9	-10.9
T1	57.1	26.7	0.0	0.0	83.9	20.4	6.7	27.1	56.7
T2	0.0	0.0	83.5	0.0	83.5	22.4	7.3	29.7	53.8
T3	59.0	24.6	82.4	0.0	166.1	19.7	6.6	26.4	139.7
High- yielding sub-population									
T0	0.0	0.0	15.0	0.0	15.0	35.5	20.6	56.2	-41.2
T1	38.7	41.3	0.0	0.0	80.0	35.9	11.3	47.2	32.8
T2	3.4	0.0	79.5	0.0	82.9	41.1	11.3	52.4	30.5
T3	47.4	36.1	83.5	0.0	167.0	43.5	11.4	54.9	112.1
K									
Low- yielding sub-population									
Treatments									
T0	0.0	0.0	17.5	0.0	17.5	53.4	83.0	136.4	-118.9
T1	237.7	163.6	0.0	0.0	401.3	61.5	87.3	148.8	252.5
T2	0.0	0.0	95.0	0.0	95.0	68.2	79.3	147.5	-52.5
T3	252.4	150.3	90.8	0.0	493.5	65.2	76.4	141.6	351.8
High- yielding sub-population									
T0	0.0	0.0	17.5	0.0	17.5	89.3	105.1	194.3	-176.8
T1	132.6	274.3	0.0	0.0	406.9	96.5	131.3	227.8	179.1
T2	14.2	0.0	90.3	0.0	104.5	105.1	146.3	251.3	-146.8
T3	174.5	220.3	95.0	0.0	489.8	119.8	141.7	261.5	228.3

T0: Farmer’s practice T1: Organic fertilizer T2: Mineral fertilizer T3: Organic and mineral fertilizers

In 1: input of crop residues; In 12: input of farmyard manure; In2: input of mineral fertilizer; ∑In: sum inputs;

Ou1 1: output of harvest product; Out 2: output of crop residues (leaves, stems) ∑Out: sum outputs

The application of organic matter, eventually in combination with mineral fertilizer may lead to an apparent overcompensation of nutrient removal. Although unproductive nutrient accumulation in soils has to be avoided, a certain initial nutrient accumulation should be tolerated for enhancing the soil’s productivity. More efforts will be needed to design management practices that optimize nutrient supply, avoiding both over- as well as undersupply, soil organic matter contents and which give the highest economic return.

It is appeared in this study that the combination of organic and mineral fertilizer gave the highest positive balance and could be the only one opportunity for the agriculture in the area of research. This result is in agreement with Pieri (1985), who has summarized many of experiments on nutrient balances, and he concluded that fertilizer application is an effective means to increase yields in arable farming systems without fallows. He cautioned that in long term problems such as acidification and micronutrient deficiencies and may arise, especially in the regions where farmer’s practices do not allow a sustainable agriculture. Application of organic and mineral fertilizers results in yield increases for some years, but in the long run it will decrease base saturation and acidify soils if liming will not be practiced. These phenomena, associated with the use of N, P and K fertilizers, are characterized by compensating deficiency observed with these nutrients. Under conditions of West Africa, the use of mineral fertilizer alone does not guaranty a sustainable agriculture on a long run. The combination of organic and mineral fertilizers is a way to sustainable agriculture. According to Pieri (1985), application of organic material such as green manure, crop residues, compost or farmyard manure can counteract the negative effects of chemical fertilizers. This leads this author to conclude that soil fertility in intensive arable farming systems in the West African can only be maintained through efficient recycling of organic material, in combination with effective use of N-fixing leguminous species and chemical fertilizers.

4.2. Conclusions and recommendations

This study showed that in Upper Oueme Catchment, organic or mineral or the combination of both fertilizers increased crop productivities and WUE of maize although a relatively high variability was observed between individual plots.

Nitrogen was the most limiting nutrients, followed by potassium and phosphorous. Although it is well recognized, that application of mineral fertilizers plays an important role in the increasing of crop production, lack of affordable and adequate supplies of fertilizers in the experimental area remains one of the major constraints for crop production.

DRIS norms established in this study were useful to evaluate crop nutritional status, to correct observed nutritional imbalances and to improve crop productivity. They can be used as a basis for a calibration of the fertilization programs of these crops, which should subsequently be validated by farmers and organizations involved in these productions.

For a future development of optimized DRIS norms, more fertilizer experiments should be set-up where a nutrient supply could be defined which makes full use of the yield potential. This research can be done according to each major type of soil and agro ecological zones in Benin. Furthermore, critical level of sufficiency ranges for these crops are necessary to be developed. Both evaluations are necessary for accurate interpretation of foliar nutrient content data.

There are some possible scenarios about implications of the nutrient depletion in the research area.

Assuming that there is no change according to actual farmer’s practice in the future, this is an unfavorable scenario as nutrient depletion continues and will become severe in the long run, as soil in the research area will provide less nutrients for crop growth.

One scenario could be the application of mineral fertilizer alone. This is one scenario which will be possible in an area where cotton is produced. But nowadays, this production is in decreasing, and thus it is not realistic to follow this scenario. Furthermore, it is not possible to minimize or stop nutrient depletion only by increasing the application of mineral fertilizer alone to one crop.

The most favorable scenario will be a combined practice for integrated soil fertility management where mineral and organic fertilizers are combined (at an adequate rate which compensates for nutrient removal). The nutrient use efficiency will thus be improved. Sustainable crop production in Upper Oueme Catchment requires a judicious management of all nutrient sources. Crop rotations including legumes to optimize nitrogen fixation, mineral fertilizer, efficient management of crop residues, and management methods that limit nutrient losses and increase water use efficiency are some of the approaches that will be used to improve and sustain soil fertility and conversely to enhance crop production in Upper Oueme Catchment. The incorporation of green manure on soil just before cropping could be the best alternative due to the grazing of almost all crop residues just after harvesting. With the first rain, farmers can grow legumes that will be used as green manure for the next crop, provided water availability will still allow double cropping and mixed cropping systems.

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Appendices

Appendix 1: Chemical characteristics of lighter soil (plough layer 0 - 20) at the beginning (2001) and the end (2002) of experiment in Beterou. In parenthesis: standard deviation

Crops	Treatments	N	P	K	pH	OM	C/N	N	P	K	pH	OM	C/N
		2001						2002					
2001 Cotton	T0	0.054	13.9	0.24	6.7	1.35	14.7	0.058	6.6	0.17	6.5	1.31	13.0
		(0.019)	(20.1)	(0.11)	(0.3)	(0.42)	(1.9)	(0.012)	(5.9)	(0.06)	(0.3)	(0.33)	(1.2)
	T1	0.056	9.9	0.25	6.7	1.38	14.6	0.060	5.2	0.21	6.6	1.33	12.8
		(0.016)	(6.9)	(0.11)	(0.3)	(0.30)	(1.8)	(0.013)	(3.3)	(0.09)	(0.4)	(0.33)	(0.9)
	T2	0.057	6.4	0.26	6.7	1.38	14.1	0.065	9.6	0.22	6.6	1.46	12.9
		(0.016)	(3.3)	(0.12)	(0.2)	(0.42)	(1.8)	(0.017)	(5.9)	(0.11)	(0.3)	(0.48)	(1.3)
	T3	0.060	8.7	0.25	6.7	1.33	13.3	0.066	9.9	0.21	6.7	1.51	13.0
		(0.018)	(5.8)	(0.08)	(0.2)	(0.34)	(3.0)	(0.024)	(11.2)	(0.09)	(0.3)	(0.74)	(1.7)
Groundnut	T0	0.061	10.5	0.22	6.7	1.38	13.1	0.057	2.9	0.14	6.5	1.24	12.7
		(0.015)	(10.0)	(0.04)	(0.4)	(0.38)	(1.7)	(0.004)	(2.6)	(0.03)	(0.2)	(0.10)	(0.8)
	T1	0.057	5.4	0.20	6.6	1.28	13.1	0.065	3.4	0.16	6.5	1.55	13.8
		(0.013)	(2.5)	(0.03)	(0.4)	(0.32)	(1.1)	(0.007)	(2.1)	(0.04)	(0.2)	(0.26)	(1.1)
	T2	0.069	7.1	0.27	6.5	1.48	12.7	0.063	4.1	0.16	6.5	1.43	13.3
		(0.011)	(2.8)	(0.07)	(0.2)	(0.21)	(1.9)	(0.014)	(3.8)	(0.03)	(0.1)	(0.33)	(0.6)
	T3	0.064	17.8	0.33	6.4	1.44	13.0	0.073	3.7	0.19	6.5	1.70	13.3
		(0.016)	(21.9)	(0.22)	(0.2)	(0.45)	(1.3)	(0.015)	(1.3)	(0.04)	(0.1)	(0.53)	(1.5)
Maize	T0	0.064	8.9	0.23	6.8	1.49	13.7	0.077	4.6	0.17	6.7	1.64	12.4
		(0.020)	(9.2)	(0.11)	(0.2)	(0.45)	1.5	0.027	2.8	0.04	(0.6)	(0.61)	(0.9)
	T1	0.071	10.3	0.28	6.8	1.77	14.4	0.073	6.7	0.19	6.7	1.60	12.6
		(0.024)	(7.6)	(0.16)	(0.2)	(0.66)	1.5	0.022	6.3	0.06	(0.4)	(0.57)	(1.3)
	T2	0.061	9.2	0.26	6.8	1.43	13.6	0.072	6.0	0.23	6.7	1.63	12.9
		(0.012)	(9.4)	(0.08)	(0.2)	(0.27)	(1.3)	0.020	4.7	0.15	(0.5)	(0.54)	(1.3)
	T3	0.058	8.6	0.29	6.8	1.41	14.2	0.076	9.4	0.25	6.6	1.55	11.9
		(0.012)	(5.8)	(0.09)	(0.3)	(0.32)	(2.2)	0.028	12.1	0.24	(0.5)	(0.64)	(1.8)
Sorghum	T0	0.059	10.8	0.21	6.7	1.50	14.8	0.059	2.9	0.14	6.5	1.22	11.9
		(0.024)	(7.4)	(0.10)	(0.2)	(0.62)	(0.8)	(0.012)	(1.7)	(0.04)	(0.4)	(0.34)	(1.4)
	T1	0.053	12.9	0.20	6.8	1.38	14.8	0.058	3.4	0.16	6.4	1.27	12.6
		(0.017)	(6.0)	(0.10)	(0.2)	(0.52)	(1.2)	(0.008)	(1.5)	(0.04)	(0.3)	(0.26)	(1.1)
	T2	0.063	14.6	0.22	6.8	1.68	15.1	0.059	2.5	0.24	6.4	1.26	12.1
		(0.019)	(10.1)	(0.07)	(0.2)	(0.68)	(1.9)	(0.013)	(1.2)	(0.19)	(0.3)	(0.43)	(1.9)
	T3	0.052	7.2	0.14	6.8	1.35	15.2	0.062	3.6	0.16	6.5	1.38	12.6
		(0.018)	(4.2)	(0.05)	(0.2)	(0.47)	(1.0)	(0.020)	(1.9)	(0.04)	(0.3)	(0.61)	(1.6)
Yam	T0	0.082	12.0	0.26	6.8	2.01	14.2	-	-	-	-	-	-
		(0.035)	(10.7)	(0.11)	(0.4)	(0.85)	(1.1)	-	-	-	-	-	-
	T1	0.073	11.1	0.29	6.7	1.86	14.6	-	-	-	-	-	-
		(0.021)	(10.7)	(0.19)	(0.3)	(0.66)	(1.9)	-	-	-	-	-	-
	T2	0.079	11.7	0.28	6.8	1.91	14.1	-	-	-	-	-	-
		(0.034)	(11.9)	(0.12)	(0.2)	(0.76)	(1.4)	-	-	-	-	-	-
	T3	0.079	24.2	0.25	6.7	1.88	14.1	-	-	-	-	-	-
		(0.032)	(34.7)	(0.15)	(0.2)	(0.63)	(2.0)	-	-	-	-	-	-

T1M: 10 t ha^{-1}crop residues

T1F: 10 t ha^{-1} of farmyard manure in 2001

T2: mineral fertilizer at the rates recommended

T3M: T2 + 10 t ha^{-1} of crop residues for mulch in 2001 and 2002

T3F: T2 + 10 t ha^{-1} of farmyard manure.

Appendix 2: Chemical characteristics of heavier soil (plough layer 0 - 20) at the beginning (2001) and the end (2002) of experiment in Beterou. In parenthesis: standard deviation

Crops	Treatments	N	P	K	pH	OM	C/N	N	P	K	pH	OM	C/N
		2001						**2002**					
2001 **Maize**	T0	0.055	22.6	0.24	6.8	1.35	14.6	0.065	3.6	0.21	6.4	1.23	11.0
		(0.014)	*(16.5)*	*(0.08)*	*(0.2)*	*(0.25)*	*(1.8)*	*(0.032)*	*(2.7)*	*(0.02)*	*(0.4)*	*(0.57)*	*(0.3)*
	T1	0.064	12.6	0.29	6.8	1.64	14.6	0.066	3.6	0.17	6.4	1.44	12.6
		(0.025)	*(8.6)*	*(0.10)*	*(0.1)*	*(0.71)*	*(1.2)*	*(0.033)*	*(3.9)*	*(0.07)*	*(0.4)*	*(0.74)*	*(1.2)*
	T2	0.107	35.2	0.32	6.8	3.31	16.5	0.047	3.8	0.14	6.4	1.02	12.6
		(0.093)	*(35.0)*	*(0.02)*	*(0.1)*	*(3.29)*	*(2.6)*	*(0.001)*	*(2.7)*	*(0.07)*	*(0.5)*	*(0.05)*	*(1.0)*
	T3	0.061	14.5	0.24	6.8	1.55	15.1	0.061	3.4	0.13	6.4	1.32	12.3
		(0.028)	*(17.6)*	*(0.08)*	*(0.0)*	*(0.72)*	*(3.6)*	*(0.032)*	*(3.6)*	*(0.07)*	*(0.5)*	*(0.80)*	*(0.9)*
Yam	T0	0.047	9.8	0.32	6.6	1.21	14.4	-	-	-	-	-	-
		(0.025)	*(10.1)*	*(0.05)*	*(0.1)*	*(0.76)*	*(1.6)*	-	-	-	-	-	-
	T1	0.057	6.4	0.39	6.6	1.39	14.0	-	-	-	-	-	-
		(0.015)	*(4.3)*	*(0.17)*	*(0.1)*	*(0.57)*	*(2.2)*	-	-	-	-	-	-
	T2	0.047	33.9	0.43	6.5	1.63	20.9	-	-	-	-	-	-
		(0.008)	*(44.1)*	*(0.10)*	*(0.1)*	*(0.34)*	*(7.9)*	-	-	-	-	-	-
	T3	0.051	5.4	0.28	6.5	1.23	14.0	-	-	-	-	-	-
		(0.006)	*(2.9)*	*(0.02)*	*(0.1)*	*(0.34)*	*(2.1)*	-	-	-	-	-	-

T1M: 10 t ha^{-1}crop residues

T1F: 10 t ha^{-1} of farmyard manure in 2001

T2: mineral fertilizer at the rates recommended

T3M: T2 + 10 t ha^{-1} of crop residues for mulch in 2001 and 2002

T3F: T2 + 10 t ha^{-1} of farmyard manure.

Appendix 3: Chemical characteristics of lighter soil (plough layer 0 - 20) at the beginning (2001) and the end (2002) of experiment in Dogue. In parenthesis: standard deviation

Crops 2001	Treatments	N	P	K	pH	OM	C/N	N	P	K	pH	OM	C/N
		2001						2002					
Maize	T0	0.045	2.4	0.09	6.3	1.04	13.5	0.060	4.3	0.16	6.3	1.16	11.2
		(0.007)	*(1.7)*	*(0.03)*	*(0.1)*	*(0.13)*	*(1.8)*	*(0.010)*	*(2.6)*	*(0.05)*	*(0.4)*	*(0.18)*	*(1.3)*
	T1	0.044	6.5	0.14	6.3	1.02	13.6	0.062	3.9	0.18	6.3	1.23	11.6
		(0.005)	*(7.1)*	*(0.09)*	*(0.2)*	*(0.17)*	*(2.2)*	*(0.012)*	*(2.3)*	*(0.10)*	*(0.4)*	*(0.24)*	*(1.2)*
	T2	0.049	2.9	0.08	6.3	1.08	13.0	0.058	4.9	0.27	6.4	1.35	13.2
		(0.012)	*(1.2)*	*(0.04)*	*(0.2)*	*(0.19)*	*(1.3)*	*(0.007)*	*(1.9)*	*(0.09)*	*(0.4)*	*(0.44)*	*(3.0)*
	T3	0.055	3.7	0.12	6.4	1.26	13.6	0.077	5.8	0.16	6.4	1.56	11.8
		(0.014)	*(1.7)*	*(0.05)*	*(0.1)*	*(0.25)*	*(1.0)*	*(0.017)*	*(3.7)*	*(0.05)*	*(0.4)*	*(0.34)*	*(1.2)*
Yam	T0	0.079	4.0	0.12	6.7	1.55	11.3	0.067	3.4	0.13	6.1	1.30	11.2
		(0.028)	*(0.2)*	*(0.08)*	*(0.4)*	*(0.68)*	*(1.6)*	*(0.006)*	*(0.7)*	*(0.04)*	*(0.2)*	*(0.37)*	*(2.5)*
	T1	0.073	3.3	0.12	6.4	1.54	12.3	0.059	3.6	0.14	6.2	1.27	12.5
		(0.010)	*(1.7)*	*(0.03)*	*(0.2)*	*(0.20)*	*(1.6)*	*(0.005)*	*(1.0)*	*(0.04)*	*(0.2)*	*(0.20)*	*(1.2)*
	T2	0.059	4.8	0.13	6.5	1.24	12.1	0.055	4.3	0.13	6.0	1.13	11.9
		(0.007)	-	-	-	*(0.36)*	*(2.1)*	*(0.007)*	*(0.4)*	*(0.01)*	*(0.3)*	*(0.23)*	*(1.9)*
	T3	0.061	4.1	0.17	6.4	1.33	12.7	0.071	2.9	0.12	6.1	1.28	10.5
		(0.004)	-	-	-	*(0.12)*	*(2.0)*	*(0.009)*	*(0.8)*	*(0.03)*	*(0.3)*	*(0.01)*	*(1.3)*

T1M: 10 t ha^{-1}crop residues

T1F: 10 t ha^{-1} of farmyard manure in 2001

T2: mineral fertilizer at the rates recommended

T3M: T2 + 10 t ha^{-1} of crop residues for mulch in 2001 and 2002

T3F: T2 + 10 t ha^{-1} of farmyard manure.

Appendix 4: Chemical characteristics of heavier soil (plough layer 0 - 20) at the beginning (2001) and the end (2002) of experiment in Dogue. In parenthesis: standard deviation

Crops 2001	Treatments	N	P	K	pH	OM	C/N	N	P	K	pH	OM	C/N
		2001						2002					
Cotton	T0	0.062	3.0	0.19	6.2	1.41	13.2	0.067	1.7	0.13	6.3	1.55	13.6
		(0.008)	*(0.3)*	*(0.14)*	*(0.1)*	*(0.36)*	*(1.7)*	*(0.004)*	*(0.5)*	*(0.04)*	*(0.1)*	*(0.09)*	*(0.0)*
	T1	0.069	2.3	0.11	6.2	1.57	13.3	0.072	1.4	0.14	6.3	1.99	16.2
		(0.001)	*(0.4)*	*(0.07)*	*(0.0)*	*(0.05)*	*(0.6)*	*(0.015)*	*(1.0)*	-	*(0.0)*	*(0.32)*	*(0.8)*
	T2	0.064	3.4	0.15	6.3	1.47	13.4	0.080	3.4	-	6.2	1.89	13.6
		(0.011)	*(1.0)*	*(0.02)*	*(0.1)*	*(0.24)*	*(0.1)*	*(0.017)*	*(1.0)*	-	*(0.1)*	*(0.49)*	*(0.7)*
	T3	0.052	3.1	0.14	6.2	1.11	12.3	0.061	8.2	0.24	6.2	1.39	13.2
		(0.004)	*(0.5)*	*(0.06)*	*(0.0)*	*(0.17)*	*(0.9)*	*(0.006)*	*(8.7)*	-	*(0.0)*	*(0.25)*	*(1.0)*
Maize	T0	0.052	5.4	0.16	6.4	1.16	13.0	0.068	6.4	0.16	6.5	1.42	12.0
		(0.007)	*(2.6)*	*(0.06)*	*(0.4)*	*(0.16)*	*(1.7)*	*(0.017)*	*(6.5)*	*(0.03)*	*(0.2)*	*(0.42)*	*(1.0)*
	T1	0.055	4.0	0.14	6.5	1.24	13.3	0.073	4.1	0.16	6.5	1.65	12.9
		(0.009)	*(1.4)*	*(0.06)*	*(0.3)*	*(0.20)*	*(1.3)*	*(0.025)*	*(1.4)*	*(0.03)*	*(0.2)*	*(0.70)*	*(1.3)*
	T2	0.063	5.3	0.14	6.4	1.17	-	0.069	4.8	0.14	6.5	1.54	12.8
		(0.012)	*(2.9)*	*(0.12)*	*(0.3)*	*(0.60)*	-	*(0.024)*	*(1.6)*	*(0.01)*	*(0.2)*	*(0.59)*	*(1.0)*
	T3	0.062	4.7	0.13	6.4	1.42	13.3	0.067	4.2	0.17	6.5	1.52	12.9
		(0.011)	*(1.8)*	*(0.06)*	*(0.4)*	*(0.37)*	*(1.9)*	*(0.026)*	*(2.1)*	*(0.05)*	*(0.2)*	*(0.75)*	*(1.4)*
Yam	T0	0.068	10.2	-	6.2	1.52	12.9	0.074	7.8	0.12	5.9	1.54	11.8
		-	-	-	-	-	-	*(0.036)*	*(6.2)*	*(0.08)*	*(0.3)*	*(0.89)*	*(1.3)*
	T1	0.079	9.6	0.21	6.4	1.82	13.4	0.077	7.1	0.15	6.1	1.34	10.2
		-	-	-	-	-	-	*(0.025)*	*(5.3)*	*(0.06)*	*(0.4)*	*(0.36)*	*(0.6)*
	T2	0.082	13.4	0.20	6.5	1.83	13.0	0.094	9.1	0.14	6.1	1.81	11.3
		-	-	-	-	-	-	*(0.050)*	*(8.1)*	*(0.08)*	*(0.4)*	*(0.94)*	*(0.2)*
	T3	0.057	5.1	0.17	6.5	1.36	13.8	0.070	4.7	0.23	6.3	1.40	11.7
		-	-	-	-	-	-	*(0.018)*	*(1.0)*	*(0.09)*	*(0.3)*	*(0.35)*	*(0.2)*
Sorghum	T0	0.064	2.7	0.19	6.4	1.43	13.0	-	-	-	-	-	-
		(0.008)	*(3.8)*	-	-	*(0.09)*	*(0.9)*	-	-	-	-	-	-
	T1	0.064	3.3	0.10	6.3	1.48	13.5	-	-	-	-	-	-
		(0.004)	*(1.1)*	*(0.00)*	*(0.1)*	*(0.08)*	*(1.6)*	-	-	-	-	-	-
	T2	0.070	3.8	0.12	6.5	1.48	12.2	-	-	-	-	-	-
		(0.005)	*(1.6)*	*(0.05)*	*(0.3)*	*(0.16)*	*(1.4)*	-	-	-	-	-	-
	T3	0.063	4.5	0.14	6.4	1.31	12.2	-	-	-	-	-	-
		(0.006)	*(1.1)*	*(0.02)*	*(0.3)*	*(0.11)*	*(0.7)*	-	-	-	-	-	-

T1M: 10 t ha^{-1}crop residues

T1F: 10 t ha^{-1} of farmyard manure in 2001

T2: mineral fertilizer at the rates recommended

T3M: T2 + 10 t ha^{-1} of crop residues for mulch in 2001 and 2002

T3F: T2 + 10 t ha^{-1} of farmyard manure.

Appendix 5: Chemical characteristics of lighter soil (plough layer 0 - 20) at the beginning (2001) and the end (2002) of experiment in Wewe. In parenthesis: standard deviation

Crops 2001	Treatments	N	P	K	pH	OM	C/N	N	P	K	pH	OM	C/N
		2001						2002					
Cotton	T0	0.066	5.8	0.09	6.7	1.19	10.8	-	-	-	-	-	-
		(0.017)	*(3.6)*	*(0.04)*	*(0.2)*	*(0.23)*	*(2.9)*	-	-	-	-	-	-
	T1	0.074	4.1	0.11	6.6	1.24	10.3	-	-	-	-	-	-
		(0.024)	*(3.2)*	*(0.04)*	*(0.1)*	*(0.12)*	*(2.7)*	-	-	-	-	-	-
	T2	0.081	12.0	0.13	6.7	1.35	11.1	-	-	-	-	-	-
		(0.040)	*(13.6)*	*(0.07)*	*(0.2)*	*(0.25)*	*(5.0)*	-	-	-	-	-	-
	T3	0.105	8.8	0.16	6.7	1.56	10.4	-	-	-	-	-	-
		(0.065)	*(6.3)*	*(0.08)*	*(0.2)*	*(0.15)*	*(4.4)*	-	-	-	-	-	-
Groundnut	T0	0.054	4.0	0.12	6.5	1.13	12.1	0.060	2.8	0.14	6.4	1.29	12.6
		(0.009)	*(1.2)*	*(0.03)*	*(0.3)*	*(0.20)*	*(0.8)*	*(0.021)*	*(1.6)*	*(0.15)*	*(0.4)*	*(0.40)*	*(0.8)*
	T1	0.059	5.8	0.13	6.5	1.27	12.3	0.070	4.7	0.14	6.5	1.52	12.6
		(0.014)	*(1.5)*	*(0.02)*	*(0.3)*	*(0.42)*	*(1.3)*	*(0.011)*	*(2.2)*	*(0.09)*	*(0.2)*	*(0.26)*	*(0.4)*
	T2	0.053	4.2	0.15	6.5	1.13	12.4	0.059	4.6	0.13	6.4	1.24	12.2
		(0.010)	*(0.7)*	*(0.03)*	*(0.3)*	*(0.25)*	*(1.1)*	*(0.015)*	*(0.8)*	*(0.06)*	*(0.2)*	*(0.37)*	*(0.7)*
	T3	0.054	5.1	0.18	6.5	1.15	12.3	0.058	5.2	0.09	6.4	1.23	12.4
		(0.007)	*(1.8)*	*(0.07)*	*(0.2)*	*(0.18)*	*(0.8)*	*(0.010)*	*(2.2)*	*(0.04)*	*(0.2)*	*(0.17)*	*(0.4)*
Maize	T0	0.043	9.3	0.15	6.6	1.11	24.5	0.055	16.4	0.38	6.7	1.18	12.3
		(0.020)	*(4.9)*	*(0.04)*	*(0.3)*	*(0.18)*	*(25.0)*	*(0.009)*	*(18.3)*	*(0.56))*	*(0.4)*	*(0.22)*	*(0.8)*
	T1	0.045	6.7	0.20	6.7	1.18	52.0	0.060	6.1	0.17	6.7	1.26	12.1
		(0.024)	*(2.8)*	*(0.09)*	*(0.2)*	*(0.20)*	*(88.3)*	*(0.015)*	*(2.5)*	*(0.05)*	*(0.4)*	*(0.39)*	*(1.4)*
	T2	0.051	6.8	0.16	6.7	1.20	16.3	0.056	7.7	0.15	6.7	1.25	12.8
		(0.018)	*(5.2)*	*(0.08)*	*(0.2)*	*(0.29)*	*(11.0)*	*(0.013)*	*(3.3)*	*(0.11)*	*(0.4)*	*(0.34)*	*(1.2)*
	T3	0.044	4.4	0.16	6.7	1.16	24.7	0.061	6.3	0.18	6.8	1.33	12.6
		(0.020)	*(1.2)*	*(0.06)*	*(0.2)*	*(0.19)*	*(26.6)*	*(0.014)*	*(2.1)*	*(0.05)*	*(0.2)*	*(0.29)*	*(1.4)*
Sorghum	T0	0.041	5.8	0.11	6.6	1.13	21.0	0.055	2.6	0.10	6.5	1.16	12.2
		(0.026)	*(1.0)*	*(0.02)*	*(0.2)*	*(0.10)*	*(15.0)*	*(0.006)*	-	*(0.08)*	-	*(0.26)*	*(1.3)*
	T1	0.040	6.1	0.12	6.6	1.12	20.7	0.060	3.2	0.15	6.5	1.29	12.5
		(0.025)	*(2.2)*	*(0.00)*	*(0.1)*	*(0.05)*	*(13.9)*	*(0.008)*	-	*(0.09)*	-	*(0.18)*	*(0.0)*
	T2	0.042	12.2	0.10	6.7	1.09	15.9	0.051	7.7	0.17	6.3	1.02	11.5
		(0.013)	*(9.9)*	*(0.02)*	*(0.2)*	*(0.07)*	*(5.8)*	*(0.003)*	-	*(0.07)*	-	*(0.16)*	*(1.2)*
	T3	0.051	6.2	0.12	6.7	1.18	13.7	0.064	7.7	0.16	6.7	1.25	11.4
		(0.009)	*(7.0)*	*(0.08)*	*(0.2)*	*(0.16)*	*(4.1)*	*(0.004)*	-	*(0.10)*	-	*(0.12)*	*(1.8)*
Yam	T0	0.063	5.5	0.17	6.6	1.49	13.8	0.052	2.3	0.25	6.6	1.15	12.9
		(0.008)	*(2.3)*	*(0.00)*	*(0.3)*	*(0.33)*	*(1.3)*	*(0.005)*	*(1.3)*	*(0.22)*	*(0.1)*	*(0.18)*	*(0.8)*
	T1	0.070	4.8	0.15	6.5	1.72	14.2	0.068	5.2	0.07	6.5	1.63	13.7
		(0.021)	*(0.5)*	*(0.02)*	*(0.3)*	*(0.66)*	*(1.3)*	*(0.018)*	*(2.6)*	*(0.02)*	*(0.0)*	*(0.66)*	*(2.1)*
	T2	0.059	4.2	0.12	6.5	1.29	12.7	0.049	3.3	0.10	6.5	1.05	12.4
		(0.009)	*(1.4)*	*(0.02)*	*(0.3)*	*(0.35)*	*(1.5)*	*(0.000)*	*(0.1)*	*(0.02)*	*(0.0)*	*(0.06)*	*(0.7)*
	T3	0.064	4.5	0.13	6.2	1.43	12.9	0.057	3.9	0.11	6.4	1.20	12.2
		(0.016)	*(1.0)*	*(0.03)*	*(0.5)*	*(0.48)*	*(1.1)*	*(0.008)*	*(0.8)*	*(0.01)*	*(0.1)*	*(0.20)*	*(0.2)*

T1M: 10 t ha^{-1}crop residues

T1F: 10 t ha^{-1} of farmyard manure in 2001

T2: mineral fertilizer at the rates recommended

T3M: T2 + 10 t ha^{-1} of crop residues for mulch in 2001 and 2002

T3F: T2 + 10 t ha^{-1} of farmyard manure.

Appendix 6: Chemical characteristics of heavier soil (plough layer 0 - 20) at the beginning (2001) and the end (2002) of experiment in Wewe. In parenthesis: standard deviation

Crops 2001	Treatments	N	P	K	pH	OM	C/N	N	P	K	pH	OM	C/N
		2001						2002					
Cotton	T0	0.078	10.3	0.30	6.9	1.50	11.0	0.062	3.8	0.13	6.7	1.32	12.3
		(0.014)	*(4.4)*	*(0.18)*	*(0.1)*	*(0.48)*	*(1.6)*	*(0.004)*	*(2.1)*	*(0.09)*	*(0.2)*	*(0.22)*	*(1.4)*
	T1	0.084	16.7	0.33	6.9	1.59	10.9	0.067	4.1	0.12	6.7	1.53	13.2
		(0.016)	*(12.8)*	*(0.14)*	*(0.1)*	*(0.39)*	*(0.6)*	*(0.003)*	*(1.4)*	*(0.01)*	*(0.1)*	*(0.05)*	*(0.8)*
	T2	0.075	9.8	0.27	6.9	1.44	10.9	0.060	4.5	0.14	6.8	1.36	13.3
		(0.016)	*(9.8)*	*(0.13)*	*(0.2)*	*(0.50)*	*(1.3)*	*(0.016)*	*(0.8)*	*(0.03)*	*(0.1)*	*(0.24)*	*(1.4)*
	T3	0.078	11.3	0.27	6.9	1.47	10.7	0.066	-	0.16	6.6	1.44	12.7
		(0.019)	*(11.8)*	*(0.12)*	*(0.2)*	*(0.54)*	*(1.4)*	*(0.007)*	-	*(0.04)*	*(0.0)*	*(0.09)*	*(0.6)*
Maize	T0	0.071	5.0	0.14	6.8	1.57	14.6	0.078	3.0	0.17	6.5	1.70	12.6
		(0.038)	*(2.7)*	*(0.13)*	*(0.2)*	*(0.59)*	*(6.1)*	*(0.018)*	*(0.3)*	*(0.08)*	*(0.3)*	*(0.44)*	*(0.3)*
	T1	0.076	10.3	0.19	6.8	1.72	14.4	0.083	3.0	0.26	6.5	1.71	11.7
		(0.033)	*(11.0)*	*(0.10)*	*(0.3)*	*(0.51)*	*(5.1)*	*(0.020)*	*(1.5)*	*(0.08)*	*(0.0)*	*(0.67)*	*(1.9)*
	T2	0.069	3.9	0.14	6.9	1.55	14.5	0.091	7.8	0.22	6.4	1.85	11.8
		(0.031)	*(1.3)*	*(0.05)*	*(0.3)*	*(0.45)*	*(6.4)*	*(0.006)*	*(2.5)*	*(0.03)*	*(0.2)*	*(0.32)*	*(1.2)*
	T3	0.073	6.8	0.18	6.8	1.67	14.9	0.086	7.0	0.09	6.4	1.91	13.0
		(0.034)	*(3.5)*	*(0.10)*	*(0.3)*	*(0.51)*	*(6.5)*	*(0.016)*	*(2.6)*	*(0.02)*	*(0.2)*	*(0.30)*	*(0.5)*
Sorghum	T0	0.046	3.9	0.17	6.7	1.07	13.9	0.057	3.3	0.11	6.8	1.21	12.2
		(0.017)	*(0.0)*	*(0.01)*	*(0.2)*	*(0.24)*	*(2.1)*	*(0.006)*	*(0.8)*	*(0.00)*	*(0.2)*	*(0.15)*	*(0.3)*
	T1	0.050	5.5	0.12	6.7	0.99	11.7	0.050	3.3	0.14	6.7	1.05	12.3
		(0.006)	*(0.5)*	*(0.04)*	*(0.3)*	*(0.05)*	*(0.9)*	*(0.001)*	*(1.7)*	*(0.05)*	*(0.2)*	*(0.08)*	*(1.1)*
	T2	0.059	4.2	0.11	6.7	1.15	11.3	0.056	5.5	0.16	6.7	1.17	12.1
		(0.011)	*(0.5)*	*(0.01)*	*(0.3)*	*(0.19)*	*(0.3)*	*(0.010)*	*(3.0)*	*(0.06)*	*(0.1)*	*(0.28)*	*(0.8)*
	T3	0.060	3.6	0.12	6.7	0.99	9.8	0.061	8.7	0.14	6.7	1.35	12.9
		(0.011)	*(0.5)*	*(0.04)*	*(0.2)*	*(0.08)*	*(1.0)*	*(0.009)*	*(7.5)*	*(0.05)*	*(0.1)*	*(0.34)*	*(1.3)*
Yam	T0	0.076	10.1	0.24	6.6	1.81	14.6	0.098	10.9	0.14	6.6	2.09	12.2
		(0.030)	*(14.6)*	*(0.13)*	*(0.2)*	*(0.82)*	*(5.2)*	*(0.029)*	*(8.4)*	*(0.04)*	*(0.3)*	*(0.76)*	*(1.1)*
	T1	0.061	6.9	0.22	6.6	1.58	16.7	0.088	6.8	0.17	6.6	1.92	12.7
		(0.020)	*(3.1)*	*(0.08)*	*(0.4)*	*(0.33)*	*(7.9)*	*(0.021)*	*(3.8)*	*(0.03)*	*(0.3)*	*(0.55)*	*(1.0)*
	T2	0.071	7.9	0.23	6.6	1.83	15.8	0.080	6.2	0.14	6.5	1.73	12.7
		(0.016)	*(3.5)*	*(0.07)*	*(0.2)*	*(0.47)*	*(6.4)*	*(0.015)*	*(2.6)*	*(0.02)*	*(0.3)*	*(0.24)*	*(0.8)*
	T3	0.061	13.1	0.21	6.6	1.58	16.6	0.078	5.8	0.17	6.7	1.65	12.2
		(0.019)	*(15.4)*	*(0.08)*	*(0.3)*	*(0.36)*	*(6.8)*	*(0.014)*	*(2.9)*	*(0.06)*	*(0.4)*	*(0.31)*	*(0.6)*

T1M: 10 t ha^{-1}crop residues T1F: 10 t ha^{-1} of farmyard manure in 2001

T2: mineral fertilizer at the rates recommended

T3M: T2 + 10 t ha^{-1} of crop residues for mulch in 2001 and 2002

T3F: T2 + 10 t ha^{-1} of farmyard manure.

Appendix 7: Composition of the individual lots of manure used in 2001

Sample	Sites	N	P	K	Ca	Mg	Na	Mn	Zn
		[%]						Mg kg^{-1}	
FD 1	**Doguè**	1,59	0,24	1,51	0,66	0,36	0,05	542,19	49,57
FW2	**Wèwè**	1,75	0,30	1,98	1,09	0,34	0,03	430,56	57,39
FW3		1,75	0,31	2,44	1,46	0,45	0,03	350,83	62,61
FW5		1,56	0,22	5,50	0,85	0,66	0,02	191,36	33,91
FWW		1,40	0,27	1,11	0,91	0,34	0,02	271,09	34,78
FB 2	**Beterou**	1,68	0,23	1,77	0,92	0,33	0,03	621,93	195,65
FB 3		1,59	0,20	2,04	0,97	0,35	0,05	494,35	86,09
FB 4		1,75	0,21	0,70	0,85	0,24	0,03	422,59	95,65
FB 7		1,46	0,24	1,46	0,92	0,38	0,03	422,59	99,13
FB 9		1,53	0,24	1,33	1,03	0,36	0,02	366,78	48,69
FB 10		1,48	0,18	2,27	0,89	0,29	0,07	430,56	58,26
FB 12		1,71	0,27	1,28	0,74	0,31	0,03	326,91	65,21
FB 13		1,50	0,23	1,89	0,76	0,34	0,05	382,72	58,26
FB 14		1,57	0,28	1,10	0,75	0,30	0,03	518,27	57,39

Appendix 8: Nutrient content in cotton at the harvest in 2001 (SD): Standard deviation

Cotton	**Yield** **Mg ha^{-1}**	**N**	**P** **--------[g kg^{-1}]-------**	**K**	**Yield** **Mg ha^{-1}**	**N**	**P** **------[g kg^{-1}]------**	**K**
Grain								
Subpopulations			**-------------------Low-------------**				**-----------------High------------**	
Treatments				**-----------------2001-----------------**				
T0	0.5	30.4	3.6	11.5	0.8	29.1	4.6	11.6
SD	0.1	4.7	1.5	0.6	0.1	15.2	1.2	0.6
T1	0.5	29.9	3.4	11.4	0.8	31.4	4.2	11.5
SD	0.1	5.3	1.3	1.1	0.1	3.3	1.3	1.0
T2	0.5	30.4	4.2	11.8	0.8	31.1	3.8	11.7
SD	0.2	7.0	1.3	1.2	0.1	5.7	1.3	0.6
T3	0.5	27.8	3.2	11.8	0.8	28.7	4.1	11.4
SD	0.1	5.7	1.3	0.5	0.1	4.5	1.3	0.7
				-----------------Lint-----------------				
T0	0.4	6.5	0.9	6.2	0.7	5.2	0.9	8.1
SD	0.1	4.2	0.3	1.2	0.2	1.3	0.2	3.1
T1	0.4	6.4	0.9	6.6	0.8	5.0	0.9	6.3
SD	0.1	3.8	0.3	0.8	0.3	1.0	0.1	0.6
T2	0.4	7.5	0.9	7.0	0.7	5.3	0.8	6.5
SD	0.1	4.6	0.2	0.8	0.1	1.0	0.2	0.7
T3	0.4	5.3	0.9	6.2	0.8	7.8	0.8	6.5
SD	0.1	0.9	0.2	1.1	0.2	7.5	0.2	0.7
				-----------------Leaves-----------------				
T0	0.9	12.6	1.8	14.3	1.7	20.5	2.8	11.0
SD	0.3	3.7	0.4	1.3	0.5	8.5	0.8	4.0
T1	0.9	14.9	2.1	15.2	1.4	17.4	2.3	14.2
SD	0.4	4.9	0.5	2.3	0.5	6.9	0.7	3.6
T2	1.0	15.0	2.1	13.4	1.5	15.2	1.8	12.2
SD	0.5	4.9	0.4	3.9	0.6	7.1	0.3	3.9
T3	0.9	13.7	2.3	15.6	1.5	17.6	2.0	13.5
SD	0.4	3.6	0.9	3.8	0.7	7.9	0.2	1.7
				-----------------Stems-----------------				
T0	2.2	8.1	1.6	11.8	3.7	7.7	1.5	12.2
SD	0.7	2.3	0.5	2.3	0.9	1.9	0.6	2.3
T1	2.4	7.9	1.5	12.6	3.3	7.6	1.6	12.2
SD	1.2	1.8	0.5	2.9	0.8	1.4	0.3	1.8
T2	2.8	8.1	1.5	12.7	4.2	7.2	1.4	10.9
SD	1.3	1.9	0.4	3.3	1.5	1.6	0.3	2.8
T3	2.8	8.5	1.4	11.9	4.0	7.5	1.6	12.3
SD	1.2	3.0	0.6	1.1	1.1	1.6	0.6	3.1

T0: Farmer's practice

T1: 10 t ha^{-1} of crop residues or of farmyard manure (2001)

T2: 51 N 46 P_2O_5 28 K_2O

T3: 51 N 46 P_2O_5 28 K_2O + 10 t ha^{-1} of crop residues or farmyard manure (2001)

Appendix 9: Nutrient content in maize at the harvest in 2001 and 2002 (SD): Standard deviation

Maize	Yield	N	P	K	Yield	N	P	K
	Mg ha^{-1}	-------[g kg^{-1}]-------			Mg ha^{-1}	---------[g kg^{-1}] -------		
				Grain				
Low yielding subpopulation								
Treatments		2001				2002		
T0	2.3	16.9	4.7	5.9	1.2	14.1	3.4	5.2
SD	0.9	3.8	1.4	2.1	0.7	1.5	0.9	0.9
T1	2.2	15.9	4.2	5.4	1.1	14.2	3.5	5.2
SD	0.8	2.4	0.7	0.9	0.8	1.9	0.9	1.1
T2	2.6	16.0	4.3	5.4	1.5	13.9	3.5	5.1
SD	0.8	2.9	1.6	1.8	0.8	1.5	0.6	0.9
T3	2.6	14.6	4.5	5.3	1.7	15.6	3.8	5.1
SD	0.7	1.8	1.3	1.1	0.7	1.8	0.7	0.8
High yielding subpopulation								
T0	4.1	13.6	3.3	4.0	3.2	15.0	3.0	6.4
SD	0.3	2.8	0.7	1.0	0.5	1.5	1.7	3.4
T1	4.1	15.8	4.8	5.9	3.4	14.4	3.8	5.1
SD	0.6	2.0	0.9	1.4	0.8	2.3	0.7	0.4
T2	4.4	18.7	5.1	7.1	3.9	16.0	4.0	5.8
SD	0.6	1.8	1.2	3.0	0.8	1.3	1.0	0.6
T3	4.7	17.4	4.4	5.3	4.2	15.4	3.8	5.8
SD	0.9	1.9	0.7	0.6	1.1	1.0	1.3	0.7
				Cob				
Low yielding subpopulation								
T0	0.4	5.5	0.8	6.6	0.3	4.6	0.7	6.3
SD	0.2	1.0	0.3	1.3	0.1	0.8	0.3	1.3
T1	0.4	5.3	0.7	6.3	0.2	5.0	0.8	6.4
SD	0.1	1.0	0.4	1.6	0.1	1.1	0.3	1.0
T2	0.4	5.2	0.8	6.1	0.1	5.5	2.4	7.5
SD	0.1	0.7	0.3	1.4	0.1	1.7	3.9	2.3
T3	0.4	5.4	0.9	6.7	0.3	5.0	0.7	7.0
SD	0.1	1.0	0.3	1.1	0.2	1.1	0.3	1.6
High yielding subpopulation								
T0	0.6	5.1	0.6	7.4	0.5	5.3	0.6	5.3
SD	0.0	0.6	0.2	2.8	0.1	0.9	0.3	1.4
T1	0.6	5.0	0.7	5.5	0.5	4.6	0.6	5.8
SD	0.1	0.8	0.1	0.8	0.1	1.0	0.2	1.1
T2	0.7	4.8	0.6	5.5	0.6	4.2	0.6	5.9
SD	0.1	1.1	0.2	1.3	0.1	0.9	0.2	2.1
T3	0.7	5.0	0.7	5.6	0.6	4.2	0.6	5.0
SD	0.1	1.2	0.4	1.1	0.2	0.7	0.2	0.9
				Stem				
Low yielding subpopulation								
T0	2.5	5.5	1.3	14.7	2.5	5.5	1.5	10.4
SD	0.9	1.3	0.6	4.5	1.7	1.6	0.6	2.4
T1	2.9	5.8	1.3	13.2	1.7	5.8	1.6	10.9
SD	1.1	1.4	0.5	2.4	0.8	2.1	0.9	2.5
T2	3.1	5.6	1.5	14.4	2.2	6.2	1.7	9.2
SD	1.1	1.0	0.7	2.7	1.7	0.8	0.9	2.6
T3	3.6	5.4	1.5	14.0	3.0	6.1	1.3	10.3
SD	1.1	1.0	0.5	4.1	1.4	1.2	0.8	3.3
High yielding subpopulation								
T0	3.3	5.0	1.3	17.6	3.0	4.5	1.0	10.5
SD	0.7	0.8	0.8	2.7	0.2	0.6	0.4	3.3
T1	3.0	4.9	1.4	13.9	4.1	4.4	2.1	11.9
SD	0.9	1.0	0.5	1.9	2.0	0.7	3.0	1.4
T2	4.1	5.4	1.2	15.0	4.4	4.6	1.0	12.6
SD	0.7	1.0	0.5	2.1	1.7	1.0	0.7	2.9
T3	4.5	5.8	1.3	15.6	4.3	5.5	1.3	14.1
SD	1.4	1.3	0.7	3.5	1.4	3.2	0.7	1.9

T0: Farmer's practice

T1: 10 t ha^{-1} of crop residues or of farmyard manure (2001)

T2: 51 N 46 P_2O_5 28 K_2O

T3: 51 N 46 P_2O_5 28 K_2O + 10 t ha^{-1} of crop residues or farmyard manure (2001)

Appendix 10: Nutrient content in groundnut at the harvest in 2001 and 2002 (SD): Standard deviation

	Yield	N	P	K	Yield	N	P	K
Groundnut	Mg ha^{-1}	----------[g kg^{-1}] -----			Mg ha^{-1}	-------[g kg^{-1}]-------		
	------------------------------------Grain------------------------------							
Low yielding subpopulation								
Treatments	**2001**				**2002**			
T0	0.6	42.6	3.9	9.9	0.9	39.8	3.4	7.6
SD	0.2	6.2	0.9	2.1	0.5	3.1	0.3	0.6
T1	0.6	41.3	4.0	10.4	1.0	39.1	3.6	8.0
SD	0.2	5.9	0.9	3.5	0.3	3.2	0.4	0.8
T2	0.6	40.3	3.9	9.0	1.0	36.4	3.5	8.0
SD	0.2	4.3	0.5	1.5	0.3	2.7	0.4	0.5
T3	0.7	40.7	3.9	9.0	1.0	38.7	3.6	8.3
SD	0.2	2.6	0.2	2.0	0.3	2.6	0.3	0.5
High yielding subpopulation								
T0	1.5	39.1	3.3	7.5	1.8	38.6	3.1	7.8
SD	0.3	1.1	0.8	0.1	0.1	3.3	0.6	0.3
T1	1.1	38.9	3.4	7.8	1.8	37.8	3.3	8.0
SD	0.2	1.9	0.6	0.8	0.1	2.1	0.4	0.7
T2	1.3	38.5	3.6	7.5	1.9	38.4	3.5	7.8
SD	0.5	2.5	0.6	0.1	0.2	2.3	0.3	0.7
T3	1.5	38.9	3.4	7.3	1.8	38.5	3.5	8.1
SD	0.0	3.1	0.9	0.5	0.2	2.5	0.3	0.4
	------------------------------------Husk-----------------------------							
Low yielding subpopulation								
T0	0.2	13.0	0.8	11.9	0.3	8.8	0.6	6.8
SD	0.1	2.9	0.2	1.6	0.2	1.2	0.1	1.7
T1	0.2	12.2	0.7	11.5	0.4	8.9	0.6	7.9
SD	0.0	2.8	0.2	2.0	0.1	1.2	0.1	2.0
T2	0.2	11.9	0.7	12.7	0.4	8.5	0.6	8.1
SD	0.0	4.7	0.2	2.0	0.2	0.5	0.2	1.7
T3	0.2	12.8	0.8	10.7	0.3	8.3	0.6	9.2
SD	0.1	2.9	0.3	2.6	0.1	0.4	0.1	1.8
High yielding subpopulation								
T0	0.4	10.5	0.5	7.4	0.6	9.8	0.6	7.4
SD	0.0	0.3	0.0	0.1	0.1	1.7	0.2	1.7
T1	0.3	11.1	0.6	9.1	0.6	9.4	0.5	7.8
SD	0.1	0.3	0.0	0.1	0.1	1.4	0.1	2.2
T2	0.3	9.9	0.6	7.6	0.6	9.4	0.6	6.8
SD	0.1	1.4	0.2	1.0	0.1	1.6	0.2	2.2
T3	0.4	9.3	0.5	4.7	0.6	9.5	0.6	7.3
SD	0.1	0.3	0.1	4.2	0.1	1.2	0.1	1.4
	----------------------------------Stem-----------------------------							
Low yielding subpopulation								
T0	1.5	21.5	1.8	22.6	1.7	18.4	1.5	26.4
SD	0.4	0.9	0.4	3.8	0.8	3.4	0.5	8.9
T1	1.6	20.4	1.9	24.0	2.2	18.5	1.6	22.4
SD	0.5	1.3	0.6	4.0	1.1	4.3	0.5	3.8
T2	1.7	20.9	1.9	19.8	1.9	18.0	1.5	22.7
SD	0.5	2.0	0.4	6.0	0.8	2.8	0.5	4.2
T3	1.8	19.9	1.9	25.3	2.1	17.8	1.7	20.6
SD	0.7	2.3	0.3	4.6	0.9	3.3	0.7	3.0
High yielding subpopulation								
T0	2.2	18.2	1.9	21.8	2.3	15.2	1.5	22.7
SD	1.0	3.4	0.9	2.9	0.7	5.2	0.5	2.4
T1	1.7	18.0	1.7	23.5	2.1	15.1	1.3	24.3
SD	1.5	2.6	0.6	1.0	0.4	5.2	0.2	1.8
T2	2.0	19.2	1.5	24.5	2.4	16.5	1.8	23.4
SD	1.0	1.8	0.5	3.2	1.0	5.0	0.4	2.4
T3	2.3	19.2	1.5	22.8	2.6	16.9	1.7	22.7
SD	5.0	3.0	0.5	3.0	0.6	4.4	0.3	3.4

T0: Farmer's practice T1: 10 t ha^{-1} of crop residues or farmyard manure (2001) or 10 t ha^{-1} of crop residues or its residual effect (2002) T2: 10 N 40 P_2O_5 (2001) or 10 N 20 P_2O_5 (2002)

T3: 10 N 40 P_2O_5 with 10 t ha^{-1} of crop residues or farmyard manure (2001) or 10 N 20 P_2O_5 + 10 t ha^{-1} crop residues or residual effect of manure (2002)

Appendix 11: Nutrient content in yam at the harvest in 2001 and 2002 (SD): Standard deviation

Yam	Yield kg ha^{-1}	N	P	K	Yield kg ha^{-1}	N	P	K
		--------[g kg^{-1}]------				--------[g kg^{-1}] -----		
		------------------------------Tuber------------------------------						
Low yielding subpopulation								
Treatments		**2001**				**2002**		
T0	2.8	9.4	1.6	11.0	2.1	10.1	1.8	13.5
SD	0.9	4.4	0.4	3.5	1.2	1.5	0.2	1.2
T1	2.5	8.0	1.5	12.1	1.9	10.2	1.9	14.0
SD	0.9	3.1	0.3	0.9	0.9	1.1	0.3	2.0
T2	3.0	6.1	1.4	12.0	2.1	10.7	1.8	13.9
SD	0.9	1.8	0.3	2.1	1.0	1.7	0.1	1.2
T3	2.9	8.7	1.4	11.8	2.3	10.6	1.8	14.0
SD	1.2	4.0	0.4	2.7	0.8	1.4	0.2	1.6
High yielding subpopulation								
T0	6.0	7.4	1.4	11.6	1.8	9.0	1.7	13.8
SD	0.6	2.6	0.2	0.4	0.2	1.3	0.5	0.8
T1	5.7	8.6	1.4	11.9	2.4	10.0	1.8	14.1
SD	0.8	3.7	0.1	1.5	1.3	1.2	0.5	1.3
T2	5.0	7.9	1.4	11.5	2.4	10.3	1.6	12.4
SD	0.8	3.5	0.2	2.0	1.2	1.9	0.6	2.9
T3	5.6	8.0	1.4	10.2	2.6	9.8	1.9	13.8
SD	0.9	3.9	0.3	4.3	1.0	1.7	0.3	2.0
	--------------------------------- Leave---------------------------							
Low yielding subpopulation								
T0	0.4	12.6	1.1	11.2	0.5	14.2	1.4	16.0
SD	0.2	2.1	0.3	3.5	0.3	2.1	0.4	5.9
T1	0.3	12.1	1.0	14.5	0.5	14.6	1.5	18.4
SD	0.1	1.4	0.2	6.4	0.4	1.9	0.5	2.7
T2	0.4	13.4	1.1	13.7	0.6	14.0	1.3	18.5
SD	0.1	2.6	0.3	4.1	0.4	3.3	0.4	3.0
T3	0.3	12.9	1.0	12.4	0.6	14.7	1.3	17.9
SD	0.1	2.6	0.2	4.3	0.4	2.0	0.4	3.4
High yielding subpopulation								
T0	0.5	11.1	0.9	14.9	0.4	14.0	1.5	12.8
SD	0.4	0.9	0.3	0.5	0.1	1.5	0.6	2.2
T1	0.6	11.9	0.9	14.1	0.4	14.2	2.0	15.7
SD	0.3	1.5	0.2	5.3	0.1	1.1	0.7	5.1
T2	0.6	13.1	1.1	12.6	0.4	14.9	1.4	15.4
SD	0.2	0.9	0.2	2.9	0.1	1.5	0.3	3.3
T3	0.6	12.1	1.0	13.5	0.4	15.2	1.5	14.7
SD	0.3	1.3	0.2	3.0	0.1	1.8	0.3	2.5
	------------------------------------Stem-------------------------------							
Low yielding subpopulation								
T0	0.4	5.1	1.1	6.7	0.5	5.8	1.3	11.7
SD	0.1	0.9	0.9	2.5	0.3	1.1	0.8	2.3
T1	0.3	5.4	0.7	8.3	0.6	6.0	1.6	12.7
SD	0.1	0.5	0.5	3.5	0.3	1.1	1.0	3.6
T2	0.3	5.5	0.5	8.1	0.7	6.0	1.1	12.7
SD	0.1	1.1	0.3	2.4	0.3	0.9	0.7	3.0
T3	0.4	5.5	0.6	7.9	0.7	6.2	1.1	13.1
SD	0.1	0.8	0.4	1.1	0.4	1.1	0.6	3.8
High yielding subpopulation								
T0	0.6	4.5	0.6	6.9	0.4	6.1	1.6	11.8
SD	0.1	0.7	0.3	0.1	0.1	2.4	1.3	2.8
T1	0.6	4.4	0.6	6.2	0.4	5.0	1.9	12.8
SD	0.2	0.3	0.3	1.5	0.1	0.8	1.1	2.6
T2	0.5	5.6	0.6	6.4	0.4	5.0	1.1	10.2
SD	0.1	1.1	0.3	1.1	0.1	0.5	0.5	2.6
T3	0.6	4.8	0.6	7.0	0.4	5.1	1.5	12.4
SD	0.1	0.7	0.3	1.3	0.1	1.0	0.7	3.9

T0: Farmer's practice

T1: 10 t ha^{-1} of crop residues or farmyard manure (2001) or its residual effect (2002)

T2: 30 N 30 P_2O_5 60 K_2O

T3: 30 N 30 P_2O_5 60 K_2O + 10 t ha^{-1} of crop residues or farmyard manure (2001) or 42 N 30 P_2O_5 60 K_2O + of crop residues or residual effect of manure (2001)

Appendix 12: Nutrient content in sorghum at the harvest in 2001 and 2002 (SD): Standard deviation

Sorghum	Yield Mg ha^{-1}	N	P	K	Yield Mg ha^{-1}	N	P	K
		--------[g kg^{-1}]		-------		--------[g kg^{-1}]		------
		-----------------------------Panicle-----------------------------						
Subpopulations		Low				High		
Treatments		----------------------------------2001-------------------------------						
T0	1.3	12.7	2.5	4.5	2.7	11.9	4.2	6.6
SD	0.7	1.7	0.9	1.6	-	-	-	-
T1	1.4	12.5	2.5	4.5	3.0	11.8	3.0	5.7
SD	0.8	1.7	0.8	1.8	0.7	2.9	1.0	1.4
T2	1.7	13.3	2.5	4.3	3.2	11.6	2.3	6.2
SD	0.8	1.2	1.1	2.1	1.1	3.0	1.0	2.9
T3	1.2	13.3	2.4	4.0	2.9	13.8	2.9	5.1
SD	0.6	2.1	0.5	1.4	0.8	1.1	1.5	1.5
	-------------------------------------Grain-------------------------------							
Treatments	-------------------------------------2002-------------------------------							
T0	0.6	17.8	3.4	4.1	1.6	16.6	3.5	4.4
SD	0.4	2.2	0.9	1.3	0.4	2.1	0.9	0.9
T1	0.7	17.4	3.6	4.3	1.8	15.7	2.7	3.6
SD	0.4	2.2	1.1	0.9	0.0	0.9	0.4	0.3
T2	0.6	18.0	3.7	4.4	1.8	15.4	4.4	5.3
SD	0.5	2.8	1.0	1.4	0.4	0.3	1.0	1.5
T3	0.5	17.2	3.8	4.5	2.0	16.0	4.4	5.0
SD	0.2	2.4	1.2	1.2	0.7	1.4	1.3	1.2
	-------------------------------------Spike------------------------------							
T0	0.5	8.5	1.5	4.3	0.7	6.3	0.9	3.7
SD	0.2	2.8	0.5	1.4	0.2	2.2	0.1	0.5
T1	0.4	7.4	1.3	4.2	0.8	8.6	1.0	7.1
SD	0.3	2.3	0.4	1.3	0.1	4.7	0.7	5.0
T2	0.4	6.8	1.6	5.2	0.7	6.4	1.3	5.5
SD	0.3	3.0	0.4	1.8	0.3	0.9	0.4	2.8
T3	0.3	7.4	1.6	4.4	0.9	6.6	1.5	4.1
SD	0.2	2.5	0.4	0.6	0.5	1.4	0.3	0.6
	--------------------------------------Stem------------------------------							
Low yielding subpopulation								
Treatments		---------2001---------				-------2002---------		
T0	8.0	2.9	0.4	10.8	8.0	3.0	0.7	10.3
SD	5.8	0.3	0.2	2.0	5.5	0.4	0.2	2.1
T1	4.7	4.2	1.2	11.1	5.0	4.1	0.9	12.1
SD	3.4	1.5	1.2	3.8	2.6	1.5	0.2	4.5
T2	7.9	3.6	0.5	12.2	6.8	3.4	0.5	12.7
SD	6.0	0.7	0.2	1.4	7.0	0.3	0.2	2.1
T3	4.8	4.1	0.8	11.3	4.0	4.4	0.9	12.1
SD	2.7	1.6	0.4	2.4	1.7	1.9	0.3	3.5
High yielding subpopulation								
T0	17.6	2.9	1.2	8.4	19.6	3.0	0.8	10.9
SD	-	-	-	-	4.4	0.5	0.4	2.1
T1	10.3	3.6	0.9	9.9	11.2	3.4	0.8	12.0
SD	4.3	0.8	0.6	4.7	5.7	0.4	0.2	1.6
T2	15.3	2.7	0.7	11.6	15.5	3.2	0.8	11.7
SD	8.3	0.3	0.3	0.2	6.8	0.7	0.3	1.4
T3	13.5	3.5	0.5	11.4	12.6	3.1	0.7	12.0
SD	2.3	0.7	0.2	1.5	6.4	0.1	0.2	2.4

T0: Farmer's practice

T1: 10 t ha^{-1} of crop residues or farmyard manure (2001) or 10 t ha^{-1} of crop residues or residual effect of manure (2002)

T2: 23 N 46 P_2O_5 (2001) or 28 N 46 P_2O_5 28 K_2O (2002)

T3: 23 N 46 P_2O_5 + 10 t ha^{-1} of crop residues or farmyard manure (2001) or 28 N 46 P_2O_5 28 K_2O + 10 t ha^{-1} of crop residues or residual effect manure (2002)

Appendix 13: Input and output of cotton at the harvest (2001)

Cotton	In 1.1	In 1.2	In 2	In 4	Σ In	Out 1	Out 2	Σ Out	*Balance*	In 1.1	In 1.2	In 2	In 4	Σ In	Out 1	Out 2	Σ Out	*Balance*
N																		
Low yielding subpopulation													High yielding subpopulation					
Treatments																		
T0	0.0	0.0	44.0	0.0	44.0	13.2	18.9	32.1	***11.9***	0.0	0.0	44.0	0.0	44.0	20.5	25.9	46.4	***-2.4***
T1	33.9	46.7	0.0	0.0	80.5	11.4	19.8	31.2	***49.3***	27.9	100.2	0.0	0.0	128.1	20.6	23.4	44.0	***84.1***
T2	0.0	0.0	51.0	0.0	51.0	17.0	22.1	39.1	***11.9***	0.0	0.0	51.0	0.0	51.0	19.0	32.6	51.7	***-0.7***
T3	33.9	46.7	51.0	0.0	131.5	14.0	27.5	41.5	***90.1***	27.9	100.2	51.0	0.0	179.1	23.3	27.7	51.0	***128.1***
P																		
T0	0.0	0.0	15.0	0.0	15.0	2.1	1.4	3.5	***11.5***	0.0	0.0	15.0	0.0	15.0	3.7	2.1	5.8	***9.2***
T1	17.2	9.6	0.0	0.0	26.7	2.0	1.6	3.6	***23.1***	12.2	19.9	0.0	0.0	32.1	3.5	2.2	5.7	***26.4***
T2	0.0	0.0	20.0	0.0	20.0	2.3	1.6	3.9	***16.1***	0.0	0.0	20.0	0.0	20.0	3.8	2.4	6.2	***13.8***
T3	17.2	9.6	20.0	0.0	46.7	2.1	1.8	3.9	***42.9***	12.2	19.9	20.0	0.0	52.1	3.8	2.4	6.2	***45.8***
K																		
Treatments																		
T0	0.0	0.0	17.5	0.0	17.5	8.2	10.6	18.8	***-1.3***	0.0	0.0	17.5	0.0	17.5	13.1	15.3	28.4	***-10.9***
T1	60.0	39.3	0.0	0.0	99.3	7.9	11.6	19.5	***79.8***	45.1	98.4	0.0	0.0	143.5	12.4	15.8	28.1	***115.4***
T2	0.0	0.0	23.3	0.0	23.3	9.3	12.2	21.5	***1.8***	0.0	0.0	23.3	0.0	23.3	13.5	18.6	32.0	***-8.7***
T3	60.0	39.3	23.3	0.0	122.6	8.5	12.8	21.3	***101.3***	45.1	98.4	23.3	0.0	166.9	14.1	17.2	31.3	***135.6***

T0: Farmer's practice

T1: 10 t ha^{-1} of crop residues or of farmyard manure (2001)

T2: 51 N 46 P_2O_5 28 K_2O

T3: 51 N 46 P_2O_5 28 K_2O + 10 t ha^{-1} of crop residues or farmyard manure (2001)

In 1: input of crop residues; In 12: input of farmyard manure; In2: input of mineral fertilizer; ∑In: sum inputs; Ou1: output of harvest product; Out 2: output of crop residues (leaves, stems) ∑Out: sum outputs

Appendix 14: Input and output of maize at the harvest (2001-2002)

Maize	In 1.1	In 1.2	In 2	In 4	Σ In	Out 1	Out 2	Σ In	*Balance*	In 1.1	In 1.2	In 2	In 4	Σ In	Out 1	Out 2	Σ Out	*Balance*
N																		
Low yielding subpopulation																		
Treatments					**2001**									**2002**				
T0	0.0	0.0	0.0	0.0	0.0	38.6	2.7	41.3	***-41.3***	0.0	0.0	0.0	0.0	0.0	15.3	1.2	16.5	***-16.5***
T1	27.3	79.8	0.0	0.0	107.2	37.4	2.7	40.1	***67.1***	18.1	0.0	0.0	0.0	18.1	21.3	1.3	22.6	***-4.5***
T2	0.0	0.0	57.6	0.0	57.6	45.8	3.0	48.8	***8.8***	0.0	0.0	75.0	0.0	75.0	23.6	1.8	25.3	***49.7***
T3	21.3	99.8	57.6	0.0	178.7	38.4	3.3	41.7	***137.0***	24.4	0.0	75.0	0.0	99.4	15.2	2.5	17.7	***81.7***
High yielding subpopulation																		
T0	0.0	0.0	0.0	0.0	0.0	62.3	3.6	65.9	***-65.9***	0.0	0.0	0.0	0.0	0.0	48.8	3.4	52.1	***-52.1***
T1	12.0	129.0	0.0	0.0	141.0	60.2	3.6	63.8	***77.3***	24.6	0.0	0.0	0.0	24.6	50.2	3.3	53.5	***-28.9***
T2	0.0	0.0	57.6	0.0	57.6	85.6	3.9	89.5	***-31.9***	0.0	0.0	75.0	0.0	75.0	64.8	3.4	68.2	***6.8***
T3	25.4	91.7	57.6	0.0	174.7	83.1	4.4	87.5	***87.2***	15.9	0.0	75.0	0.0	90.9	64.2	3.5	67.7	***23.1***
P																		
Low yielding subpopulation																		
T0	0.0	0.0	0.0	0.0	0.0	10.9	0.5	11.3	***-11.3***	0.0	0.0	0.0	0.0	0.0	3.9	0.2	4.2	***-4.2***
T1	14.7	12.1	0.0	0.0	26.8	10.5	0.4	10.9	***15.9***	5.8	0.0	0.0	0.0	5.8	5.7	0.3	5.9	***-0.1***
T2	0.0	0.0	17.4	0.0	17.4	12.0	0.5	12.5	***4.8***	0.0	0.0	17.4	0.0	17.4	6.1	0.7	6.7	***10.7***
T3	13.3	15.0	17.4	0.0	45.7	12.7	0.6	13.3	***32.4***	10.0	0.0	17.4	0.0	27.4	3.6	0.5	4.1	***23.4***
High yielding subpopulation																		
T0	0.0	0.0	0.0	0.0	0.0	13.7	0.5	14.2	***-14.2***	0.0	0.0	0.0	0.0	0.0	9.8	0.5	10.2	***-10.2***
T1	3.8	20.8	0.0	0.0	24.6	16.8	0.6	17.3	***7.3***	4.5	0.0	0.0	0.0	4.5	13.6	0.8	14.5	***-9.9***
T2	0.0	0.0	17.4	0.0	17.4	21.5	0.6	22.1	***-4.7***	0.0	0.0	17.4	0.0	17.4	16.2	0.5	16.7	***0.7***
T3	11.3	14.3	17.4	0.0	43.0	20.9	0.7	21.6	***21.4***	2.2	0.0	17.4	0.0	19.6	16.3	0.6	16.9	***2.7***
K																		
Low yielding subpopulation																		
T0	0.0	0.0	0.0	0.0	0.0	13.7	4.0	17.7	***-17.7***	0.0	0.0	0.0	0.0	0.0	5.7	1.9	7.6	***-7.6***
T1	41.9	90.1	0.0	0.0	132.0	13.5	3.8	17.3	***114.6***	32.3	0.0	0.0	0.0	32.3	8.3	2.1	10.4	***21.9***
T2	0.0	0.0	0.0	0.0	0.0	15.1	4.7	19.8	***-19.8***	0.0	0.0	20.0	0.0	20.0	7.9	2.8	10.7	***9.3***
T3	27.5	111.1	0.0	0.0	138.7	14.6	5.4	20.0	***118.7***	51.1	0.0	20.0	0.0	71.1	5.2	3.1	8.2	***62.9***
High yielding subpopulation																		
T0	0.0	0.0	0.0	0.0	0.0	15.9	5.9	21.8	***-21.8***	0.0	0.0	0.0	0.0	0.0	20.3	4.0	24.3	***-24.3***
T1	15.2	196.4	0.0	0.0	211.6	20.1	5.0	25.1	***186.5***	42.5	0.0	0.0	0.0	42.5	17.7	5.0	22.7	***19.8***
T2	0.0	0.0	0.0	0.0	0.0	28.4	5.8	34.2	***-34.2***	0.0	0.0	20.0	0.0	20.0	23.1	5.8	28.9	***-8.9***
T3	40.5	122.9	0.0	0.0	163.4	25.2	6.4	31.7	***131.7***	23.0	0.0	20.0	0.0	43.0	24.3	5.4	29.7	***13.3***

T0: Farmer's practice

T1: 10 t ha^{-1} of crop residues or of farmyard manure (2001)

T2: 51 N 46 P_2O_5 28 K_2O

T3: 51 N 46 P_2O_5 28 K_2O + 10 t ha^{-1} of crop residues or farmyard manure (2001)

In 1: input of crop residues; In 12: input of farmyard manure; In2: input of mineral fertilizer; ∑In: sum inputs;
Ou1: output of harvest product; Out 2: output of crop residues (leaves, stems) ∑Out: sum outputs

Appendix 15: Input and output of groundnut at the harvest (2001-2002**)**

Groundnut	In 1.1	In 1.2	In 2	In 4	Σ In	Out 1	Out 2	Σ Out	*Balance*	In 1.1	In 1.2	In 2	In 4	Σ In	Out 1	Out 2	Σ Out	*Balance*
N																		
Low yielding subpopulation																		
Treatments				**2001**									**2002**					
T0	0.0	0.0	0.0	30.1	30.1	23.9	30.4	54.3	***-24.2***	0.0	0.0	0.0	38.5	38.5	36.1	45.2	81.3	***-42.9***
T1	19.8	99.8	0.0	30.9	150.4	26.5	29.2	55.7	***94.7***	38.1	0.0	0.0	42.0	80.1	38.5	45.2	83.7	***-3.6***
T2	0.0	0.0	10.0	22.1	32.1	24.8	33.0	57.7	***-25.6***	0.0	0.0	10.0	25.2	35.2	34.2	24.2	58.4	***-23.2***
T3	19.8	99.8	10.0	19.8	149.3	25.2	35.0	60.2	***89.1***	36.3	0.0	10.0	21.4	67.7	37.6	15.0	52.6	***15.1***
High yielding subpopulation																		
T0	0.0	0.0	0.0	55.2	55.2	57.8	39.5	97.3	***-42.2***	0.0	0.0	0.0	54.3	54.3	68.6	70.9	139.5	***-85.2***
T1	28.7	0.0	0.0	40.8	69.5	43.9	31.7	75.7	***-6.2***	11.0	0.0	0.0	40.7	51.7	66.1	44.9	110.9	***-59.2***
T2	17.8	0.0	10.0	30.2	58.0	49.2	36.2	85.4	***-27.4***	0.0	0.0	10.0	37.5	47.5	71.8	27.8	99.6	***-52.1***
T3	55.4	0.0	10.0	32.3	97.7	59.3	42.1	101.4	***-3.8***	24.5	0.0	10.0	48.6	83.1	68.1	41.5	109.6	***-26.5***
P																		
Low yielding subpopulation																		
T0	0.0	0.0	0.0	0.0	0.0	2.3	2.4	4.7	***-4.7***	0.0	0.0	0.0	0.0	0.0	3.1	3.9	7.0	***-7.0***
T1	9.3	15.1	0.0	0.0	24.5	2.5	2.6	5.2	***19.3***	6.9	0.0	0.0	0.0	6.9	3.6	2.9	6.5	***0.4***
T2	0.0	0.0	17.4	0.0	17.4	2.4	2.8	5.2	***12.2***	0.0	0.0	8.7	0.0	8.7	3.3	2.8	6.2	***2.5***
T3	9.3	15.1	17.4	0.0	41.9	2.4	3.5	5.9	***35.9***	4.6	0.0	8.7	0.0	13.3	3.5	1.6	5.1	***8.2***
T0	0.0	0.0	0.0	0.0	0.0	4.8	3.4	8.2	***-8.2***	0.0	0.0	0.0	0.0	0.0	5.5	7.3	12.9	***-12.9***
T1	10.5	0.0	0.0	0.0	10.5	3.9	2.3	6.1	***4.4***	1.0	0.0	0.0	0.0	1.0	5.8	4.6	10.4	***-9.4***
T2	6.8	0.0	17.4	0.0	24.2	4.3	2.5	6.9	***17.3***	0.0	0.0	8.7	0.0	8.7	6.5	3.3	9.7	***-1.0***
T3	20.7	0.0	17.4	0.0	38.1	5.1	3.0	8.1	***30.0***	3.6	0.0	8.7	0.0	12.3	6.1	3.0	9.1	***3.2***
K																		
Low yielding subpopulation																		
T0	0.0	0.0	0.0	0.0	0.0	5.8	30.6	36.4	***-36.4***	0.0	0.0	0.0	0.0	0.0	6.9	50.5	57.4	***-57.4***
T1	29.0	110.8	0.0	0.0	139.8	6.5	32.7	39.3	***100.5***	62.1	0.0	0.0	0.0	62.1	8.1	49.8	57.8	***4.2***
T2	0.0	0.0	0.0	0.0	0.0	5.4	32.4	37.8	***-37.8***	0.0	0.0	0.0	0.0	0.0	7.6	33.6	41.2	***-41.2***
T3	29.0	110.8	0.0	0.0	139.8	5.5	41.9	47.4	***92.4***	68.0	0.0	0.0	0.0	68.0	8.0	21.6	29.6	***38.4***
High yielding subpopulation																		
T0	0.0	0.0	0.0	0.0	0.0	11.0	43.4	54.4	***-54.4***	0.0	0.0	0.0	0.0	0.0	13.9	75.2	89.1	***-89.1***
T1	18.8	0.0	0.0	0.0	18.8	8.9	35.5	44.4	***-25.6***	8.3	0.0	0.0	0.0	8.3	14.0	60.4	74.4	***-66.1***
T2	27.5	0.0	0.0	0.0	27.5	9.5	41.9	51.4	***-23.9***	0.0	0.0	0.0	0.0	0.0	14.6	52.9	67.5	***-67.5***
T3	60.1	0.0	0.0	0.0	60.1	11.1	45.9	57.0	***3.1***	29.1	0.0	0.0	0.0	29.1	14.4	51.6	65.9	***-36.8***

T0: Farmer’s practice T1: 10 t ha^{-1} of crop residues or farmyard manure (2001) or 10 t ha^{-1} of crop residues or its residual effect (2002) T2: 10 N 40 P_2O_5 (2001) or 10 N 20 P_2O_5 (2002)

T3: 10 N 40 P_2O_5 with 10 t ha^{-1} of crop residues or farmyard manure (2001) or 10 N 20 P_2O_5 + 10 t ha^{-1} crop residues or residual effect of manure (2002)

In 1: input of crop residues; In 12: input of farmyard manure; In2: input of mineral fertilizer; In 4: N derived from symbiotic fixation ∑In: sum inputs; Ou1 1: output of harvest product; Out 2: output of crop residues (leaves, stems) ∑Out: sum outputs

Appendix 16: Input and output of yam at the harvest (2001-2002)

Yam	In 1.1	In 1.2	In 2	In 4	Σ In	Out 1	Out 2	Σ Out	*Balance*	In 1.1	In 1.2	In 2	Σ In	Out 1	Out 2	Σ Out	*Balance*
N																	
Low yielding subpopulation																	
Treatments						**2001**								**2002**			
T0	0.0	0.0	0.0	0.0	0.0	18.7	1.0	19.7	***-19.7***	0.0	0.0	0.0	0.0	20.7	0.6	21.3	***-21.3***
T1	25.5	26.5	0.0	0.0	52.0	24.0	1.0	25.0	***27.1***	13.6	0.0	0.0	13.6	19.3	0.7	20.0	***-6.4***
T2	0.0	0.0	30.0	0.0	30.0	21.5	1.4	23.0	***7.0***	0.0	0.0	42.0	42.0	22.2	0.8	23.0	***19.0***
T3	29.8	0.0	25.0	0.0	54.8	30.9	1.6	32.5	***22.4***	16.0	0.0	42.0	58.0	22.1	0.9	23.0	***35.0***
High yielding subpopulation																	
T0	0.0	0.0	0.0	0.0	0.0	34.4	2.4	36.8	***-36.8***	0.0	0.0	0.0	0.0	12.5	0.5	13.0	***-13.0***
T1	19.4	40.1	0.0	0.0	59.6	39.8	2.0	41.8	***17.8***	11.6	0.0	0.0	11.6	18.8	0.4	19.2	***-7.6***
T2	0.0	0.0	30.0	0.0	30.0	49.8	1.8	51.5	***-21.5***	0.0	0.0	42.0	42.0	20.3	0.4	20.7	***21.3***
T3	18.5	45.4	30.0	0.0	93.9	46.2	1.9	48.1	***45.8***	9.5	0.0	42.0	51.5	16.8	0.4	17.2	***34.3***
P																	
Low yielding subpopulation																	
T0	0.0	0.0	0.0	0.0	0.0	3.1	0.1	3.2	***-3.2***	0.0	0.0	0.0	0.0	3.7	0.1	3.8	***-3.8***
T1	16.8	3.8	0.0	0.0	20.7	4.4	0.1	4.5	***16.2***	4.6	0.0	0.0	4.6	3.6	0.2	3.8	***0.8***
T2	0.0	0.0	13.0	0.0	13.0	5.0	0.1	5.1	***8.0***	0.0	0.0	13.0	13.0	3.8	0.1	4.0	***9.1***
T3	19.9	0.0	10.9	0.0	30.7	5.0	0.2	5.2	***25.6***	4.5	0.0	13.0	17.6	3.7	0.1	3.8	***13.8***
High yielding subpopulation																	
T0	0.0	0.0	0.0	0.0	0.0	5.2	0.2	5.4	***-5.4***	0.0	0.0	0.0	0.0	2.2	0.1	2.3	***-2.3***
T1	13.6	6.3	0.0	0.0	19.8	7.0	0.2	7.2	***12.7***	2.8	0.0	0.0	2.8	3.1	0.2	3.3	***-0.5***
T2	0.0	0.0	13.0	0.0	13.0	8.0	0.2	8.1	***4.9***	0.0	0.0	13.0	13.0	3.2	0.1	3.3	***9.7***
T3	12.9	6.6	13.0	0.0	32.6	9.1	0.2	9.3	***23.3***	1.4	0.0	13.0	14.5	3.9	0.1	4.1	***10.4***
K																	
Low yielding subpopulation																	
T0	0.0	0.0	0.0	0.0	0.0	21.2	1.3	22.5	***-22.5***	0.0	0.0	0.0	0.0	27.7	1.3	29.0	***-29.0***
T1	46.5	25.7	0.0	0.0	72.2	34.2	1.0	35.2	***37.0***	27.2	0.0	0.0	27.2	26.1	1.5	27.6	***-0.4***
T2	0.0	0.0	50.0	0.0	50.0	40.7	1.2	42.0	***8.0***	0.0	0.0	50.0	50.0	28.9	1.7	30.7	***19.3***
T3	53.6	0.0	41.7	0.0	95.2	43.6	1.6	45.2	***50.0***	24.2	0.0	50.0	74.2	29.1	1.9	31.0	***43.2***
High yielding subpopulation																	
T0	0.0	0.0	0.0	0.0	0.0	47.0	2.0	49.0	***-49.0***	0.0	0.0	0.0	0.0	19.9	1.0	20.9	***-20.9***
T1	31.8	53.8	0.0	0.0	85.6	55.9	2.0	58.0	***27.6***	21.3	0.0	0.0	21.3	26.4	1.1	27.5	***-6.2***
T2	0.0	0.0	50.0	0.0	50.0	54.7	1.8	56.5	***-6.5***	0.0	0.0	50.0	50.0	24.8	0.8	25.6	***24.4***
T3	30.3	44.0	50.0	0.0	124.3	80.0	2.5	82.5	***41.8***	18.4	0.0	50.0	68.4	30.1	1.2	31.3	***37.1***

T0: Farmer's practice

T1: 10 t ha^{-1} of crop residues or farmyard manure (2001) or its residual effect (2002)

T2: 30 N 30 P_2O_5 60 K_2O

T3: 30 N 30 P_2O_5 60 K_2O + 10 t ha^{-1} of crop residues or farmyard manure (2001) or 42 N 30 P_2O_5 60 K_2O + of crop residues or residual effect of manure (2001)

In 1: input of crop residues; In 12: input of farmyard manure; In2: input of mineral fertilizer; ∑In: sum inputs;

Ou1: output of harvest product; Out 2: output of crop residues (leaves, stems) ∑Out: sum outputs

Appendix 17: Input and output of sorghum at the harvest (2001-2002)

Sorghum	In 1.1	In 1.2	In 2	In 4	Σ In	Out 1	Out 2	Σ Out	*Balance*	In 1.1	In 1.2	In 2	Σ In	Out 1	Out 2	Σ Out	*Balance*
N																	
Low yielding subpopulation																	
Treatments					**2001**									**2002**			
T0	0.0	0.0	0.0	0.0	0.0	16.6	9.6	26.2	***-26.2***	0.0	0.0	0.0	0.0	11.2	11.7	23.0	***-23.0***
T1	58.0	22.7	0.0	0.0	80.7	17.7	11.7	29.5	***51.2***	13.4	0.0	0.0	13.4	12.1	10.9	23.1	***-9.6***
T2	0.0	0.0	23.0	0.0	23.0	24.2	9.8	34.0	***-11.0***	0.0	0.0	28.0	28.0	10.9	10.9	21.8	***6.2***
T3	68.8	0.0	23.0	0.0	91.8	16.2	8.7	24.9	***66.9***	11.8	0.0	28.0	39.8	8.1	9.5	17.6	***22.2***
High yielding subpopulation																	
T0	0.0	0.0	0.0	0.0	0.0	17.0	20.0	37.0	**-37.0**	0.0	0.0	0.0	0.0	20.5	13.9	34.4	**-34.4**
T1	17.7	106.0	0.0	0.0	123.7	37.2	16.8	53.9	***69.7***	0.7	0.0	0.0	0.7	26.9	22.2	49.1	***-48.4***
T2	0.0	0.0	23.0	0.0	23.0	38.1	23.1	61.2	***-38.2***	0.5	0.0	16.8	17.3	27.7	21.8	49.5	***-32.2***
T3	30.6	79.5	23.0	0.0	133.1	42.3	20.6	62.9	***70.3***	4.1	0.0	28.0	32.1	29.2	21.2	50.4	***-18.3***
P																	
Low yielding subpopulation																	
T0	0.0	0.0	0.0	0.0	0.0	3.7	1.3	5.0	***-5.0***	0.0	0.0	0.0	0.0	2.2	3.2	5.4	***-5.4***
T1	19.4	3.3	0.0	0.0	22.7	3.8	1.6	5.3	***17.4***	2.4	0.0	0.0	2.4	2.7	2.2	5.0	***-2.6***
T2	0.0	0.0	20.0	0.0	20.0	5.0	1.9	6.9	***13.1***	0.0	0.0	20.0	20.0	2.5	2.4	5.0	***15.0***
T3	19.7	0.0	20.0	0.0	39.7	2.5	1.1	3.6	***36.0***	2.4	0.0	20.0	22.4	2.0	2.0	4.0	***18.4***
T0	0.0	0.0	0.0	0.0	0.0	18.0	21.0	39.0	***-39.0***	0.0	0.0	0.0	0.0	4.4	4.0	8.5	**-8.5**
T1	16.7	15.7	0.0	0.0	32.4	9.5	5.2	14.7	***17.7***	0.1	0.0	0.0	0.1	5.2	4.3	9.5	***-9.4***
T2	0.0	0.0	20.0	0.0	20.0	8.3	6.7	15.0	***5.0***	0.1	0.0	12.0	12.1	6.6	4.1	10.6	***1.4***
T3	17.9	11.5	20.0	0.0	49.4	9.7	5.5	15.2	***34.2***	0.4	0.0	20.0	20.4	8.1	5.0	13.0	***7.4***
Low yielding subpopulation																	
T0	0.0	0.0	0.0	0.0	0.0	6.8	32.8	39.6	***-39.6***	0.0	0.0	0.0	0.0	2.7	22.5	25.1	***-25.1***
T1	79.8	22.0	0.0	0.0	101.8	7.3	35.9	43.2	***58.6***	36.8	0.0	0.0	36.8	3.3	24.6	27.9	***8.9***
T2	0.0	0.0	0.0	0.0	0.0	9.2	31.7	40.8	***-40.8***	0.0	0.0	23.3	23.3	3.0	26.0	29.1	***-5.7***
T3	92.6	0.0	0.0	0.0	92.6	5.2	31.9	37.0	***55.5***	38.8	0.0	23.3	62.1	2.4	19.9	22.3	***39.9***
High yielding subpopulation																	
T0	0.0	0.0	0.0	0.0	0.0	19.0	22.0	41.0	**-41.0**	0.0	0.0	0.0	0.0	5.5	26.0	31.5	**-31.5**
T1	35.9	101.7	0.0	0.0	137.6	18.5	71.4	89.9	***47.7***	1.2	0.0	0.0	1.2	6.7	50.7	57.4	***-56.2***
T2	0.0	0.0	0.0	0.0	0.0	19.9	85.8	105.7	***-105.7***	0.8	0.0	14.0	14.8	8.2	60.6	68.8	***-53.9***
T3	49.3	77.0	0.0	0.0	126.3	16.9	72.0	88.9	***37.4***	7.9	0.0	23.3	31.2	9.4	63.9	73.3	***-42.1***

T0: Farmer's practice T1: 10 t ha^{-1} of crop residues or farmyard manure (2001) or 10 t ha^{-1} of crop residues or residual effect of manure (2002) T2: 23 N 46 P_2O_5 (2001) or 28 N 46 P_2O_5 28 K_2O (2002) T3: 23 N 46 P_2O_5 + 10 t ha^{-1} of crop residues or farmyard manure (2001) or 28 N 46 P_2O_5 28 K_2O + 10 t ha^{-1} of crop residues or residual effect manure (2002)

In 1: input of crop residues; In 12: input of farmyard manure; In2: input of mineral fertilizer; ∑In: sum inputs;
Ou1 1: output of harvest product; Out 2: output of crop residues (leaves, stems) ∑Out: sum outputs

Curriculum vitae

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EDUCATION

1985: Diplôme d'Ingénieur Agronome
Specialisation: Soil Science. Faculty of Agronomy Sciences (FSA) of the National University of Benin (UNB)

1998: Maitrise en Sciences Economiques (Option: Gestion des Entreprises). Faculté des Sciences Juridiques, Economiques et Politiques (UNB)

1980: Baccalaureate (BAC) Série D: High School Diploma: Lycée Béhanzin Porto-Novo, Benin

1977: Secondary School Diploma (BEPC): Lycée Béhanzin Porto-Novo, Benin

PROFESSIONAL EXPERIENCES

1986: Installation and supervision of experiments in Mono department de la Coopération Technique Universitaire (CTU) Project of FSA.

1986 - 1988: Agronomist at *Division Analyses des Sols, Eaux et Végétaux (DASEV)* of *Centre National d'Agro-Pédologie (CENAP)*, carrying out and supervising physical and chemical analyses on soil, plant, water, fertilizer and other substrates.

1987: Supervision of students establishing and conducting experiments in Mono department.

1988 – 1998: Director of DASEV at CENAP:

- Supervision and evaluation of soil, plant; water fertilizer and other substrate analysis; all management tasks; morpho-pedological studies
- Supervision of final works of students from "Collège Polytechnique Universitaire (CPU)" and "Lycée Agricole Médji de Sékou (LAMS) in Bénin".

- Teaching of Pedology at Lycée Agricole Médji de Sékou (LAMS) and of Soil Amendment at “Centre de Traitement des Ordures Ménagères (CTOM) **EMAÜS-BENIN”** (1993-1998).
- Collaboration between Sasakawa Gbobal 2000 (PSG 2000) Project and CENAP (1994-1998): Designing experiments on cover crop (*Mucuna utilis*), carrying out on-station and on-farm research and writing reports.
- Collaboration between PSG 2000 and World Institute of Phosphate (IMPHOS) (1996-1999): carrying out of on-station and on-farm research and writing reports.
- **From 1998 to March 2000:** Agronomist at *Cellule Gestion de Terroir*, Parakou: Participatory approaches at village level; working on technical, methodological and organisational innovations with the two teams of on-farm research in northern Benin; training on participatory approaches to improve soil fertility management of the technical staff of “*Projet d’Appui au Développement de la Circonscription Urbaine de Kandi (PADEC)*” and on participatory approaches of the technical staff of “*Projet de Microfinance et de Commercialisation (PROMIC)”.*

  Teaching of participatory approach on soil fertility management of Research and development‘s team in the southern of Benin
- **Since March 2000**: Agronomist at the Centre des Recherches Agricoles Nord (CRA-N).Performing of participatory approach on soil fertility management with the research and development team of Atacora (Northern Benin)
- **From 2001-2003**: Field experiment and data collection for PhD at the Institute of Plant Nutrition of University of Bonn. Germany
- **Since 2002**: Lecture on catchment improvement at Faculté des Lettres Arts et Sciences Humaines of University of Abomey-Calavi.
- **Since 2004:** Lecture on soil chemistry and soil fertility at the Faculty of Agronomy at University of Parakou.