SPATIAL ANALYSIS OF SOIL FERTILITY MANAGEMENT USING INTEGRATED HOUSEHOLD AND GIS DATA FROM SMALLHOLDER KENYAN FARMS

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ABSTRACT

Although soil fertility is recognized as a primary constraint to agricultural production in developing countries, use of fertilizer in Sub-Saharan Africa is declining. Smallholder farmers still rely heavily on livestock manure for soil fertility management. To explore the determinants of soil fertility management practices, including both the use of cattle manure and inorganic fertilizer, data are used from a sample of 3,330 geo-referenced farm households across Central and Western Kenya. A bivariate probit model is applied to jointly examine the use of the two technologies. Particular attention is given to measures of location related to market access and agroclimate, which in the adoption literature have typically been addressed using crude proxies. To avoid such proxies, GIS-derived variables are integrated into the household decision model. Their use also allows the spatial prediction of uptake based on parameter estimates. The results show clearly the derived-demand nature of soil fertility services, based on markets for farm outputs. They also illustrate that supply of manure for soil fertility amendments is conditioned by demand for livestock products, especially milk. The integration of GIS-derived variables is shown to better estimate the effects of location than the usual measures employed, and offers scope to wider use in technology adoption research.

Jel Classification: Q12, Q16
Keywords: spatial analysis; soil fertility; market access; technology adoption

INTRODUCTION

Soil fertility is one of the primary constraints to agricultural production in SSA (Gruhn et al, 2000). Increasing population pressure on the continent has contributed to this constraint, leading to reduced sizes of land holdings and consequently to reduced fallow periods. This is particularly true where population densities are high, such as highland areas of East Africa, and parts of humid and sub-humid West Africa. This has led to concerns over the long-term sustainability of agriculture. The reduced ability to use traditional soil fertility management practices such as fallow and rotation to restore soil fertility limits farmers to the main other option, that of increased soil fertility inputs. These include organic inputs (either green manure, or livestock manure) and inorganic chemical fertilizer.

However, in comparison to the rest of the world, fertilizer use in SSA is low, and continues to decline. In 1996, SSA consumed on average only 8.9 kgs of fertilizer per hectare of arable land, compared to 97.7 kgs globally. While fertilizer use per hectare grew in developing countries overall by a rate of 3.1 percent annually, it declined in SSA (Gruhn et al., 2000). Partially as a consequence, per capita food production has been declining since the early 1990s (de Jager, 1998). In SSA livestock continue to provide a large share of soil fertility amendments, as they do globally in developing countries.

In developing countries overall, more than half of total fertilizer is provided in the form of livestock manure; this rises to 70% in lower income countries (Fresco and Stienfeld, 1997). Given the low use of inorganic fertilizer, and the significant changes in output markets and technology that would be needed to increase demand for fertilizer, the dependency on manure for soil fertility inputs is likely to continue for some time.

Kenya is typical of this situation. Most agricultural production occurs in the medium to high potential highlands, in the context of small (1-5 ha) mixed farms growing maize and beans, tea or coffee, over half of which keep either traditional Zebu cattle or crossbred dairy cattle. Due to good bimodal rainfall (over 1200ml in highland areas) and so intensive annual cropping, soil nutrient balances are negative on many farms (de Jager 1998), and sloped terrain in some areas contributes further to soil degradation. Fertilizer use is low (39 kg/ha in Central Kenya, Omamo et al., 2002), and so livestock have to play a key role in soil fertility management. This is particularly true in the crop-dairy systems that dominate much of Central and Western Kenya. Strong market demand for milk allows farmers to keep dairy cattle on small holdings, with a significant proportion of feed brought or bought from off farm. Milk and animal sales provide economic sustainability of the enterprise, which through manure provides a key input to nutrient sustainability of the soil on the farm. Use of off farm feed insures that new nutrients are continually imported into the farm system through the cattle and manure. Use of manure is somewhat dependent on cattle keeping system. The more intensive systems that use cut-and-carry of fodder to staff-fed animals allow easier collection of manure. However, there is observed wide heterogeneity in soil fertility management practices, even among neighboring farms.

To better understand this heterogeneity, and particularly to understand its spatial components, this paper examines the use of soil fertility management practices of manure and inorganic fertilizer application in mixed crop-livestock farms across a range of market, agro-climate and household settings. An integrated household and GIS model is used to examine the determinants of the rate of adoption of these practices at the farm plot level in Central and Western Kenya.

SPATIAL ASPECTS OF DEMAND FOR AND SUPPLY OF SOIL SERVICES

Soil fertility can be viewed in an economic framework, in the context of derived demand emanating from farmer objectives for utility through farm product sales and consumption. The demand for the services that farm land or farm soil offers is thus largely derived from the need for that land as an input to farm production, whether of crops directly or indirectly of livestock through pasture, planted forages or crop residues. Soil fertility management practices can be seen as management of soil services, to increase the quality and durability of those services. Increased demand for soil services is likely to lead to increased use of soil fertility management practices.

In that conceptual context, the spatial location of a specific plot of land has several important aspects. If demand for soil services is derived from marketed outputs, then level of market access, and associated transfer and transactions costs will influence that demand, as well relative prices of outputs, factors, and inputs. Every location will of course have particular market access characteristics that are associated with distances to demand and supply centers and quality of transport/road infrastructure. Omamo et al (2002), in another study of soil fertility management in Kenya, show that level of fertilizer use is significantly related to market access costs. As well as on the output side, market access will also affect the real price of fertilizer or soil nutrients sourced from the market to be applied on farm. Within the farm, increased distance of a plot from the farm household may alter demand for soil services, either through lowering the effective prices of outputs or increasing input costs, both through increased within-farm transport costs. Location of the farm land also has obvious supply side characteristics, particularly in the form of agroclimate; in the absence of climate change, rainfall and temperature patterns will be fixed on average, and soil type and characteristics only partially amenable to change. These affect the quality of soil services, and their marginal productivity.

MEASURES OF LOCATION IN ANALYSIS OF FARM PRACTICES

An area where economists have put a lot of effort, yet where they have systematically under-represented spatial factors, is in the understanding of choices in farm practices, among which soil fertility management is an example. This despite the fact that processes such as the diffusion of information and agricultural technology are dynamic and often spatial (Bockstael, 1996).

Household-level statistical analyses of farm practices in developing countries have long suffered from having to use poor proxies variables to represent spatially-related factors. Although the basic economic activity of production and exchange have a large spatial component, the market access indicators typically employed in farmer choice analysis are generally coarse, and typically consist of proxies. Locational dummy variables are the most commonly used. Such measures have shortcomings, in that they proxy a variety of spatial factors ranging from market and institutional access to agro-climate, cultural and historical variation. The interpretation of the results obtained requires a fair bit of speculation as to which of these factors are associated with the observed outcomes. Even when distance or time to market outlets are used, they are often based only on farmer judgement and recall in survey questionnaires. While some studies employ such locational dummy variables (Kaliba et al., 1997), or conduct separate estimates for different locations (Lapar and Pandy, 1997). At the end of the scale, many farm technology uptake studies include no explicit spatial variables at all (e.g. Nkonya et al, 1997; Adesina et al, 2000). The same picture is seen in studies more specifically of uptake of soil fertility or conservation management technology. While some have used explicit measures of market access (Omamo et al., 2002), others have included no measures of location (Ali, 1996). Some include measures ostensibly of agro-climatic zone (Shiferew et al., 1998), but they are likely to proxy a wide range of factors related to location. Some studies of nutrient flows on farm use a farm enterprise defined measure of market orientation (A. de Jager et al 1998).

Relatively recent advances in GIS tools now offer to social scientists better measures of location, in all its manifestations of market access, agro-climate, etc. Most have been applied to land use analysis, using only GIS derived data, either in the form of grids or road networks. (e.g. Chomitz and Gray, 1996; Nelson and Hallerstein, 1997). Market access is typically included in a relatively coarse form compared to environmental and agro-climatic measures, where a great deal of effort is placed on achieving high resolution. These data are typically generated from remote sensing, or compiled from administrative-level aggregate data interpolated over a landscape surface. However, such data cannot easily capture socieconomic features of locations that cannot be obtained from remote sensing, and assume a certain level of homogeneity among economic agents, such as households. In order to better measure those, a few studies have linked survey-based data with these GIS data applied to agricultural development, such as Mertens et al. (2000) and Swallow et al. (2000). Mertens et al. use household-derived data linked to remotely sensed data to examine the impact of macroeconomic changes on deforestation in Cameroon, while Swallow et al. used GIS tools applied to household survey data to examine livestock disease control technology uptake in Ethiopia. In a study related to that being presented here, Staal et al (2002) use integrated GIS and household data to assess the effects of location on uptake of livestock production technologies. For more detailed description of the principles of measurement of location in agriculture, and of examples from the literature, refer to that paper.

The key is to more effectively integrate spatially-differentiated measures of both the non-physical social and economic landscapes with the physical. The approach employed in this paper for addressing this is to integrate spatially referenced household data with point data derived from digital surfaces and infrastructure maps.

DATA SOURCES

Diagnostic surveys to characterize smallholder production systems were conducted in across 16 districts in Central and Western regions of Kenya by a collaborative team from the Ministry of Agriculture, the Kenya Agricultural Research Institute (KARI), and ILRI, during the period 1996-2000. Using a stratified random sampling procedure, based on market access, human population density, and agro-ecological zone, a total of 3,330 geo-referenced households were sampled.

The primary new GIS coverage needed was a detailed road network, for which digitised maps at the level of resolution required were not available. Using topographic maps, three classes of roads were digitised: 1) all weather, bound surface, 2) all weather, loose surface, and 3) dry weather only, supplemented by local auxiliary grids. Additionally, a human population density layer was developed at ILRI based on the 1989 Kenya census. The agro-climatic information (precipitation / potential evapotranspiration or PPE) was taken from the database contained in the Almanac Characterization Tool (Corbett 1999). See Staal et al (2002) for details.

MODEL

A farmer's decision to apply a technology such as soil fertility management can be explained by a set of factors that influence the welfare criterion of expected utility. These factors are related to both the characteristics of the technology, its environment and the potential adopter. The set of factors that influence the technology choice can be broadly categorised into four major groups, technology attributes; farmer's resources; policy and institutional environment; and farmer's attributes, including preferences, risk profile, and ability to use information. In this case the specific attributes of the soil fertility management technology are assumed to be uniform across the sample, such as how manure is managed and applied, and the type of inorganic fertilizer used. To represent the above factors, a number of variables were derived from both the household survey data, and from the GIS surfaces. Household variables include sex, experience and education of the household head, access to extension, land holding and herd size, and details of the farm plots. GIS-derived variables include the human population density around each farm, an index of climatic potential (PPE), general soil type, and high resolution measures of distances to the main urban area (Nairobi) and to the two nearest urban areas. Distances to the latter are separated into the three road types mentioned above, in order to capture differential effects of road quality. See Staal et al (2002) for details on use of these multiple measures of market access.

The decision variable is measured at the farm plot level, and in the case of manure takes a value of 1 if the farmer reports applying manure currently to that plot, and 0 otherwise. A separate decision variable is derived for use of inorganic fertilizer in the same manner. Some 58% and 75% of plots were found to have manure and fertilizer applied, respectively. However, the decision to apply manure to farm land is clearly not independent of the decision to apply inorganic fertilizer (Omamo et al, 2002). Although the two technologies have different characteristics in terms of the level and availability of nutrients, organic matter, etc, they are both aimed at raising the quality of soil services demanded by the farmer. To accommodate this non-independence, a bivariate probit model is used to simultaneously estimate the effect on the probability of use of the two technologies of a common set of explanatory variables.

The model can be expressed as:

$$Y_{1i},Y_{2i} = x_{i\cdot}\ \beta_1 + z_{i\cdot}\ \beta_2 + \varepsilon_1 \qquad (1)$$

where Y_1 and Y_2 are the two decision vectors, x_i is a vector of explanatory variables derived from household surveys, with β_1 as a the corresponding regression coefficients, and z_i is another vector of explanatory variables derived from GIS surfaces, and β_2 the corresponding coefficients. Both types of variables are evaluated at the farm plot level, with non-independence of multiple plots from individual farms controlled for through clustering.

When using spatially-differentiated data, the existence of spatial autocorrelation can reduce the efficiency of otherwise unbiased parameter estimates. Spatial autocorrelation is simply the lack of independence which may be present among neighbouring or proximate observations. However, spatial econometrics for limited dependent variables is a developing field and as Bockstael (1996) indicates, no satisfactory methods are available for addressing spatial autocorrelation in such models. One way to control for spatial dependence is to include variables that account for interactions among farmers. In this analysis, the argument is made that the GIS- derived distance variables control for the occurrence of spatial autocorrelation by capturing the interactions between neighbours. See Staal et al., (2002) for more details.

SUMMARY OF RESULTS AND DISCUSSION

The results from the bivariate probit model for probability of use of manure and inorganic fertilizer on farm plots are shown in Table 1, expressed as the marginal effect of the base change indicated for each variable. Overall, the fit is good, with over 70% of correct predictions in both technology cases. Some household head characteristics have important implications for use of soil fertility management practices. Male-headed households have some 7% higher probability of using manure than female-headed households, although there is no difference in fertilizer use. This result is curious and unexplained, in that women manage much of the farm production.

Table 1. Estimated bivariate probit model for use of manure and fertilizer on Kenyan smallholder farms (plot level analyses).

Variable description	Manure		Fertiliser	
	Marginal Effect (%)	Base Change	Marginal Effect (%)	Base Change
Household head characteristics (Household survey)				
Sex of hh head (1=male, 0=female)	7.17***	1,0 change	NS	
Years of farming experience of hh head	0.30***	1 unit	NS	
Years of formal education for the hh head	NS		0.42**	1 year
Household characteristic (Household survey)				
Number of adults per acre	-0.96**	1 unit	-0.28*	1 unit
Extension availability (% households in locale that say yes)	NS		20***	10%
Number of cattle per acre	5.17***	I unit	NS	
Total land size (Acres)	NS		NS	
Plot characteristics				
Distance of plot from homestead (kms)	-1.38***	1 km	NS	
Plot planted with fodder (1=yes, 0=no)	12.21***	1,0 change	NS	
Plot planted with some cash crops (1=yes, 0=no)	14.60***	1,0 change	13.79***	1,0 change
Plot planted with pasture/nothing (1=yes, 0=no)	-13.80***	1,0 change	-23.31***	1,0 change
Tenure of plot (1=owned, 0=rented/borrowed)	37.03***	1,0 change	4.66**	1,0 change
Neighbourhood characteristics (GIS variables)				
Annual PPE (index of rainfall and temperature)	15.11***	1 unit	46.11***	1 unit
Population mean (avg within 5 km radius)	NS		-0.07**	10 persons
Soil texture1 (Heavy clay)	-5.18**	1,0 change	5.27***	1,0 change
Soil texture3 (Loamy)	-6.30**	1,0 change	11.11***	1,0 change
Soil texture4 (Sandy)	NS	1,0 change	NS	
Market infrastructure (GIS)				
Distance to Nairobi (kms)	-0.11***	1km	0.06***	1 km
Distance to 2 urban centres on road type 1	-0.55***	1 km	0.30***	1 km
Distance to 2 urban centres on road type 2	-0.57***	1 km	-0.40***	1 km
Distance to 2 urban centres on road type 3	-1.52***	1 km	-0.81***	1 km
Number of observations	4649 *1=2,683* *0=1,966*		4649 *1=3,271* *0=1,378*	
Log of likelihood function	-5094		-5094	
Overall percent correct prediction	72		75	
Percent correct prediction: adopters	72		75	
Percent correct prediction: non-adopters	70.76		71	
Correlation (rho) from bivriate probit regression	0.37			

*Significant at 0.1; **Significant at 0.05; ***Significant at 0.0

Greater farming experience leads to significantly more use of manure, while more education is associated with more use of fertilizer. Availability of extension leads to significantly higher probability of fertilizer use; such use is likely a common extension message, which appears to be heard. Having more cattle is as expected associated with using manure, but is independent of the probability of fertilizer use. This suggests that farmers do not regard manure as a substitute for fertilizer: those with easy access to manure still use fertilizer. Within the farm, the distance to the plot from the homestead significantly lowers the probability of manure use, but has no effect on the use of fertilizer. Given the low nutrient content per kg of manure, in the context of transporting to distant plots, this is expected. The type of crops planted have a significant association with both manure and fertilizer use. Compared to a base of food crops, both planted fodder and cash crops are significantly more likely to receive manure application. Since fodder is mainly used for milk production, this follows closely the hypothesis that demand for soil services is derived from marketed output.

The tenure of a plot has large and significant effects on manure use. If the plot is a farmer's own, rather than borrowed or rented, s/he is 37% more likely to apply manure on it. The comparable effect on use of fertilizer is only some 5%. This is expected, given that soil fertility effects of manure and organic matter use are known to be longer lasting than inorganic fertilizer (Ali, 1996), and longer term investment in soil services are unlikely applied to temporary land holdings. The measure of positive climatic and rainfall conditions, PPE, has a large and significant effects on use of both technologies, but particularly in the case of fertilizer. The marginal returns from fertilizer use, given crop choices, are likely to be highest in high potential areas.

The market access measures are all significant. In the case of manure, distance to urban areas uniformly is associated with lower probability. The effect is stronger on the worst roads (Type 3), where every additional kilometer of poor feeder road separating a farm from main roads reduces the probability of manure use by some 1.5%. In the case of fertilizer, distance by main tarmac road actually increases likelihood. This may be a locational effect related to a rural-urban interface, and was similarly found in the cases of some other technologies (Staal et al 2002). For the poor road types 2 and 3 however, the negative market access effect is significant and strong.

The bivariate probit model also calculates a correlation coefficient (rho) between the two decision variable that reflects the degree of remaining association after the variation represented by the independent variable has been removed. In this case, the value is 0.37 which suggests a somewhat positive remaining association between the two soil fertility management technologies. This is expected, given the known benefits of the interaction of the two (Hoffman et al., 2001). However, it differs from the results of Omamo et al (2002), who found a negative relationship from a smaller sample in one Kenyan district.

Given the good overall predictive power of the model, and the fact that GIS surfaces provide measures in zones other than those sampled, the GIS-derived variables can be used to make spatial predictions. Spatial predictions of probability of use of the two technologies were made using only the significant GIS-derived variables, including PPE, population density, the soil categories and the distance measures, with all other variables held constant at their mean. The resulting probability of uptake maps are shown in Figures 1 and 2, for manure and fertilizer use respectively. The spatial patterns of manure use show close correspondence with markets and agroclimatic potential, and probabilities are high only in areas of their intersection. Fertilizer use, on the other hand, is more widely dispersed into a range of settings.

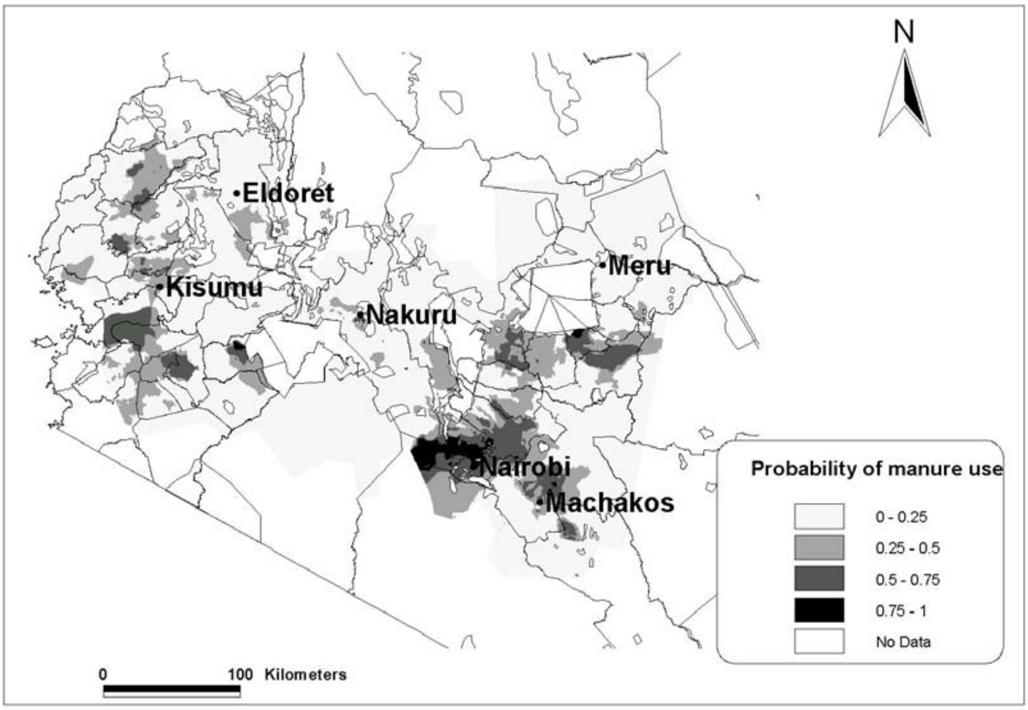

Figure 1. Map of spatial prediction of probability of manure use, based on parameter estimates of GIS-derived variables.

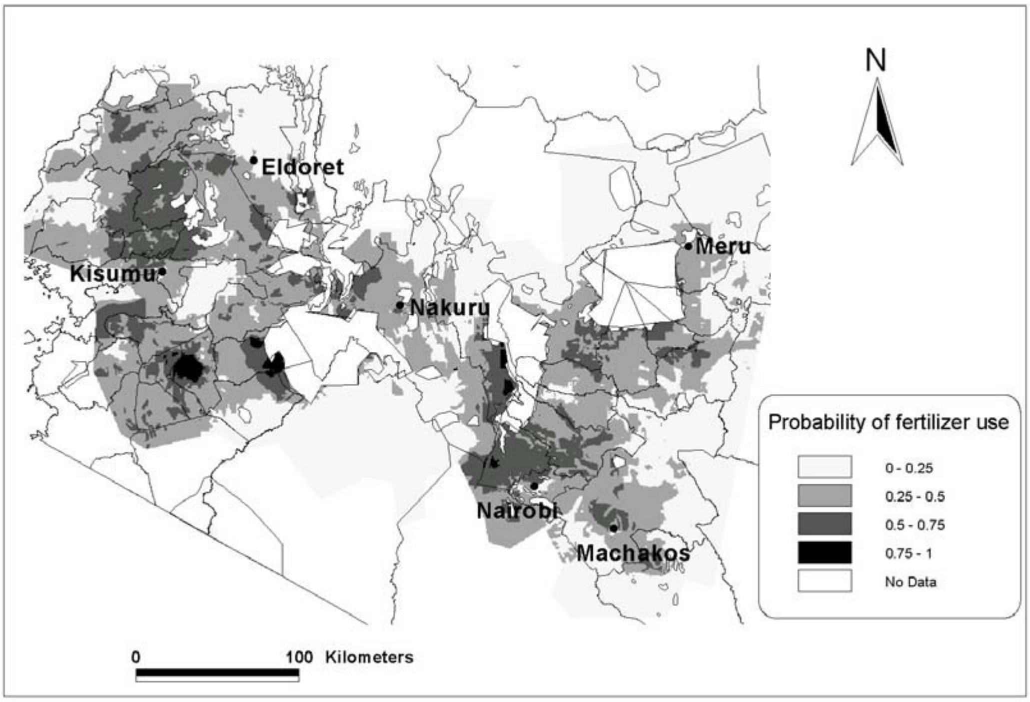

Figure 2. Map of spatial prediction of probability of fertilizer use, based on parameter estimates of GIS-derived variables.

The manure results are likely to be closely tied to dairy cattle keeping, which is characterised by stall-feeding of cattle and thus the easily collection of manure. Such systems are in turn closely associated with markets for perishable milk, while fertilizer supply variability is dependent mainly on transport costs, which will be lower than those for milk. The spatial variation may thus reflect mainly supply of soil fertility technology, and underlines the fact even though demand for the two technologies may be similar, that while fertilizer supply is independent, manure supply is conditioned by the market and household demand for livestock and their outputs.

CONCLUSIONS

The results of this analysis confirm expected effects on demand for soil services, and thus on the use of soil fertility management technologies, of farmer human capital, characteristics of the farm land and crop choices, and of the location of the farm, including climate and market access. While derived demand for soil services is hypothesized to be the principle driving factor in uptake, the results show clearly that uptake is conditioned by demand for other products (milk and livestock), the production of which generates soil fertility inputs. The integrated household and GIS model further demonstrates the ability to better measure the effects of spatially-differentiated attributes of location on farm/household technology decisions than standard survey-only models, and to take a further step in providing spatial predictions of uptake.

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