International Scholars Journals

African Journal of Tropical Agriculture ISSN 2375-091X Vol. 5 (2), pp. 001-009, February, 2017. Available online at www.internationalscholarsjournals.org © International Scholars Journals

Full Length Research Paper

Target area identification using a GIS approach for the introduction of legume cover crops for soil productivity improvement: a case study eastern Uganda

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Accepted 23 August, 2016

Amidst the economic backdrop of resource-poor farmers, combined research and extension efforts in developing countries have focused on developing and promoting potentially adaptable and economically acceptable agronomic technologies that suit farmers' situations. Practices like improved fallows with woody and herbaceous legumes (e.g. *Canavalia* sp., *Crotalaria* sp., *Mucuna* sp., *Lablab* sp., and *Tephrosia* sp.) are considered an appropriate approach to improving soil fertility management and an alternative to expensive, and often not available, inorganic fertilizers. However the challenge remains of how to target such technologies to different socio-economic and biophysical niches at the farm level. Targeting of legume cover crops (LCC) to areas with actual and potential soil fertility management problems using a GIS approach was investigated. Using available datasets it was possible to define, identify, and map potential areas for targeting of LCC soil fertility improvement technologies by overlaying maps of soil fertility status, cropping systems, population density and climate for the eastern region of Uganda. We showed that a geographic information systems based decision support system could provide targeted dissemination output to aid decision making. Shortcomings in the use of available data are discussed, as are the practical applications of this approach in choosing appropriate legume species.

Key words: LCC (legume cover crops), GIS (geographic information systems), targeting, agro-technology transfer, improved decision-making, soil fertility improvement.

INTRODUCTION

Low soil fertility is recognized as a serious constraint to increased food production and farm income in sub-Saharan Africa (Stoorvogel et al., 1993; Sanchez et al., 1996; Shepherd and Soule, 1998). Crop and animal productivity are low throughout much of sub-Saharan Africa because of increasing land degradation and declining soil fertility (Rowe et al., 2006). Population pressures, intensive cultivation and shortening fallow periods have often been identified as crucial factors contributing to declining soil fertility and unsustainable agricultural production (Lal and Cummings, 1979; Kang et al., 1991; Sanchez and Hailu 1996; Weber, 1996; Franzelnebbers et al., 1998; IITA, 1998; Buckles et al., 1998).

One of the biggest challenges in the tropics is therefore to develop alternative organic matter technologies that address the farmer resource constraints, increase food production, reduce risk, and enhance soil fertility (Snapp et al., 1998). Defining the appropriate boundary conditions within which such technologies are to be disseminated, principally taking into account the variability of the farmers' socio-economic, as well as, biophysical condi-

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tions, is crucial to a successful introduction of such technologies.

Many authors have reported that there is little inorganic fertilizer use in the tropics and that the nutrient balances for cropland are typically negative (Wortmann and Kirungu, 2000; Esilaba et al., 2005; Zingore et al., 2007). Snapp and Benson (1995) identified many challenges to developing fertilizer recommendations, for example, high soil variability, uneconomical returns to fertilizer use and considerable/expensive research investment, particularly in the development and testing of resource management strategies to improve soil fertility.

Targeted fertilizer recommendations are essential in increasing yields and maintaining soil fertility in southern and eastern Africa. Jones and Wendt (1994) showed that soil fertility decline could be reversed through targeted fertilizer applications to maximize fertilizer use efficiency and by matching fertilizer type to soil nutrient deficiencies. This targeting of fertilizer requires the use of geo-referenced data management systems, which provide a tool to extrapolate from a limited number of empirical fertilizer trials to area- specific fertilizer recommendations. The geo-referencing of data allows integration of diverse data sets, including climate, soil type and soil fertility data (Snapp and Benson, 1995).

Experience from research studies elsewhere indicates that the niches for LCC species, in terms of socio-economic and biophysical conditions, need to be well defined to increase the probability of effective dissemination (Drechsel et al., 1996; Wortmann and Kirungu, 2000; Ojiem 2006). For example, Wortmann and Kirungu (2000) pointed out that in Benin, *Mucuna pruriens* was more preferred in the humid south than the drier north, and adoption was most likely to occur where the growing season was seven months long or more. Similarly, they also discovered that relay inter-cropping of *Lablab purpureus* with maize at Kitale, Kenya, requires a long rainy season as the legume makes much of its growth after the maize harvest. The complexity at the farm-level makes definitive targeting impossible, and only allows a narrowing of the legume options that should be offered to farmers for evaluation within a sustainable land management system.

Soil fertility is yet another boundary condition that was highlighted in the studies above that should be considered when identifying area- specific domains for introducing LCC. It is acknowledged that low soil fertility may favour greater use of legumes, since legumes have nitrogen-fixation capacity that may contribute to the improvement of soil fertility. However, legume performance may be poor on soils, which are acidic or have low phosphorous concentrations. For example, low soil fertility appeared to favour adoption of *M. pruriens* in Benin; on the other hand the effectiveness of green manure and improved fallows was reduced on low phosphorous soils in Uganda and Zambia (Wortmann and Kirungu, 2000).

An array of integrated research and extension tools ranging from basic process research, to widespread on-farm targeting and verification is required. All need to be organized in a more interactive institutional mode with the effective participation of the main client, the farmer (Snapp et al., 1998). Flexible approaches to recommenddation (using decision trees), as applied in Malawi, means that area specific messages are becoming available (Snapp and Benson, 1995). In conformity with the authors above, Amede and Kirkby (2001) stressed targeting different legume types to different niches of different agro-ecologic and socio-economic strata with the farmers' participation. This guideline was used to identify potential niches for the integration of legumes into multiple cropping systems in Areka, Ethiopia. Similar to Amede and Kirkby (2001), Palm et al., (1996; 2001) developed and tested a decision support system to select organic inputs and their management for a given cropping system, soil type and environment. The decision support system involves socio-economic as well as biophysical characterization, and field-testing of technology options as inputs into the model. Snapp et al. (1998) hasten to add that the applicability of the guidelines as described by the authors above can quickly become complex and difficult to maintain, if the assumption of the farmers' understanding of their microenvironments is not critically synthesized.

The GIS approach has proven useful in complementing technology dissemination programmes that have been carried out by other stakeholders from elsewhere. For example, Walters et al. (1993) acknowledged GIS as an appropriate tool for use in developing area specific fertilizer recommendations. They too reiterate that information on rainfall, temperature, soil type, sample site, nutrient data, elevation and cropping history can be combined to provide criteria to determine which areas with given soil fertility characteristics will most likely have a given response to a fertilizer recommendation. Alternatively, GIS tools can be used to verify assumptions regarding the required conditions for successful up-take of the technology.

The decision guide consists of a set of decision rules that serve to match requirements for the growth and cultivation of the LCC to conditions existing in the field as described by the available data sources. Detail and accuracy of the resulting target domains depends directly on the scale and level of detail of the data sources. The objective of this study was to investigate if it was possible to use a range of existing data sources to develop a decision guide, using spatial analysis, for targeting legume cover crops to areas with potential and actual soil fertility management problems. Such a tool would be useful for researchers and extension managers alike, to provide them with more focussed recommendations on where and how to introduce legume cover crops into certain land use units within their research and extension system

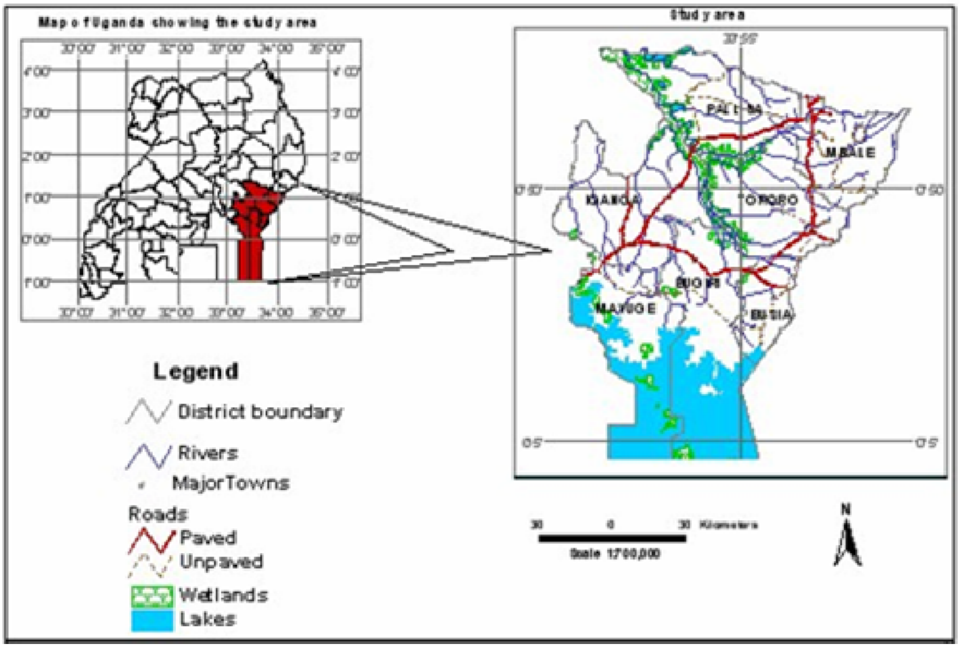

Figure 1. The study area in eastern Uganda (1º20'S-1º20'N; 33º14'-34º31' east) containing Mbale, Tororo, Busia, Bugiri, Iganga, Mayuge and Pallisa districts.

METHODS AND MATERIALS

Study area

The study area is situated in the eastern part of Uganda (between 1º20'S and 1º20'N and 33º14' and 34º31' east) and focused on Mbale, Tororo, Busia, Bugiri, Iganga, Mayuge and Pallisa districts (Figure 1). These districts fall within three Agricultural Research Development Centres (ARDCs), which have been established according to delineated Agro-ecological Zonations (AEZs). These are (i) Ikulwe ARDC, which covers the districts of Iganga, Mayuge, Busia and Bugiri (ii) Serere ARDC, which covers the districts of Pallisa and Tororo; and (iii) Bulengeni ARDC, which covers Mbale district. This study area was selected because of an ongoing research programme on LCC. This study would provide the programmme with target areas for possible scaling out of their activities. The methods presented can equally well be applied to other AEZ for identifying target areas for the introduction of LCC.

Data sources

All the data used are from secondary datasets, namely, a land resources database of Uganda consisting of maps and associated attributes of soil, climate, landforms, altitude, population, cropping systems and administrative units all compiled and stored in ArcView retrievable shape files and dbase files (Wortmann and Eledu, 1999). These are then converted into relevant thematic map layers for matching with the LCC growth requirements as listed in the reviewed LCC database (Lexsys, 1999). The soil and climatic map layers are overlain with map layers representing socio-economic (population density) and agronomic (cropping systems) themes of the pilot region to create unique mapping units that are then rated in terms of suitability on the basis of predefined LCC climatic and soil in growth requirements.

Evaluation and classification of soil fertility related management problem areas

Areas, where the problem of soil fertility is considered most severe or acute, are targeted for improved soil fertility management through the introduction of LCC. In doing so the actual soil fertility status needs to be assessed in relation to the actual or potential demands on the soil. A measure of the soil fertility status is obtained by combining data on exchangeable bases and organic matter levels in the soil as presented in Table 1. This results in the definition of five classes of soil fertility status. A measure of the intensity of use (or demand on the soil) is derived from data on population density and intensity of the production systems, being the driving forces in land degradation and hence soil fertility decline.

Population density is described in the original database by five classes. For the purpose of this study the number of classes were reduced to three and redefined according to the specification in Table 2. The definition of the classes is based on the frequency distribution of the sub- county population density, such that sub-counties are more or less equally distributed over the three resulting classes. Classes for the intensity of cropping system are specified for each of the six major food crops in the area. "Intensity" in this case is the percentage of the area under cultivation with the particular crop. The original database specifies area percentages for each of the crops listed per one km^2 grid cell. Table 3 gives the specification of the classes for each of the major food crops. The principle aim in combining inherent soil nutrient status with factors that cause decline of soil fertility (intensity of production of relevant food crops) and population density with ecologically suitable legume cover crop(s) is to identify target areas with probable higher incidences of land and soil related management problems as a result of multiple cause factors prevalence. The variables selected are considered the most suitable proximate variables to describe the factors that determine soil fertility and soil fertility related problems, given the data available and considering

Table 1. Ratings of exchangeable bases (meq %) and Organic Matter (%) used in evaluation of fertility status (inherent soil nutrient status).

Rating	Calcium	Magnesium	Potassium	Organic matter
Very high	>20	>8	>1.2	>6.0
High	10-20	3-8	0.6-1.2	4.3-6.0
Medium	5-10	1.5-3.0	0.3-0.6	2.1-4.2
Low	2-5	0.5-1.5	0.1-0.3	1.0-2.0
Very low	<2	<0.5	<0.1	<1.0

Source: Agricultural Compendium (1989).

Table 2. Derivation of numeric and qualitative classification of population using density estimates at sub-county for 2002 Uganda population and housing census.

Population density five interval source data classification	Class labels for the two classification systems(5 and 3 classes respectively)		Population density three interval reclassification
15 – 208	Very low	Low	15 - 337
209 – 401	Low		
402 – 595	Moderate	Moderate	338 – 659
596 – 788	High	High	660 - 982
789 – 982	Very high		

Source: UBOS (2002)

Table 3. Area percentage classification and priority rating system for intensity of cultivation of selected food crops.

Food crops	Production intensity class distribution		
	High	Medium	Low
Banana	53% – 80%	27% – 53%	0% – 27%
Cassava	17% – 25%	9% – 17%	0% – 9%
Maize	41% – 62%	21% – 41%	0% – 21%
Sweet potato	28% – 42%	15% – 28%	1% – 15%
Finger millet	12% – 18%	7% – 12%	1% – 7%
Sorghum	4% – 7%	2% – 4%	0% – 2%

Source: Wortmann and Eledu (1999).

the regional context. For example, areas with a high percentage under cultivation indicate a high demand for agricultural land and that the land is almost continuously cultivated leading to a decline in soil fertility. Likewise, a high population density, within the rural setting probably signifies a high degree of land fragmentation and consequently intensive use of the land, while it indicates at the same time that many large populations are dependent on the productivity of the land for livelihood. Against the logical presupposition above, the criteria for targeting such problem prone areas would feasibly justify targeting an organic fertility technology following such clues.

Climatic and soil suitability evaluations

In disseminating a crop technology, an assessment of suitable eco-logical conditions within which it can grow is a prerequisite. Precipitation, temperature, altitude, soil type and pH, were used in evaluating the suitability of each LCC to grow in the pilot area (Table 4).

Decision trees and suitability rating of each LCC

Decision trees criteria as described by Sys et al. (1991a; 1991b) were constructed to match the LCC growth requirements with the land qualities and assign suitability classes. The FAO (1976) land evaluation method (that is, the most limiting factor determines the ultimate suitability class) is used to classify and define the upper and lower limits for each class. This process results in the identification and assignment of three suitability classes (highly suitable – S1 -, moderately suitable – S2 – and low suitable - S3) within areas areas with already suitable climate and soil conditions for growing LCC. With the latter two classes, lower case letters were suffixed to indicate the nature of limiting conditions (the growth conditions that would not be sufficiently met) if the crops were grown in that area. Figure 2 presents the decision tree for the suitability rating for *Crotalaria juncea,* considering soil type and soil reaction (a) and climatic variables (b). The same process is applied to each of the legume cover crops separately, based on the information presented in, amongst others, in Table 4. The whole area is within the 300 – 2000 m altitude range considered (highly) suitable for *C. juncea*, and therefore no further distinction is made according to altitude and rules concerning altitude are not included in the decision tree. The requirements are matched with the land and soil conditions to assign a suitability class label to each observation in a process called “spatial query” by translating the decision rules into ArcView compatible format, resulting in suitability maps for each LCC (Wortmann and Eledu, 1999).

Table 4. Land use requirements and suitability rating of climate and soil conditions for selected legume species

LCC	Diagnostic factor	Temperature(c)			Moisture availability(mm)			Nutrient availability (pH)			Altitude (m)		
	Suitability rating	S1	S2	N1	S1	S2	N1	S1	S2	N1	S1	S2	N1
Canavalia ensiformis		15-28	28-30	<15 &>30	900-1200	640-900 & 1200-2500	<640 &>2500	5.0-7.3	4.3-4.9 &7.4-8.0	<4.3 & >8.0	0-900	900-1800	0 & >1800
Crotalia juncea		12-28	8-12 & 28-35	<8 & >35	700-3000	490-700 & 3000-4290	<490 &>4290	5.0-7.0	4.5-4.9 &7.1-7.5	<4.5 & >7.5	300-2000	0-300 & 2000-2500	0 & >2500
Mucuna pruriens		19-27	15-19 & 27-35	<15 &>35	1000-2500	650-1000 & 2500-3000	<650 &>3000	5.0-7.0	4.5-4.9 &7.1-7.7	<4.5 & >7.7	0-1600	1600-2100	0 & >2100
Lablab purpureus		18-28	15-18 & 28-35	<15 &>35	800-1500	600-800 & 1500-2500	<600 &>2500	5.0-7.5	4.5-4.9 &7.6-7.8	<4.5 & >7.8	0-800	800-2100	0 & >2100
Tephrosia vogelii		3-26	26-29	<13 & >29	900-2500	70-900 & 2500-2670	870 & >2670	0-6.5	4.5-4.9	4.5 & >6.5	0-1600	500 & 00-2100	0 & >2100

Source: Lexsys database (1999).

RESULTS AND DISCUSSION

Targeting LCC to different suitability classes

Initial broad analysis using the decision trees outlined in Figure 2, to determine which LCC will grow where in the pilot districts, showed that *C. juncea*, and *M. pruriens* are the most widely adapted and thus would be suitable for dissemination (Figure 3). This overall potential suitability for each legume in the pilot area shows that other species showed moderate ecological conditions (S2a) for *L. purpureus* and *Tephrosia vogelii* with only altitude as the limiting condition and (S2ap) for *Canavalia ensiformis* with altitude and precipitation as the limiting conditions. *C. juncea* and *M. pruriens* also had areas with soil pH as the only limiting condition *(S2c*). *L. purpureus* and *T. vogelii (S2ac)* had areas with altitude and soil pH as the limiting conditions and *C. ensiformis* (S2acp) with altitude, soil pH and precipitation as the limiting conditions (Figure 3).

Sequential addition of socio-economic and production systems information refines the targeting of LCC to areas of high intensive land use types, particularly population density (Figure 4). It is assumed that high population density is indicative of intensive use of the land, caused by limited availability of land for agricultural production. Under the present socio-economic conditions and agronomic practices we may expect that problems with soil fertility status is most severe in these area, or at least that these areas pose a severe threat to the soil fertility status. At the same time, the potential impact of the planned intervention will be highest in areas with high population den-sity where the problems are most acute. Figure 4 show that there is only a small pocket with high population density and no limitations to the cultivation of either *C. juncea* or *M. pruriens*. There is a larger area with high population density, but with moderate limitations to the cultivation of *C. juncea* or *M. pruriens* because of soil type constraints. On the other hand we see larger pockets with medium population density, but where there are no constraints to the growth of both LCCs.

The other criteria for targeting LCC relates to the cropping systems. Not all cropping systems (or crops) are suited for incorporating LCCs and one will want to consider only those cropping systems that are most suited for the incorporation of LCC in the system. For each of those crops it is of interest to know the areas where the cultivation of the particular crops is most prominent (inten-sive) to guide the strategy for introduction of the technology. We used finger millet as an example of a staple food crop to illustrate the targeting of LCC use (Figure 5). Figure 5 indicates that there is one area where finger millet is most intensively cultivated that does not pose any limitation to the growth of either *C. juncea* or *M. pruriens.* To its north- east there is another area suitable for finger millet, but where the conditions are less favoura-

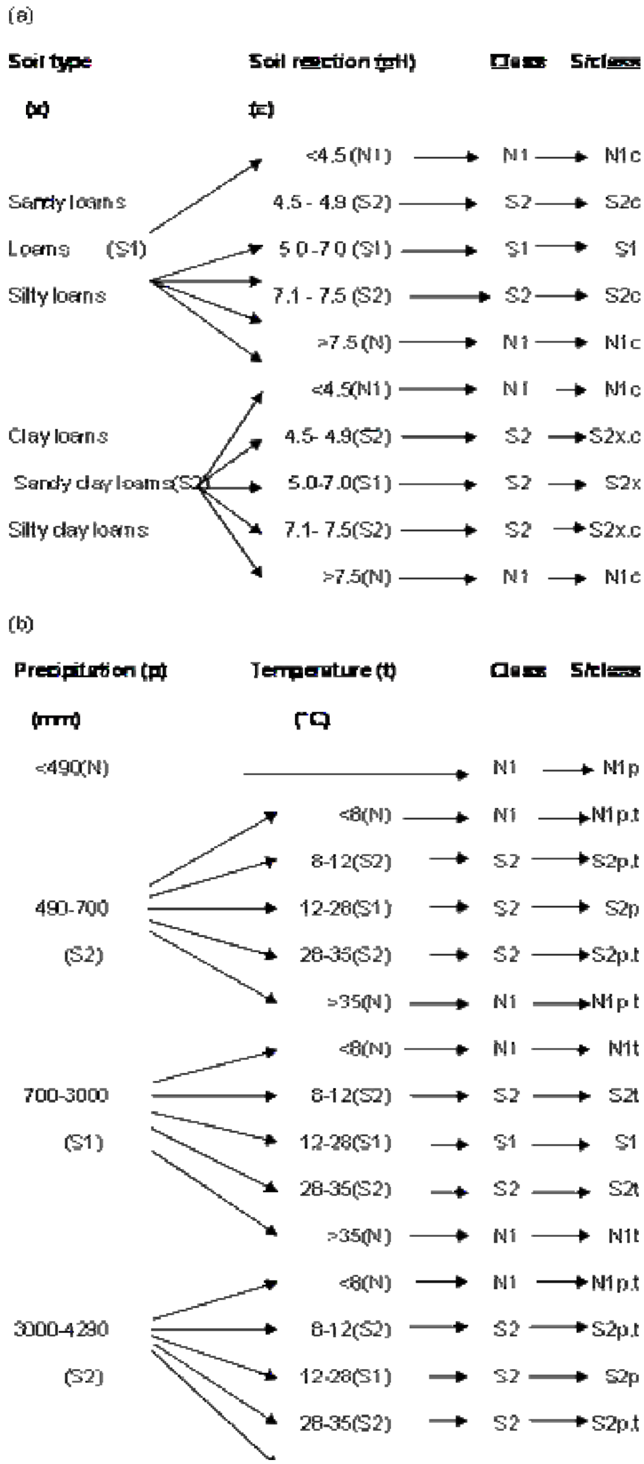

Figure 2. Decision tree to determine the suitability rating of the target areas for *Crotalaria juncea* considering (a) two different groups of soil types and (b) and climatic variables.

able for the above mentioned LCCs. There are larger areas (colour coded in red) where millet is cultivated less intensively, but still in considerable quantities, but where conditions are very favourable for *C. juncea* or *M. pruriens.*

In the end there are strategic decisions to be taken on how to weight the various factors (related to suitability, population density and production area of target crops) in defining the areas to concentrate the efforts in introducing legume cover crops. The results indicate that large areas (in fact the majority of the areas in the pilot site) are not recommendable for introduction of LCC as a technology because of either (relatively) low population density or low intensity of production in case of finger millet.

The soil suitability ratings do not provide any quantitative measure of the production potential. This is because the definition of the suitability classes is not based on a systematic assessment of yield in relation to the parameter investigated. The decline in yield for a particular cover crop moving from a S1 soil type to a S2 soil type may be very different from the decline in yield resulting from moving from a S1 soil reaction (pH) to a S2 for soil reaction, and will probably depend on other climatic conditions as well. The interpretation of a final suitability class S2, therefore, will depend on the limiting factor that determines the final rating (e.g. soil type or soil reaction). The suitability classes are therefore qualitative in nature and based on expert knowledge; the individual parameters are not weighted according to their effect on yield. The same applies, for a different reason to the classes of population density and percentage of the cultivated area for a particular crop. These classes are defined based on the observed variation of the variable in the study area. This assures the relevance of the classes in the sense that there will not be any class values that do not occur in the area, but it does not give information on the critical values in relation to potential for introducing the improved technologies.

Whilst this approach has shown that target areas for legume use can be identified, this analysis is based on only a few of the many decisions that farmers use to make such as management changes within their farms. The use of decision trees is a good approach for targeting, but it has to be remembered that the integration of any legumes into the farming system depends on other criteria like labour, market access, the trade- off between legumes for soil fertility alone, markets alone or for dual-purpose use. These criteria can be added to this decision support tool in the future now that the usefulness of the tool has been demonstrated. The outcomes of this tool then need to be translated into on-farm demonstration and research by scientists and extensionists, where new options can be demonstrated through action research approaches, like Farmer Field Schools and other group approaches.

Conclusion

This study shows that specific recommendation domains,

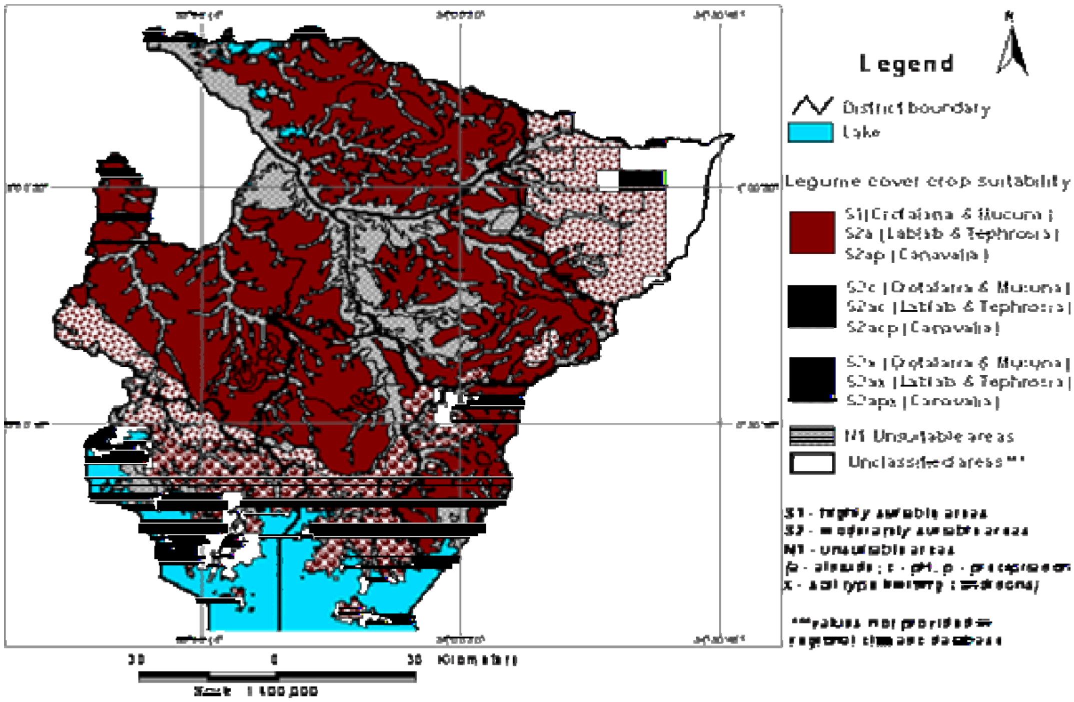

Figure 3. Ecologically suitable (soil and climatic) areas for growing the legume cover crops with (S1) optimal, (S2) moderately suitable and (N1) unsuitable/least suitable conditions for the respective LCC.

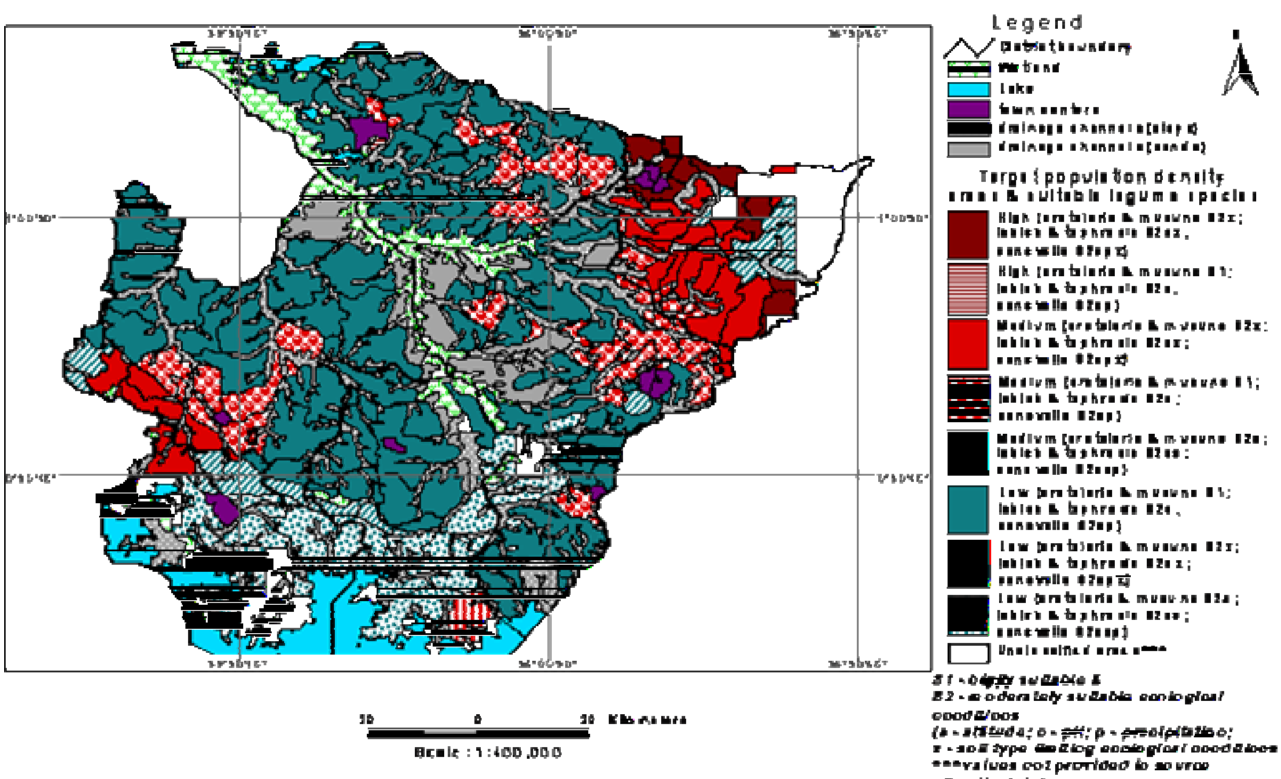

Figure 4. Identification of priority target problem areas for use of LCC in mitigating soil/land fertility related management problems associated with population density.

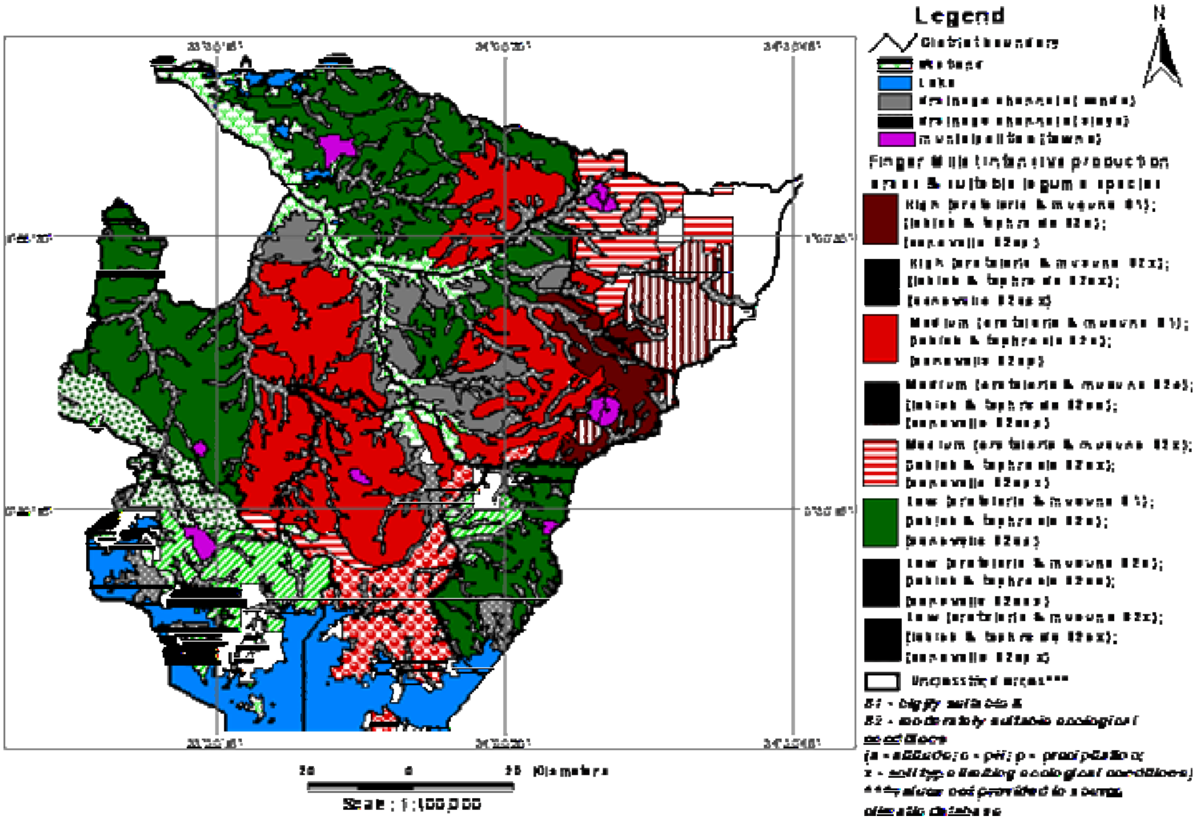

Figure 5. Identification of priority areas for mitigating use of LCC in soil fertility related management problems associated with intensive cropping systems, using finger millet as an example food crops).

in support of decisions to target areas for the introduction of legume cover crops for improved soil fertility management, can be derived from readily available information on soils, climate and demographic data using decision rules, informed by a database on growth condition for various cover crops. The resulting target areas informs the decision maker of the areas where problems with soil fertility are probably most severe or acute and assist in the selection of the cover crop that is likely to perform best given the prevailing environmental conditions. It therefore allows for the targeting of those areas where the highest impact can potentially be achieved with the selected technology.

By identifying probable areas for introduction of the LCC technology, this method represents a first step in the process of identifying specific target areas for the introducetion of LCC. The conditions in the field need to be verified before any further planning and initiation of a programme to promote the use of LCC in undertaken. This touches upon the validity of the criteria used (and the underlying assumptions) for the selection, the accuracy and reliability of the data. For example, the use of population density as a proxy for the area of cultivated land per household or person and therefore of the relative importance of the soil fertility to provide for adequate yields, needs to be verified. The same applies to the use of area percentage under cultivation of a particular food crop as a relevant criterion for the selection of target areas. Whilst it can be argued that the criteria used and their limits are not 100% accurate, the fact that a limited dataset can be used for this targeting work is a very useful result in itself.

One could adopt more sophisticated methods to overcome the limitations referred to above, but this would increase the data demand considerably and would require considerable investment in the quality of the data. At the same time one could argue that this would probably not result in an improvement in the accuracy, precision and reliability of the results, because the inherent variability of the determinant factors in the field and because of the use of proxies for soil fertility assessment, as well as, socio-economic characteristics. The present approach is therefore a pragmatic first step approach to the identification of target areas for the introduction of LCCs that makes efficient use of the available data resources. The approach presented here could be easily expanded to include other strategies or technologies for improved soil fertility management, or indeed applied for targeting of other technologies using a different set of criteria relevant to the technology under consideration.

Studies like this may assist ARDC, mentioned in the introduction, in targeting and prioritizing their activities, or assist those involved with agro-technology transfer provided all necessary datasets are compiled, and stored in a consisted format. The output shows the feasibility in land suitability assessment not only for legume cover crops but also other legume crops, and for including other criteria related to dual-purpose use of legumes for soil fertility and food, or for introducing legumes with a market demand.

Whilst this tool has been used at the regional level within a country, it can either be scaled down to farm level (with increased data demands) or be scaled up to a national level, where it can be used to generate recommendation domains for potential suitable legumes across a land use classification.

ACKNOWLEDGEMENTS

The authors wish to thank the Rockefeller Foundation for financial support to this work through the INSPIRE project.

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