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CHEMICAL CHARACTERISTICS OF SOIL AND SORGHUM FROM *STRIGA*-INFESTED REGIONS OF TANZANIA, AND THE INFLUENCE OF FERTILISER APPLICATION.

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Preface

Striga species, the parasitic witchweeds, are widespread in small holder crops in semi-arid areas of Eastern and Southern Africa. These weeds attack and reduce the yield of finger millet, maize, sorghum and upland rice in these regions. In many areas it is the crops of resource-poor households which are particularly affected. They impose an additional stress with which people, who have little capacity for investment in crop production, have to cope in an environment characterised by marginal rainfall for cropping and declining soil fertility. Since 1996 staff from the Department of Agricultural Research, and Sokoine University in Tanzania and, Natural Resources Institute and University of Sheffield in UK have collaborated to develop integrated *Striga* management practices. Studies are being undertaken on-station and on infested farmers fields in affected communities in the Central, Eastern, Lake and Southern Highlands agricultural zones in Tanzania, with laboratory studies at the University of Sheffield. On-farm work is implemented in collaboration with District Agricultural Extension. Current work emphasises:

- the farmer assessment of tolerant sorghum cultivars and cultural practices which reduce the impact of the parasite;
- the development of learning tools which can provide farmers with a greater understanding of the *Striga* problem;
- understanding the differential performance of sorghum cultivars under a range of levels of soil fertility;
- the identification of traits which confer tolerance to *Striga* in maize;
- assessment of practices to reduce the impact of *Sriga* in upland rice

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Chemical characteristics of soil and sorghum from *Striga*-infested regions of Tanzania, and the influence of fertiliser application.

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ABSTRACT

Agricultural soils in Central, Lake and Eastern Zones of Tanzania were investigated for their capacity to support the growth of novel sorghum lines (Hakika, Macia and Wahi) with low susceptibility to the parasitic flowering plants *Striga asiatica* and *S. hermonthica*. Trials on farms, field stations and in the laboratory probed the relationship between soil fertility, fertiliser application and the host/parasite relationship. Wahi and Hakika plants have a greater tolerance to *Striga* infection and are not stunted to the same degree as cultivar Pato, with yields in the field being equal to or far surpassing Pato even on infertile soils; Macia has an intermediate growth response. Cattle manure application increased yields for all cultivars but Hakika and Wahi were more reliable, showing the least variation in yield with differing soil N status. During workshops at the conclusion of the project (March 2003) the following recommendations were made to stakeholders (including local extension workers): either manure or urea can be applied to young sorghum to suppress *Striga*, manure can be applied just once and will remain in the soil and is recommended as a good all-round plant food, urea is washed out of sandy soils and if used it should be reapplied in small amounts periodically, apply as much fertiliser as can be acquired. Sorghum Hakika is recommended on extremely infertile or variable luseni and itogolo soils (Lake Zone) and isanga, isanga chitope, ngogomba and nkuluhi soils (Central Zone). Wahi is recommended on more consistent, fertile mbuga and ibushi soils (Lake Zone), although Hakika and Macia also provide further choices for these soils.

INTRODUCTION

Farmers' perceptions of soil productivity and ease of cultivation determines land values in the Central, Lake (northern) and Eastern Zones of Tanzania. For example, in 1994 an acre of sandy luseni soil in Kwimba and Misungwi districts (Lake Zone) was worth 2,000 Tanzanian Shillings, and more productive mbuga soil valued at Tsh 4-8,000 an acre (Lamboll et al., 2001a). While a range of soil resources is evident, all major agricultural soil types in Tanzania are believed to be of low to moderate fertility (Lamboll et al., 2001). For regions infested with witchweed (*Striga* spp., Scrophulariaceae), a root parasite attacking mainly cereal crops, this is of critical importance as *Striga* development is hindered at higher nitrogen availabilities. Indeed, *Striga* is more problematic on low fertility soils (Agabawi & Younis, 1965), and high nitrogen availability has been shown to suppress *Striga* germination and attachment (Smaling et al., 1991; Cechin and Press 1993), possibly by limiting host root exudate production (a requirement of *Striga* germination; Yoder, 2001). Higher nitrogen availability also lessens the impact of infection on subsequent growth. *Striga* severely stunts the growth of host cereals by out-competing host sinks, and possibly also by the action of cytotoxic secondary compounds (Parker, 1984a; Parker 1984b; Rank et al., 2003), and can decimate harvests. Small hold farmers in economically underdeveloped regions cannot afford higher-technology solutions to the *Striga* problem and thus soil fertility, often enhanced by application of fertilisers such as farmyard manure (FYM) or urea, is an important determinant of the economic impact of *Striga*.

Another promising low-technology approach to *Striga* control is the breeding of cereal cultivars with low susceptibility to the parasite, the potential of which is greatest if used in concert with soil fertility management. To date true resistance to the penetration of the parasite into the host has not been determined for cereals. However, certain cereal cultivars exude less germination stimulants (xenognosin compounds). Alternatively, the growth of cereals may be little following infection of tolerant hosts (tolerance). Staple cereal crops infected by *Striga* include maize (*Zea mays* L.) and sorghum (*Sorghum bicolor* (L.) MOENCH), the former being the preferred food and well suited to less arid conditions near the coast of Tanzania (i.e. Eastern Zone), and the latter more tolerant of semi-arid conditions and dominating agricultural production in the Central and Lake Zones. Indeed, although maize is preferred sorghum must, by law, be grown by farmers in the Central Zone as this crop is less likely to fail in drier years. Sorghum-producing regions of

Tanzania typically experience only 500-700 mm of annual rainfall, with a 3-3.5 month growing season (starting in December) on low fertility sandy/loamy soils (Ley et al., 2001).

The present study uses standard soil and plant tissue analysis techniques to assess the chemical makeup of the major agricultural soil types of Tanzania, and also to investigate the impact of manure and urea application on *Striga* emergence, soil fertility and plant nutrition. The principal aim is to evaluate a number of sorghum cultivars thought to have a lack of susceptibility to *Striga* infection, and to determine the influence of soil type and fertiliser addition on cultivar responses to *Striga*. These sorghums include cultivars P9405 and P9406 (now registered as Hakika and Wahi in Tanzania, respectively) that were bred for low germination stimulant production at Purdue University (Indiana, USA), and show low levels of infection with both *Striga asiatica* and *S. hermonthica* when compared to a susceptible check (cv. Shanqui Red). Pato and Macia are release varieties in Tanzania, and along with Hakika and Wahi are consistently popular and highly ranked by farmers in Central and Lake Zones (Lamboll et al., 2001b). Evaluations of the host-parasite relationship at different levels of nutrition were conducted with various degrees of precision; on farms with manure as the fertiliser, in fully replicated field station trials with manure and urea, and in controlled-environment conditions in which nitrogen availability was precisely controlled.

The following hypotheses were investigated:

1. Sorghum lines Hakika and Wahi are less susceptible to *Striga* infection than currently released sorghum lines.
2. The degree of susceptibility is dependent on soil resources (including fertiliser application).

METHODS

On-farm trials

Participating farmers from Mwagala village (Ukiriguru ward, Misungwi District, Lake Zone), Iteja village (Misungwi District, Lake Zone) and Chipanga village (Dodoma Rural, Central Zone), Tanzania, grew plots of *Sorghum bicolor* cultivars Hakika, Macia, Pato and Wahi on a range of agricultural soil types (detailed in Table 1) during rainy seasons in 2001 and 2002. Where possible additional rows of these cereals were fertilised using farmyard manure from cattle, with 0.25 or 0.5 kg applied to the base of each plant early in development. Additionally, chemical analysis was undertaken for tifutifu (red soil), the soil dominating Maramba district (near Tanga, Eastern Zone), with samples taken from sites in Mtakuja village. Farmers' perceptions of soil qualities were noted, and the names of soil types presented are the regional Kiswahili names.

Field station trials

In addition to on-farm trials, fully replicated random-block experimental designs were implemented at field stations in the Lake Zone (Lake Zone Agricultural Research and Development Institute, Ukiriguru; luseni soil) and Central Region (Hombolo; nkuluhi soil). Bird-scarers were employed. At Ukiriguru, station managers applied farmyard manure at rates of 8.5, 17 and 34 kg per row of plants (with a control, unfertilised treatment) following planting. At Hombolo either FYM was applied at rates of 0.25 or 0.5 kg to the base of each plant or 50 kg urea per plot.

Soil chemical characteristics

Soil samples were collected using a trowel, and placed into labelled plastic bags for transportation to the laboratory at Mlingano, Eastern Tanzania. Here samples were air-dried. Soil pH was determined in water and in KCl as detailed by McLean (1982). Total soil nitrogen (N) was determined by micro-Kjeldahl digestion (Bremner & Mulvaney, 1982). Available phosphorus (P) was determined by the Bray 1 method (Bray & Kurtz, 1945). Cation exchange capacity (CEC) was determined via the neutral ammonium acetate saturation method, as detailed in Thomas (1982). Exchangeable bases K^+, Ca^{2+}, Mg^{2+} & Na^+ in the ammonium acetate extracts were determined by atomic adsorption spectrophotometry (Thomas 1982). Soil organic carbon was determined via the wet oxidation method detailed in Nelson & Sommers (1982).

Foliar and grain mineral content

Leaf blade samples from the on-farm and field station trials were removed from one side of the midrib, mid way along the second youngest fully expanded leaf. Grain samples were taken by removing a lower branch from the mature panicle. Samples were air-dried and stored in paper bags, and approximately 0.1 g of material subsequently digested in sulphuric and salicylic acid via the Kjeldahl method (Allen 1974; also detailed in Hind 1993). Flow injection analysis was then used to determine foliar N content (as ammonium), using a Tecator 5012 Analyser with a 5042 detector (Foss UK Ltd, Didcot, Oxfordshire, UK) measuring at 590 nm (method based on Tecator application notes ASN 50/84 & ASN 50-02/84). Phosphorus (orthophosphate) content was determined at 690 nm.

Laboratory investigation of N and infected sorghum growth

Plants were grown in sand culture in 2 L pots in controlled environmental conditions. Pots were lined with nappy liner (Boots Plc., Nottingham, UK) to retain sand, and partially filled with washed silver sand. Seed of *Striga hermonthica* (35 mg, ~3000 seeds; seed from Kibos, Kenya, collected in August 1997) was mixed with sand and this mixture placed in the pots at 5 cm depth, with pots subsequently filled. Pots were kept at a day/night temperature of 28/22 ºC, a relative humidity of 70/50 %, with water supplied via an automated irrigation system. After 7 d, sorghum cultivars were assigned to pots according to a randomised block design, with two seeds of a particular cultivar placed in each pot and covered by sand to a depth of 1 cm. Pots were then supplied with 40 % Long Ashton nutrient solution modified to provide nitrogen at either 0.25, 0.5 and 1 mM N as ammonium nitrate (NH_4NO_3) (Hewitt 1966). Following establishment (10 days after planting [dap]) sorghum seedlings were thinned to one per pot. Sorghum was grown at a light intensity (photosynthetic photon flux density [PPFD]) of ~500 µmol m^{-2} s^{-1} at plant height with a 12 h photoperiod.

At 58 dap chlorophyll fluorescence characteristics of the youngest fully expanded leaf (YFEL) of sorghum plants were determined. Plants were first dark-adapted for a minimum of 30 min, and then an area two thirds along the length of the YFEL placed in a PLC3 leaf cuvette (ADC Bioscientific), connected by fibre optic to both an actinic light source and a PAM-101 modulated chlorophyll fluorometer (H. Walz, Effeltrich, Germany). Chlorophyll fluorescence quenching analysis was conducted using the saturated pulse method detailed by Bolhàr-Nordenkampf and Öquist (1993), at a temperature of 25 ºC, a relative humidity

(RH) of 60 %, a carbon dioxide (CO_2) concentration of 360 µmol mol^{-1} (air supply *via* gas mixer). Following induction, photosynthetic electron transport rate calculated as detailed by Maxwell and Johnson (2000). Immediately following determination of photosynthetic characteristics, leaf discs were taken from the YFEL and dried at 70 ºC until constant weight. Leaf discs were subsequently digested via the Kjeldahl method and nitrogen and phosphorus concentration determined via the method detailed above.

At 85 dap the number of *Striga* shoots visible above ground was recorded, and then sorghum roots washed of sand. The number of *Striga* individuals attached to the roots of each sorghum plant was recorded, and then parasites separated from the host. Host plants were then further divided into root, pseudostem (true stem together with leaf sheaths), dead/senescent leaf material and green leaf material. All plant parts were then bagged separately, dried at 70 ºC until constant weight, and subsequently weighed. Instantaneous specific leaf area (SLA; m^2 g^{-1}) was calculated from leaf discs of known area and dry weight.

RESULTS

Soil characteristics

All major agricultural soil types in the Central, Lake and Eastern Zones of Tanzania are of poor fertility in terms of nitrogen (N) (Table 1). The quality of the organic component of the soils examined was good in all cases, as indicated by a low C/N ratio (<14), however the absolute amount of soil organic carbon (C) was low to moderate in all cases (≤ 2.1 %; Table 1).

In the Lake Zone, dark mbuga soils were identified by farmers as the most productive. Indeed this clayey soil had the highest N, C and available phosphorus (P) contents of any soil in the region. Cation exchange capacity (CEC), Ca and K contents of mbuga were all very high (Table 1). Dark ibushi soils were identified as moderately productive, and indeed had chemical characteristics intermediate between mbuga soils and the unproductive itogolo and luseni soils. Sandy luseni soils had particularly low C, N, Ca and K contents, low CEC and moderate P availability (Table 1).

The Central Zone also consisted of four major agricultural soils. Chemical analysis determined that isanga soil from fields in which sorghum was grown had the highest C, N, CEC, Ca and K of any in the region, with a high P availability. However, farmers also disclosed that isanga is not a soil on which sorghum can be grown; possibly isanga is a highly variable soil type, with only isanga capable of supporting sorghum being sampled in the present study. Isanga chitope, ngogomba and nkuluhi soils all had very low N contents, very low/low CEC, Ca and K, but moderate to high P availability (Table 1).

Tifutifu soil in the Eastern Zone was regarded as productive, but had low N and P contents and moderate CEC (Table 1).

Manure addition on farms

Although approximately ten farmers in each village were initially involved in the study, a large proportion of these could not contribute data due to external factors such as insect attacks (stem borer, midge, mole cricket), or a lack of manure availability during part or all of the trial. Data is therefore restricted to single farmers from each village who were able to maintain fertilised trial plots throughout the growth season.

Addition of FYM to luseni soil increased pH, soil organic carbon, N, available P, CEC, Ca, Mg, K, Na and electrical conductivity (EC; Table 2). Decreased C/N ratios with manure addition indicate an increased quality in the soil organic component. FYM applications of 0.5 kg/plant suppressed the emergence of *Striga asiatica* and *S. hermonthica* on luseni soils (Table 3), although *S. asiatica* was more abundant on cultivar Pato when fertilised. *Striga asiatica* was also more abundant on Pato when nkuluhi soils were fertilised, with cultivars Hakika, Macia and Wahi supporting fewer *Striga* plants (Table 3). Grain yields of all cultivars were higher when fertilised (N.B. midge attack resulted in loss of grain yield on luseni soil), with Pato yielding the least grain (1.1 kg/plot) and Hakika yielding four times as much as Pato (4.5 kg/plot) and Macia and Wahi also yielding well. Hakika and Wahi also had particularly high yields when no fertiliser was applied (3.4 and 3.1 kg/plot, respectively).

Soil, leaf and grain N & P contents were too variable to distinguish the effects of manure addition on farmers' fields (Table 4). However, low soil N contents were again observed for isanga chitope and luseni soils, with leaf N contents particularly low on luseni soils, and soil P availability high but leaf P contents low (Table 4). Grain N and P contents did not differ different between soil types.

Manure and urea addition during field station trials

Soil N was low (0.3 – 0.5 g kg^{-1}) and P availability very high (28 – 168 mg kg^{-1}) for luseni soil at the Ukiriguru field station, and yields were low, not exceeding 0.7 t ha^{-1} for heavily fertilised Wahi. Manure addition increased soil pH and N, leaf N and grain yields (Table 5). However, soil available P, leaf and grain N & P contents were not consistently altered by manure addition. *Striga* was present throughout the plots, but was extremely abundant towards one end of the field and showed no consistent trend in relation to experimental treatments (Table 5).

At Hombolo field station FYM did result in decreased numbers of emerged *S. asiatica*, also increasing grain yields for all cultivars (Table 6). Urea was as effective as FYM at decreasing *Striga*, and yields were increased, but application of either 0.25 or 0.5 kg FYM resulted in the highest yields for all cultivars. Soil pH, N and also available P were increased by FYM addition, but urea did not increase soil N for soil supporting cultivars Hakika, Macia and Wahi. Similarly, leaf N content was increased by FYM but not by urea, indicating that extra N from urea was not present in the soil or plants towards the end of the experiment. Grain quality, in terms of Ca, Mg, N and P contents, was not altered by fertiliser treatments (Table 6). Cultivar Pato had the highest yield when fertilised with 0.5 kg FYM (2.5 t ha^{-1}), but one of the lowest yields without fertilisation (along with Macia; 1.0 and 0.9 t ha^{-1}, respectively). Yields of Hakika and Wahi were consistently high, with 1.8 and 1.7 t ha^{-1}, respectively, in control plots, with up to 2.3 t ha^{-1} with added FYM (Table 6). When urea was used to fertilise plots, Hakika and Wahi had the highest yields (2.0 and 1.8 t ha^{-1}, respectively) and Pato the lowest (1.3 t ha^{-1}; Table 6).

Cultivar response to Striga and nitrogen in the laboratory

The relative size of representative plants of each cultivar and each treatment is illustrated in Fig. 1. Control plants of sorghum cultivar Pato attained the greatest height of the cultivars tested, achieving 756 cm after 85 d of growth at 1 mM N (*cf.* 330 – 411 cm for other cultivars; not shown). All cultivars were markedly shorter on infection, and reached approximately the same absolute height of ~200 cm at 1 mM N, with lower nitrogen availability resulting in shorter plants irrespective of *Striga* infection. Pseudostem length of infected hosts, as a proportion of that of control plants, was greatest in cultivar Wahi at 1 mM N (73.8 % at 85 dap), but was less apparent at lower N availabilities (e.g. 49.6 % at 0.5 mM N). Cultivars Hakika and Macia also showed less response to infection in terms of plant height than did cv. Pato, in which pseudostems of infected plants were only 26.6 % of uninfected plants at 85 dap (data not shown).

Striga infection decreased whole plant biomass for all cultivars, and increased nitrogen availability resulted in increased total biomass for all cultivars (Table 7). Biomass of roots was not affected by *Striga* infection, with pseudostem and leaf biomass accounting for differences in whole plant biomass. This was reflected by higher root:shoot ratios for all cultivars and at all nitrogen availabilities (Table 7). Pseudostems of infected Pato attained only 15.2 % the dry weight of uninfected control plants at 1 mM N, whereas pseudostems of infected Wahi achieved 52.3 % (although values for this cultivar were 13.1 and 13.9 % at lower nitrogen availabilities; Fig. 2). Pseudostems of infected Hakika attained between 24.8 and 27.5 % the dry weight of control plants (Fig. 2). Macia exhibited decreased pseudostem dry weight in response to lower nitrogen availability, but with pseudostems of infected plants being 21.2 % the biomass of controls at 1 mM N, appeared more tolerant to *S. hermonthica* than Pato (Fig. 2). The effects of *Striga* infection on pseudostem biomass were mediated by higher N availability ($p < 0.05$ for all cultivars), particularly so for Wahi ($f = 4.38$, $p = 0.024$).

The number of *Striga* individuals attached to sorghum roots was highly variable, with no difference between nitrogen treatments for any cultivar excepting that between 0.25 and 0.5 mM N for Macia. *Striga* numbers tended to be lowest at the higher nitrogen availability (1 mM N), although this was not statistically significant for any cultivar (i.e. $p > 0.05$; Table 7).

Photosynthetic characteristics (electron transport rate, efficiency of photosystem II, specific leaf area) and leaf N & P contents were not significantly altered by *Striga* infection of N availability (Table 8), with the exception of high leaf N for infected Pato. Photosynthetic capacity (A_{max}) of all cultivars was relatively low (i.e. <11 µmol m^{-2} s^{-1}), but no trends were apparent between treatments (not shown).

DISCUSSION

Soil types and fertilisers

The high availability of phosphorus for unproductive sandy soils such as luseni, and increasing foliar nitrogen and yields in response to greater nitrogen availability, indicate that N is the limiting macronutrient for the growth of sorghum in the field. Both farmyard manure and urea suppress *Striga* when applied early in the growth season, when *Striga* attaches to host roots. However, when urea was applied to nkuluhi soil a lack of extra N was evident in the soil/plant system at the end of the growth season (*cf.* unfertilised controls). With relatively small or no increases in grain yields (*cf.* FYM) this indicates that urea was leached from the soil. Indeed, nkuluhi at Hombolo is composed of 80 % sand, with a low organic carbon content (0.25 %), and has a rapid infiltration rate of 10 cm h^{-1} making it prone to erosion (Ngalesoni 2001). In comparison, soils with higher clay contents (46 – 82 %) and organic carbon contents (1.2 – 2.8 %) retain urea, which is also evident as enhanced crop growth (Temba 1999; Kwacha 2001). Increased nitrate application increases infiltration rates, thereby exacerbating leaching (Errebhi et al., 1998; Temba 1999). Urea is hydrolysed to ammonia (Temba 1999), with both of these compounds being leached during heavy rainfall (Preez & Burger 1986). Heavy rainfall did occur at Hombolo during the start of the growth season (personal observation of A.M. Mbwaga). Thus, heavy application of urea fertiliser to sandy soil with little organic carbon, in combination with high rainfall, could explain the observed losses of urea N. Extension workers in the Dodoma region of Tanzania report that farmers have found urea fertilisation to be very inconsistent (P. Lameck, pers. comm.).

Conversely, manure is rich in organic matter and will retain nitrogenous compounds for longer, in addition to containing other macro- and micro-nutrients such as Ca, K and P. Although it is technically possible to apply so much fertiliser that nitrogen becomes toxic to the plant (Marschner, 1999), plant growth and yields were highest at excessive manure application in the Ukiriguru trial, indicating that for the nutrient-poor agricultural soils of Tanzania the upper limit to manure application will be constrained more by economics than by toxicology. This relationship between manure application and the growth response of crops was also recorded by Nonga (1999), who also determined that poultry manure had the highest nutrient contents and provoked the greatest plant response, followed by goat and finally cattle manure. Possibly, supplementing urea with organic matter in the form of green manures may retain nitrogen in the soils and increase productivity. Low rates of urea application should also avert excessive leaching.

Sorghum cultivar responses

The sorghum cultivars investigated showed consistent responses to *Striga* and fertiliser both in the field and in the laboratory. The laboratory study showed that when supplied with sufficient nitrogen, cultivar Pato attained the greatest pseudostem biomass and height of the cultivars tested, but this was drastically curtailed by infection with *S. hermonthica* (i.e. Pato is heavily stunted). Wahi and Hakika, although smaller in stature, were not stunted to the same extent, with pseudostems of infected plants larger when considered as a proportion of uninfected control plants (Fig. 2). Also, despite severe nitrogen limitation to growth at 0.25 mM N, cultivar Hakika retained the same degree of tolerance to *S. hermonthica* infection, as indicated by pseudostem biomass. Indeed, in the field Hakika and Wahi also showed grain yields equal to or far surpassing those of Pato and Macia when no fertiliser was added to soils.

Thus, perhaps most importantly for the farmers who rely on sorghum in times of drought, Hakika in particular is relatively consistent (hence the name which in the Kiswahili language means ‘certain’ - Wahi means ‘on time’ due to its early flowering characteristics). Early flowering characteristics allow a greater likelihood of yielding should rains fail towards the end of the season, and if rain is plentiful an additional harvest may be achieved. Hakika, Wahi and Macia also support markedly less fungal pathogens, such as rust, leaf blight, sooty stripe and long smut, than Pato (A.M. Mbwaga, unpublished data). Both the field and laboratory studies determined that cultivar Macia is intermediate between Pato and Wahi in its growth response to *Striga* and fertiliser, and provides another good choice for farmers who currently grow Pato. Pato may also yield well and provide a good choice where soil fertility is particularly high or where *Striga* is absent. Grain of all cultivars was of consistent quality (in terms of N, P and metallic constituents), with only yields being affected by soil type or fertiliser.

These findings have been distilled into the following recommendations for farmers of Tanzanian soils:

1. Either manure or urea can be applied to young sorghum to suppress *Striga*.
2. Manure can be applied just once and will remain in the soil, and is recommended as a good all-round plant food.
3. Urea is not recommended as it is not an all-round plant food and is washed out of sandy soils; if used it should be reapplied in small amounts periodically.
4. Apply as much fertiliser as can be acquired.
5. Hakika is recommended over other cultivars on extremely infertile and variable luseni and itogolo soils (Lake Zone) and isanga, isanga chitope, ngogomba and nkuluhi soils (Central Zone).
6. Wahi is recommended on more consistent, fertile mbuga and ibushi soils (Lake Zone), although Hakika and Macia are also good choices for these soils.

The decision trees presented in Figs. 3 & 4 represent guidelines for the implementation of these recommendations, and were identified by stakeholders as useful and easy to utilize in devising flexible, local recommendations. However, these decision trees are based only on the data presented here, and stakeholders identified a need to incorporate other factors that influence the growth of crops in future versions.

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Table 1. Characteristics of major agricultural soil types in Tanzania. Data represent the mean ± 1 SE of nine replicates (n=6 for nkuluhi soil), with samples taken from farmers' fields in the Central, Lake and Eastern Zones of Tanzania in October 2000. CEC = Cation exchange capacity.

Soil type	Description	Chemical characteristics							
		pH (in H_2O)	Organic C (%)	Total N (%)	C:N	Avail. P (mg kg^{-1})	CEC (meq. kg^{-1})	Ca (meq. kg^{-1})	K (meq. kg^{-1})
Lake Zone									
Ibushi	Clay loams to clay, grey/black. Moderate productivity. Friable when dry, becomes hard if left fallow. Retains water and is prone to waterlogging in lowlands, but is not prone to erosion when wet.	7.6 ±0.05	1.5 ±0.04	0.11 ±0.002	13.3 ±0.32	6.2 ±0.64	21.2 ±2.40	16.1 ±1.78	1.0 ±0.11
Itogolo	Dark grey sandy clay loam. Heavy and sticky. Moderate/poor productivity. Hard if dry, difficult to cultivate. Poor infiltration rate; water may stand on surface.	7.6 ±0.05	1.1 ±0.04	0.09 ±0.002	11.6 ±0.24	1.0 ±0.03	11.7 ±0.45	9.7 ±0.60	0.7 ±0.02
Luseni	Sandy, Red in lowland, white in uplands. Easy to cultivate but unproductive.	7.0 ±0.03	0.4 ±0.01	0.04 ±0.001	11.9 ±0.28	4.2 ±0.60	1.6 ±0.05	0.9 ±0.04	0.1 ±0.00
Mbuga	Dark grey/brown, clay or sandy clay. Very productive. Difficult to cultivate unless moist for substantial period.	6.7 ±0.03	2.1 ±0.06	0.17 ±0.005	13.3 ±0.34	10.8 ±1.10	71.6 ±0.60	39.3 ±0.47	3.1 ±0.04
Central Zone									
Isanga	Coarse loam, sandy, yellow/brown. Very easy to dig.	7.2 ±0.01	1.5 ±0.05	0.13 ±0.002	11.2 ±0.33	18.4 ±2.16	6.6 ±0.27	4.3 ±0.12	0.7 ±0.02
Isanga chitope	Sandy clay. Productive.	6.7 ±0.07	0.5 ±0.03	0.05 ±0.003	11.6 ±0.30	14.9 ±0.98	4.8 ±0.23	2.3 ±0.12	0.4 ±0.03
Ngogomba	Grey clayey soil. Dry and hard, very difficult to dig. Prone to surface runoff.	6.6 ±0.03	0.9 ±0.04	0.10 ±0.003	9.4 ±0.21	22.1 ±0.46	1.1 ±0.14	0.6 ±0.09	0.2 ±0.03
Nkuluhi	Red sandy clay loam. Easy to dig. Low productivity.	6.6 ±0.10	0.8 ±0.02	0.09 ±0.003	8.2 ±0.13	10.3 ±0.96	6.4 ±0.22	2.7 ±0.14	0.6 ±0.03
Eastern Zone									
Tifutifu	Red clay-loam. Sticky and productive.	6.9 ±0.03	1.9 ±0.05	0.18 ±0.003	11.1 ±0.12	1.0 ±0.12	8.5 ±0.22	4.7 ±0.15	0.5 ±0.02

Table 2. The effect of farmyard manure (FYM) application on the chemical characteristics of luseni soil of farmer Kashija Malinganya (Mwagala village, Ukiriguru ward, Misungwi District, Lake Zone, Tanzania) supporting *Sorghum bicolor* cultivars Hakika, Pato and Wahi. Soil samples were taken at 2-5 cm depth at the base of the sorghum plants. Data represent the mean ± 1 S.E. of nine replicates. CEC = cation exchange capacity. EC = electrical conductivity.

FYM application (kg/plant)	**pH in H_2O**	**Organic C ($g\ kg^{-1}$)**	**Total N ($g\ kg^{-1}$)**	**C:N**	**Avail. P ($mg\ kg^{-1}$)**	**CEC ($meq.\ kg^{-1}$)**	**Exchangeable bases Ca ($meq.\ kg^{-1}$)**	**Mg ($meq.\ kg^{-1}$)**	**K ($meq.\ kg^{-1}$)**	**Na ($meq.\ kg^{-1}$)**	**EC ($ms\ cm^{-1}$)**
0	7.0 ±0.09	5.6 ±0.55	0.4 ±0.06	14.4 ±0.78	11.6 ±1.62	36 ±2.8	20 ±1.7	8.4 ±1.28	3.9 ±0.75	2.6 ±0.09	0.03 ±0.004
0.25	7.2 ±0.05	6.6 ±0.93	0.6 ±0.13	15.2 ±0.98	26.7 ±4.32	38 ±6.0	23 ±4.4	7.7 ±1.27	5.3 ±0.94	3.1 ±0.12	0.06 ±0.013
0.5	7.4 ±0.13	8.1 ±1.25	0.7 ±0.12	13.9 ±0.65	22.0 ±5.42	52 ±7.4	32 ±5.3	12.2 ±2.78	6.3 ±0.83	3.8 ±0.38	0.10 ±0.029

Table 3. The effect of farmyard manure (FYM) addition on numbers of emerged *Striga* and grain yield of different sorghum cultivars in a 25 m^2 plot of nkuluhi soil belonging to farmer Richard Nyamwanji (Mvumi, Central Zone, Tanzania) and luseni soil belonging to Ramadhani Mashara (Iteja, Lake Zone). Emerged *Striga* was counted at 12 weeks after planting (WAP) and at grain harvest, and at 9 WAP on luseni soil. *S.a.* = *Striga asiatica*, *S.h.* = *S. hermonthica*. No yields are presented for luseni soil due to severe losses to insect pests subsequent to grain sampling for N & P contents.

Soil type	**Cultivar**	**FYM application (kg/plant)**	***Striga* count/plot (25 m^2)**						**Yield (kg/plot)**
			9 WAP		**12 WAP**		**At harvest**		
			Striga asiatica						
Nkuluhi	**Hakika**	0	-		450		948		3.4
		0.5	-		61		325		4.5
	Macia	0	-		105		2378		2.5
		0.5	-		73		1485		3.5
	Pato	0	-		116		545		0.8
		0.5	-		340		892		1.1
	Wahi	0	-		172		1204		3.1
		0.5	-		97		537		3.5
			S.a.	***S.h.***	***S.a.***	***S.h.***	***S.a.***	***S.h.***	
Luseni	**Hakika**	0	0	10	0	11	0	19	-
		0.5	0	6	0	6	1	11	-
	Macia	0	2	14	5	16	15	30	-
		0.5	1	10	5	18	10	25	-
	Pato	0	0	32	0	30	2	60	-
		0.5	1	20	6	30	8	45	-
	Wahi	0	2	15	6	19	10	30	-
		0.5	1	9	5	16	5	20	-

Table 4. Effects of farmyard manure (FYM) addition on soil, leaf and grain mineral contents for four sorghum cultivars (Hakika, Macia, Pato, Wahi) grown on isanga chitope soil by farmer Richard Nyamwanji (Mvumi, Central Zone, Tanzania), luseni soil by farmer Ramadhani Mashara (Iteja, Lake Zone), and ngogomba soil by farmer Rose Makasi (Chipanga, Central Zone; grain not filled at sampling). Data are means ± 1 S.E. of three replicates. Emboldened data (0.5 kg FYM) are significantly different from controls (0 kg FYM) at the P ≤ 0.05 level as determined by Student's *t*-test.

Soil type	**Cultivar**	**Fertiliser (kg FYM)**	**Soil** C:N	N (g kg^{-1})	P (mg kg^{-1})	**Leaf** N (mg g^{-1})	P (mg g^{-1})	**Grain** N (mg g^{-1})	P (mg g^{-1})
Isanga chitope	**Hakika**	0	8.3 ±0.49	0.3 ±0.03	5.1 ±1.05	29.4.±1.27	1.9 ±0.24	17.5 ±0.51	2.6 ±0.22
		0.5	8.2 ±0.44	0.3 ±0.06	**1.9 ±0.15**	**34.5 ±0.76**	2.0 ±0.42	19.3 ±1.21	3.5 ±0.31
	Macia	0	15.3 ±1.17	0.2 ±0.00	3.3 ±0.76	33.7 ±0.66	1.5 ±0.12	14.3 ±1.81	1.8 ±0.33
		0.5	14.3 ±3.48	0.5 ±0.25	4.4 ±1.44	30.3 ±3.38	1.3 ±0.02	14.7 ±0.74	1.9 ±0.12
	Pato	0	14.0 ±0.82	0.4 ±0.07	2.9 ±0.21	35.3 ±1.11	1.8 ±0.19	12.8 ±0.98	1.9 ±0.10
		0.5	16.7 ±1.20	0.3 ±0.03	**7.0 ±0.41**	**28.3 ±.1.51**	1.4 ±0.12	12.7 ±4.18	1.9 ±0.66
	Wahi	0	15.3 ±0.39	0.3 ±0.03	5.0 ±0.62	33.6 ±2.94	2.2 ±0.29	16.8 ±0.71	3.1 ±0.45
		0.5	**18.6 ±0.30**	0.4 ±0.03	4.6 ±0.38	33.7 ±0.66	1.6 ±0.18	16.2 ±1.20	2.5 ±0.10
Luseni	**Hakika**	0	14.0 ±0.58	0.4 ±0.00	46.8 ±5.50	13.0 ±0.36	1.3 ±0.05	12.7 ±3.42	3.2 ±1.24
		0.5	14.3 ±1.86	**0.2 ±0.03**	39.2 ±12.42	15.8 ±1.47	**2.2 ±0.22**	17.4 ±1.37	3.3 ±0.08
	Macia	0	18.0 ±1.15	0.4 ±0.03	63.7 ±4.43	15.8 ±1.89	2.5 ±0.53	18.8 ±1.09	3.2 ±0.19
		0.5	16.7 ±1.20	0.3 ±0.00	**40.6 ±2.88**	10.6 ±0.79	1.4 ±0.18	19.0 ±2.61	3.1 ±0.14
	Pato	0	15.7 ±0.88	0.3 ±0.03	49.6 ±8.89	13.3 ±0.96	2.4 ±0.16	13.7 ±2.58	3.1 ±0.11
		0.5	13.7 ±2.73	0.3 ±0.03	63.7 ±4.43	12.7 ±1.18	1.8 ±0.13	13.5 ±4.67	7.1 ±3.31
	Wahi	0	17.0 ±1.00	0.3 ±0.03	55.1 ±7.00	17.2 ±0.80	2.1 ±0.40	18.3 ±1.92	3.3 ±0.11
		0.5	15.7 ±1.20	0.3 ±0.03	30.2 ±9.17	14.3 ±1.80	1.5 ±0.27	14.6 ±5.54	6.5 ±3.45
Ngogomba	**Hakika**	0	11.1 ±0.75	1.0 ±0.00	4.1 ±0.61	48.1 ±2.76	4.1 ±0.35	-	-
		0.5	9.6 ±0.89	1.0 ±0.00	**6.9 ±0.36**	50.3 ±3.81	5.3 ±0.36	-	-
	Macia	0	11.6 ±2.86	0.8 ±0.20	4.2 ±0.70	44.9 ±1.79	5.2 ±0.04	-	-
		0.5	9.6 ±0.72	1.0 ±0.00	6.5 ±0.73	43.1 ±1.12	**3.9 ±0.35**	-	-
	Pato	0	9.1 ±0.76	1.0 ±0.00	9.1 ±3.17	34.2 ±5.50	3.4 ±0.78	-	-
		0.5	10.3 ±2.02	1.0 ±0.00	**29.3 ±5.30**	42.5 ±1.53	4.9 ±0.16	-	-
	Wahi	0	11.9 ±0.42	1.0 ±0.00	4.0 ±1.87	51.3 ±3.49	5.4 ±0.45	-	-
		0.5	9.1 ±0.76	1.0 ±0.00	8.4 ±3.16	51.0 ±2.34	4.8 ±0.46	-	-

Table 5. Soil characteristics supporting four cultivars of sorghum at Ukiriguru research station (Lake Zone, Tanzania) grown with 8.5, 17 or 34 kg FYM per row of plants, or no fertiliser treatment (control) on Luseni soil infested with *Striga asiatica* and *S. hermonthica*. Data represent the mean ±1 SE of four replicates.

Cultivar	Fertiliser treatment	*S. asiatica* at final harvest (plants m^{-2})	*S. hermonthica* at final harvest (plants m^{-2})	Soil				Leaf		Grain		
				pH (in H_2O)	**Total N (g kg^{-1})**	**C:N**	**Avail. P (mg kg^{-1})**	**N (mg g^{-1})**	**P (mg g^{-1})**	**N (mg g^{-1})**	**P (mg g^{-1})**	**Yield (t ha^{-1})**
Hakika	Control	0.0 ±0.00	0.0 ±0.00	7.5 ±0.20	0.3 ±0.05	12.8 ±1.44	75.4 ±16.72	23.6 ±1.02	3.3 ±0.29	12.8 ±0.60	4.0 ±0.29	**0.3 ±0.08**
	8.5 kg	0.0 ±0.00	1.0 ±0.41	7.4 ±0.14	0.3 ±0.04	13.3 ±1.02	39.9 ±3.37	25.4 ±1.20	3.3 ±0.34	13.9 ±2.04	3.9 ±0.15	**0.4 ±0.04**
	17 kg	8.8 ±8.75	3.5 ±2.22	7.4 ±0.11	0.4 ±0.06	13.2 ±0.69	65.2 ±14.55	27.2 ±2.78	3.5 ±0.19	11.8 ±1.62	3.4 ±0.43	**0.5 ±0.06**
	34 kg	0.3 ±0.25	6.8 ±4.87	7.6 ±0.08	0.6 ±0.13	11.8 ±1.08	55.9 ±12.11	28.8 ±1.71	3.6 ±0.14	15.3 ±2.47	3.6 ±0.23	**0.5 ±0.15**
Macia	Control	4.0 ±2.27	1.0 ±1.00	7.2 ±0.10	0.3 ±0.10	12.1 ±1.49	88.4 ±30.26	24.3 ±0.80	3.6 ±0.08	10.6 ±1.27	3.8 ±0.37	**0.4 ±0.07**
	8.5 kg	0.0 ±0.00	5.8 ±4.77	7.3 ±0.11	0.3 ±0.05	13.8 ±1.93	56.4 ±14.74	27.5 ±1.43	3.4 ±0.27	12.7 ±1.19	3.8 ±0.11	**0.5 ±0.14**
	17 kg	24.0 ±22.02	4.0 ±3.67	7.4 ±0.12	0.4 ±0.10	13.6 ±0.69	47.7 ±11.00	25.5 ±1.59	2.9 ±0.28	10.1 ±0.57	3.2 ±0.11	**0.5 ±0.17**
	34 kg	3.3 ±1.60	5.0 ±2.83	7.4 ±0.05	0.5 ±0.11	13.8 ±1.38	82.5 ±19.42	26.5 ±1.64	3.1 ±0.28	12.3 ±0.89	3.7 ±020	**0.6 ±0.18**
Pato	Control	2.3 ±1.93	0.5 ±0.29	7.3 ±0.09	0.3 ±0.08	12.1 ±1.21	52.0 ±19.10	20.8 ±1.32	2.7 ±0.16	12.0 ±1.17	3.9 ±0.14	**0.4 ±0.04**
	8.5 kg	0.3 ±0.25	2.3 ±1.93	7.2 ±0.18	0.3 ±0.05	14.9 ±0.48	48.4 ±10.62	23.6 ±0.63	2.8 ±0.16	14.5 ±2.83	4.2 ±0.57	**0.5 ±0.08**
	17 kg	1.5 ±0.87	2.3 ±1.65	7.5 ±0.12	0.3 ±0.03	15.5 ±0.35	62.1 ±19.42	24.5 ±0.76	3.3 ±0.16	16.4 ±3.81	5.4 ±0.36	**0.6 ±0.06**
	34 kg	0.0 ±0.00	2.8 ±2.14	7.5 ±0.12	0.5 ±0.07	13.9 ±1.03	56.9 ±21.51	25.8 ±1.41	2.9 ±0.07	18.8 ±4.08	4.5 ±0.60	**0.6 ±0.07**
Wahi	Control	7.8 ±7.75	2.5 ±1.85	7.2 ±0.07	0.3 ±0.07	11.8 ±0.80	46.1 ±15.49	24.6 ±2.20	3.2 ±0.29	16.6 ±2.39	4.1 ±0.19	**0.4 ±0.12**
	8.5 kg	0.0 ±0.00	8.0 ±3.72	7.3 ±0.14	0.4 ±0.07	13.1 ±1.08	28.4 ±1.20	27.1 ±2.30	3.3 ±0.28	17.1 ±2.74	4.4 ±0.39	**0.3 ±0.10**
	17 kg	0.0 ±0.00	0.8 ±0.75	7.3 ±0.05	0.5 ±0.14	13.0 ±0.64	56.3 ±17.10	26.4 ±1.81	3.1 ±028	14.6 ±0.95	4.1 ±0.32	**0.6 ±0.08**
	34 kg	0.0 ±0.00	0.5 ±0.50	7.5 ±0.12	0.5 ±0.06	14.3 ±0.93	167.9 ±87.57	30.1 ±1.41	3.3 ±0.34	13.9 ±0.97	3.9 ±0.07	**0.7 ±0.19**

Table 6. Soil, leaf and grain characteristics of four cultivars of sorghum at Hombolo research station (Central Zone, Tanzania) grown with 0.25, 0.5 kg FYM per plant or 50 kg of Urea, or no fertiliser treatment (control) on Nkuluhi soil infested with *Striga asiatica*. Data represent the mean ±1 SE of four replicates.

Cultivar	**Fertiliser treatment**	***Striga* count at final harvest (plants m^{-2})**	**Soil**				**Leaf**		**Grain**				
			pH (in H_2O)	**Total N (g kg^{-1})**	**C:N**	**Avail. P (mg kg^{-1})**	**N (mg g^{-1})**	**P (mg g^{-1})**	**N (mg g^{-1})**	**P (mg g^{-1})**	**Ca (mg g^{-1})**	**Mg (mg g^{-1})**	**Yield (t ha^{-1})**
Hakika	Control	5.7 ±4.17	6.5 ±0.11	0.5 ±0.17	12.4 ±1.95	4.7 ±2.97	16.0 ±2.42	1.2 ±0.23	18.6 ±1.34	2.5 ±0.36	0.1 ±0.01	1.2 ±0.07	**1.8 ±0.30**
	0.25 kg FYM	3.0 ±2.42	7.0 ±0.16	0.9 ±0.01	10.8 ±1.02	13.9 ±1.18	19.2 ±1.87	1.6 ±0.24	17.3 ±0.35	3.8 ±0.39	-	-	**1.8 ±0.21**
	0.5 kg FYM	1.0 ±0.41	6.8 ±0.04	0.9 ±0.13	12.8 ±0.84	23.3 ±6.68	24.4 ±1.58	2.1 ±0.47	16.5 ±0.87	3.3 ±0.37	0.1 ±0.03	1.4 ±0.11	**2.1 ±0.09**
	Urea	4.3 ±4.33	5.9 ±0.13	0.4 ±0.12	13.9 ±1.39	2.6 ±0.62	15.6 ±0.95	1.4 ±0.40	16.8 ±0.40	2.6 ±0.13	-	-	**2.0 ±0.22**
Macia	Control	42.5 ±30.71	6.5 ±0.14	0.7 ±0.16	12.1 ±1.97	2.2 ±0.19	16.6 ±0.80	0.9 ±0.10	17.0 ±0.08	2.1 ±0.11	0.1 ±0.03	0.9 ±0.07	**0.9 ±0.36**
	0.25 kg FYM	13.0 ±4.27	6.9 ±0.10	0.8 ±0.17	10.5 ±1.61	9.4 ±1.17	19.0 ±1.08	1.2 ±0.08	18.4 ±0.81	3.0 ±0.23	-	-	**1.9 ±0.21**
	0.5 kg FYM	7.1 ±3.23	6.8 ±0.10	0.9 ±0.07	12.0 ±0.69	16.6 ±6.82	20.1 ±1.56	1.2 ±0.12	16.0 ±0.67	2.8 ±0.23	0.1 ±0.02	1.2 ±0.09	**1.6 ±0.19**
	Urea	7.4 ±5.88	6.1 ±0.12	0.5 ±0.07	13.5 ±1.10	2.4 ±1.03	16.2 ±2.04	1.1 ±0.21	20.6 ±0.72	2.6 ±0.16	-	-	**1.5 ±0.41**
Pato	Control	49.0 ±29.23	6.5 ±0.20	0.5 ±0.18	12.1 ±1.51	5.3 ±1.66	12.1 ±2.42	0.8 ±0.04	15.8 ±1.32	1.9 ±0.11	0.1 ±0.02	0.9 ±0.03	**1.0 ±0.30**
	0.25 kg FYM	38.9 ±28.15	6.9 ±0.13	0.8 ±0.13	11.1 ±1.50	10.6 ±2.59	9.8 ±1.14	0.8 ±0.12	16.5 ±0.86	2.5 ±0.24	-	-	**2.4 ±0.50**
	0.5 kg FYM	11.1 ±4.34	6.9 ±0.07	1.0 ±0.16	11.1 ±0.57	16.4 ±7.77	15.0 ±1.37	1.1 ±0.22	13.9 ±0.77	2.9 ±0.29	0.1 ±0.02	1.2 ±0.05	**2.5 ±0.07**
	Urea	6.5 ±5.84	6.3 ±0.05	0.7 ±0.18	10.9 ±1.95	3.5 ±0.50	10.7 ±1.28	0.7 ±0.06	19.2 ±1.69	2.5 ±0.17	-	-	**1.3 ±0.40**
Wahi	Control	11.6 ±6.63	6.5 ±0.10	0.6 ±0.19	13.3 ±1.84	2.9 ± 0.86	19.0 ±1.62	1.2 ±0.21	17.9 ±0.79	2.7 ±0.41	0.2 ±0.02	1.2 ±0.05	**1.7 ±0.27**
	0.25 kg FYM	14.3 ±12.59	6.8 ±0.16	1.0 ±0.00	9.1 ± 0.53	12.4 ±2.38	11.9 ±1.56	0.9 ±0.17	18.7 ±1.12	3.4 ±0.31	-	-	**2.3 ±0.40**
	0.5 kg FYM	6.3 ±3.51	7.0 ±0.11	1.0 ±0.05	10.8 ±0.29	22.8 ±5.19	19.5 ±1.43	1.2 ±0.12	17.9 ±1.08	2.9 ±0.09	0.1 ±0.02	1.2 ±0.08	**2.1 ±0.26**
	Urea	7.0 ±6.78	6.0 ±0.16	0.5 ±0.08	13.0 ±1.01	2.8 ±0.20	17.1 ±1.83	1.1 ±0.15	18.3 ±1.44	2.8 ±0.26	-	-	**1.8 ±0.20**

Table 7. Phenotype of sorghum cultivars Hakika, Macia, Pato and Wahi after 85 d in response to infection by *Striga hermonthica* in a controlled environment pot study. Data represent the mean ± 1 SE of six replicates. Different letters indicate significant differences between means for each cultivar at the P ≤ 0.05 level as determined by Tukey's multiple comparison procedure (ANOVA).

Cultivar	**Treatment**		**Sorghum**					***Striga***		
	N supply (mM)	***Striga***	**Root biomass (g d.wt.)**	**Pseudostem biomass (g d.wt.)**	**Leaf biomass (g. d.wt.)**	**Total biomass (g d.wt.)**	**Root:shoot**	**Total biomass (g d.wt.)**	**Number of emerged shoots**	**Number of attachments**
Hakika	0.25	Control	1.8 ±0.21a	2.2 ±0.42b	2.2 ±0.30a	6.1 ±0.89a	0.4 ±0.06a	-	-	-
		Infected	2.2 ±0.26a	0.6 ±0.17a	1.4 ±0.30a	4.2 ±0.59a	1.3 ±0.24b	0.2 ±0.15	0.2 ±0.20	20.0 ±8.31
	1.00	Control	11.7 ±1.69b	11.9 ±0.99c	10.1 ±0.82c	33.7 ±3.22c	0.5 ±0.05a	-	-	-
		Infected	7.9 ±1.77b	2.9 ±0.37b	4.9 ±0.50b	15.8 ±1.75b	1.1 ±0.27b	0.4 ±0.33	1.6 ±0.87	17.6 ±3.80
Macia	0.25	Control	3.6 ±0.51b	2.2 ±0.29b	2.4 ±0.13b	8.2 ±0.82b	0.8 ±0.09a	-	-	-
		Infected	1.5 ±0.34a	0.2 ±0.07a	0.6 ±0.16a	2.3 ±0.57a	2.1 ±0.46b	0.1 ±0.10	0.2 ±0.20	8.8 ±2.99
	1.00	Control	9.6 ±2.28c	10.4 ±1.54c	9.1 ±1.20c	29.0 ±3.78c	0.5 ±0.13a	-	-	-
		Infected	6.8 ±1.07bc	2.2 ±0.84b	4.3 ±1.03bc	13.4 ±2.13b	1.3 ±0.35b	2.4 ±1.49	2.6 ±1.40	15.0 ±5.53
Pato	0.25	Control	2.8 ±0.23ab	4.4 ±0.30bc	3.4 ±0.26b	10.6 ±0.73b	0.4 ±0.02a	-	-	-
		Infected	1.8 ±0.33a	0.3 ±0.08a	1.0 ±0.25a	3.0 ±0.65a	2.3 ±0.89b	0.2 ±0.21	1.2 ±0.80	29.8 ±5.62
	1.00	Control	12.2 ±1.91b	18.3 ±1.45c	12.0 ±0.68b	42.5 ±3.52c	0.4 ±0.06a	-	-	-
		Infected	14.0 ±6.45b	2.8 ±1.24b	4.8 ±1.58b	21.5 ±9.04ab	1.8 ±0.47b	1.8 ±0.98	2.6 ±1.25	16.0 ±7.13
Wahi	0.25	Control	2.2 ±0.16a	2.6 ±0.12b	2.9 ±0.11b	7.7 ±0.15b	0.4 ±0.04a	-	-	-
		Infected	1.8 ±0.42a	0.3 ±0.04a	1.0 ±0.12a	3.2 ±0.50a	1.3 ±0.26b	0.5 ±0.44	1.2 ±0.49	24.0 ±6.44
	1.00	Control	8.9 ±2.22b	8.2 ±1.17c	8.8 ±1.26c	25.3 ±4.74c	0.5 ±0.07ab	-	-	-
		Infected	9.2 ±2.14b	3.9 ±1.40bc	6.1 ±1.42bc	19.3 ±3.51c	1.4 ±0.72ab	1.0 ±0.45	2.6 ±1.29	8.6 ±6.94

Table 8. Physiological characteristics of the youngest fully expanded leaf of sorghum cultivars Hakika, Macia, Pato and Wahi grown at 0.25, 0.5 or 1 mM N and either uninfected or infected with *Striga hermonthica*. ETR = electron transport rate; SLA = specific leaf area. F_v/F_m = the ratio of dark adapted maximal to variable chlorophyll fluorescence, and equates to the efficiency of photosystem II. Data represent the mean ± 1 SE of six replicates. Different letters indicate significant differences between means for each cultivar at the $P \leq 0.05$ level as determined by Tukey's multiple comparison procedure (ANOVA).

Cultivar	**N supply (mM)**	***Striga***	**F_v/F_m**	**ETR (µequiv. m^{-2} s^{-1})**	**N content (mg g^{-1} d.wt.)**	**P content (mg g^{-1} d.wt.)**	**SLA (m^{-2} g^{-1})**
Hakika	0.25	Control	0.74 ±0.015 a	44 ±6.4 a	12 ±2.1 a	4.0 ±0.29 a	0.18 ±0.005 a
		Infected	0.70 ±0.036 a	35 ±6.4 a	14 ±1.9 a	3.5 ±0.50 a	0.19 ±0.020 a
	1.00	Control	0.73 ±0.010 a	64 ±6.6 a	12 ±1.1 a	3.7 ±0.52 a	0.17 ±0.004 a
		Infected	0.75 ±0.013 a	38 ±7.3 a	12 ±3.0 a	4.4 ±0.54 a	0.17 ±0.002 a
Macia	0.25	Control	0.77 ±0.007 a	41 ±9.2 a	15 ±2.8 a	3.2 ±0.66 a	0.18 ±0.01 a
		Infected	0.73 ±0.014 a	33 ±2.9 a	14 ±4.0 a	4.0 ±0.99 a	0.21 ±0.03 a
	1.00	Control	0.76 ±0.008 a	66 ±5.3 a	11 ±0.5 a	3.3 ±0.08 a	0.16 ±0.01 a
		Infected	0.76 ±0.004 a	46 ±9.0 a	21 ±2.8 a	4.0 ±0.24 a	0.21 ±0.01 a
Pato	0.25	Control	0.75 ±0.008 a	36 ±5.5 a	11 ±0.7 a	2.5 ±0.23 a	0.17 ±0.006 a
		Infected	0.81 ±0.040 a	54 ±7.4 a	18 ±1.5 b	3.9 ±0.89 a	0.17 ±0.006 a
	1.00	Control	0.75 ±0.006 a	47 ±7.5 a	11 ±0.3 a	2.9 ±0.17 a	0.24 ±0.038 a
		Infected	0.76 ±0.009 a	42 ±5.6 a	20 ±1.0 b	4.0 ±0.41 a	0.21 ±0.011 a
Wahi	0.25	Control	0.73 ±0.008 a	52 ±6.9 a	9 ±0.6 a	2.5 ±0.35 a	0.18 ±0.003 a
		Infected	0.69 ±0.019 a	39 ±8.3 a	16 ±2.3 a	4.1 ±0.31 b	0.22 ±0.044 a
	1.00	Control	0.72 ±0.013 a	51 ±8.4 a	10 ±1.1 a	3.8 ±0.4 ab	0.16 ±0.007 a
		Infected	0.74 ±0.009 a	59 ±4.8 a	14 ±3.4 a	3.4 ±0.3 ab	0.17 ±0.005 a

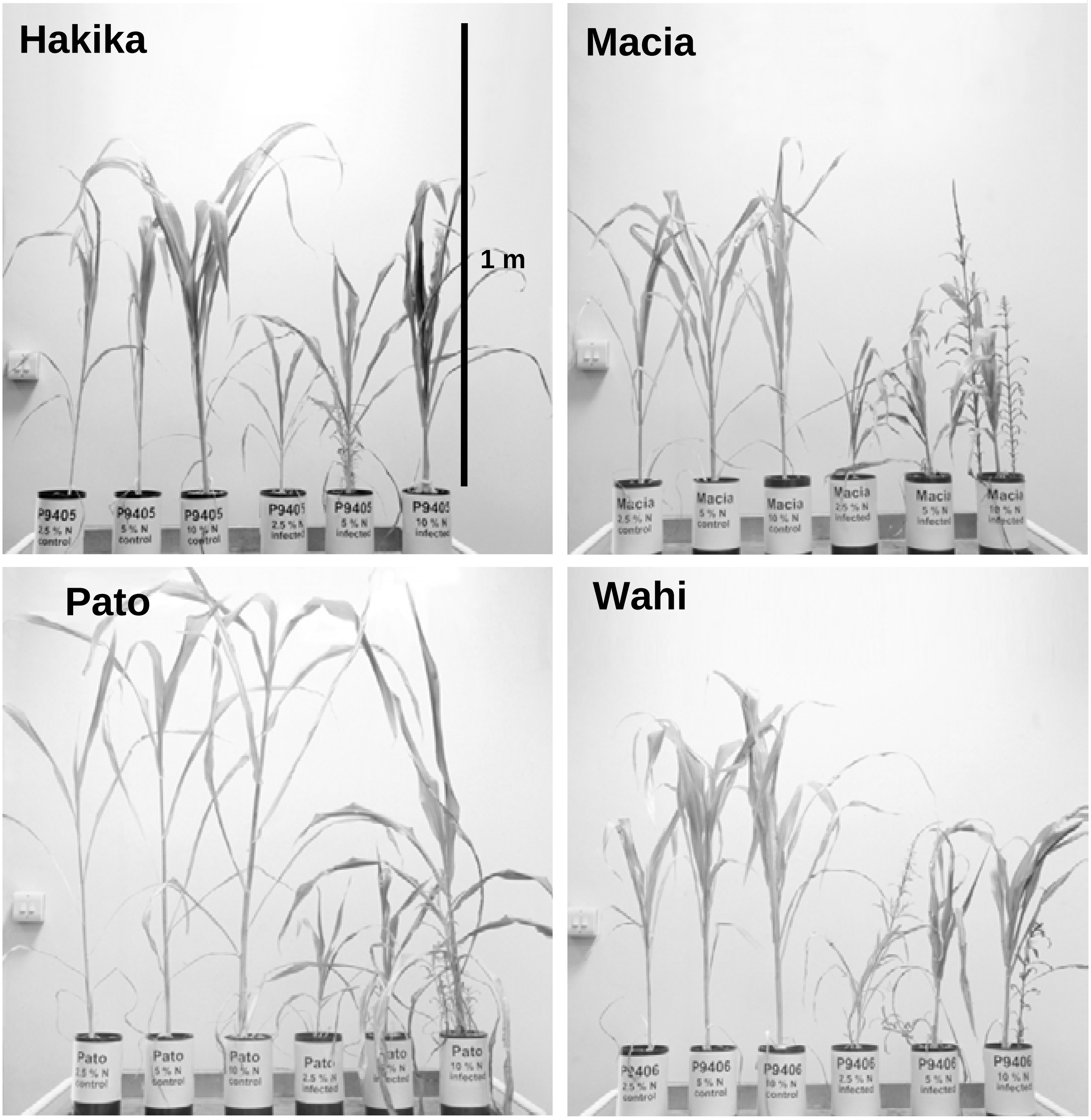

Fig. 1. Representative individuals of each cultivar of *Sorghum bicolor* (Hakika, Macia, Pato and Wahi) and of each treatment (uninfected control or infected with *Striga hermonthica*; 0.25, 0.5 and 1.0 mM N) at 80 days after planting (dap).

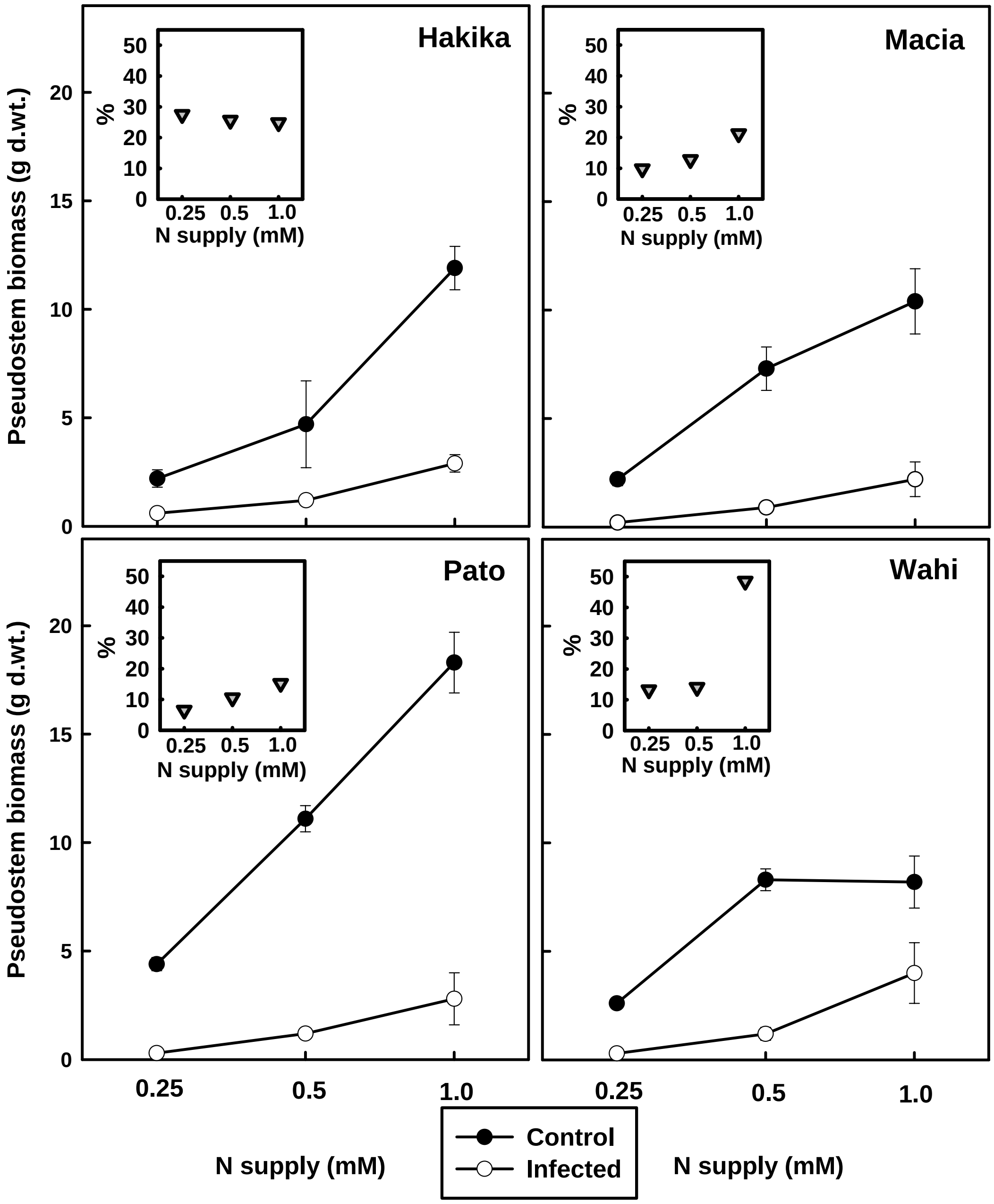

Fig. 2. Pseudostem biomass of *Sorghum bicolor* cultivars Hakika, Macia, Pato and Wahi at 85 days after planting (dap), either with (open symbols) or without (closed symbols) infection by hemiparasitic *Striga hermonthica* under conditions of different nitrogen availability (0.25, 0.5 or 1.0 mM N as ammonium nitrate). Inset panels present the data as infected plants as a proportion of uninfected controls. Data represent the mean ± 1 S.E. of six replicates.

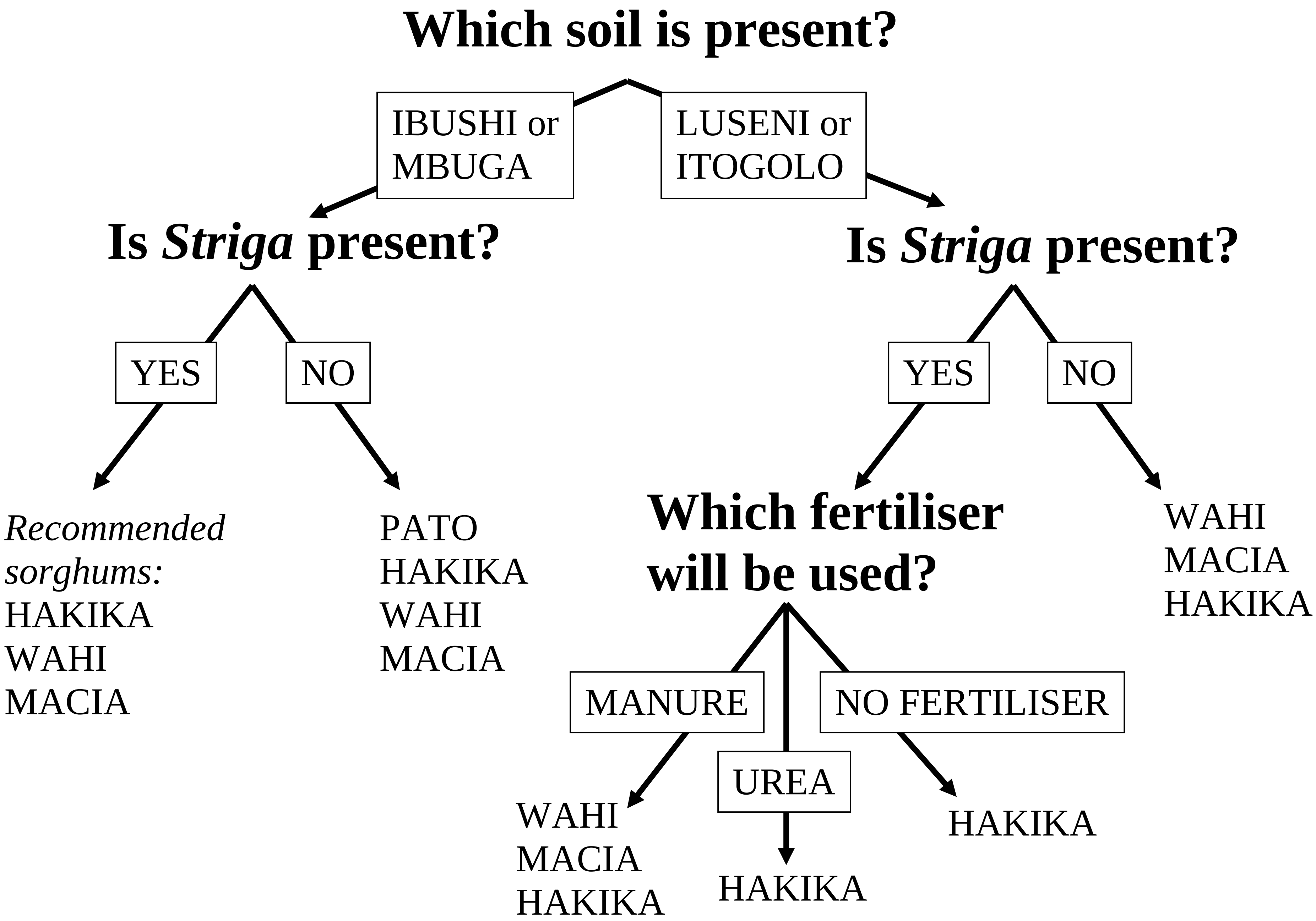

Fig. 3. Decision tree outlining the choices of sorghum cultivars recommended for growth on soils in the Lake Zone of Tanzania, based on data from the present study.

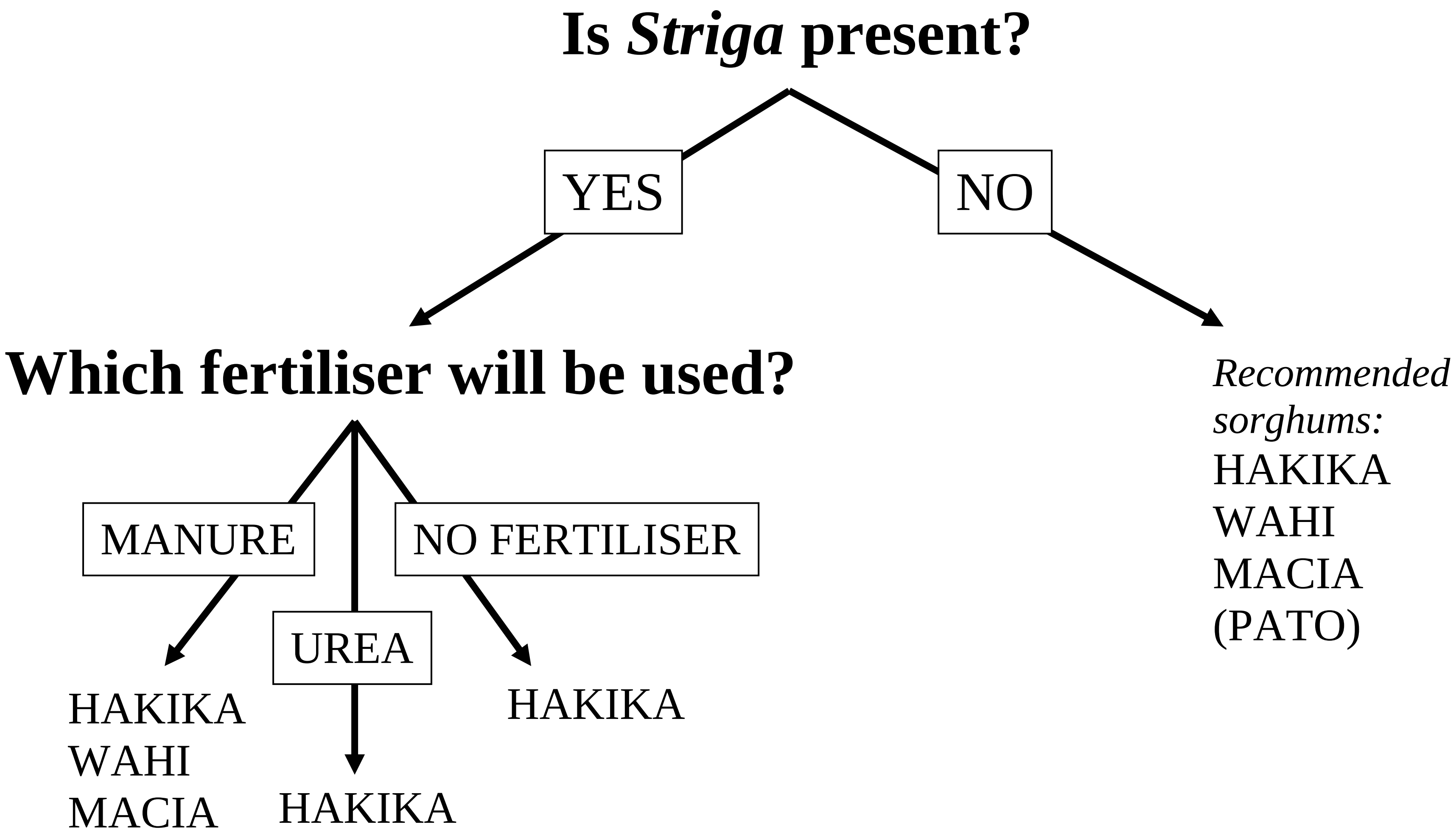

Fig. 4. Decision tree outlining the choices of sorghum cultivars recommended for growth on soils in the Central Zone of Tanzania, based on data from the present study.