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Location and uptake: integrated household and GIS analysis of technology adoption and land use, with application to smallholder dairy farms in Kenya

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Abstract

GIS-derived measures of location and space have increasingly been used in models of land use and ecology. However, they have made few inroads into the literature on technology adoption in developing countries, which continues to rely mainly on survey-derived information. Location, with all its dimensions of market access, demographics and agro-climate, nevertheless remains key to understanding potential for technology use. The measures of location typically used in the adoption literature, such as locational dummy variables that proxy a range of locational factors, now appear relatively crude given the increased availability of more explicit GIS-derived measures. This paper attempts to demonstrate the usefulness of integrating GIS-measures into analysis of technology uptake, for better differentiating and understanding locational effects. A set of GIS-derived measures of market access and agro-climate are included in a standard household model of technology uptake, applied to smallholder dairy farms in Kenya, using a sample of 3330 geo-referenced farm households. The three technologies examined are keeping of dairy cattle, planting of specialised fodder, and use of concentrate feed. Logit estimations are conducted that significantly differentiate effects of individual household characteristics from those related to location. The predicted values of the locational variables are then used to make spatial predictions of technology potential. Comparisons are made with estimations based only on survey data, which demonstrate that while overall explanatory power may not improve with GIS-derived variables, the latter yield more practical interpretations, which is further demonstrated through predictions of technology uptake change with a shift in infrastructure policy. Although requiring large geo-referenced data sets and high resolution GIS layers, the methodology demonstrates the potential to better unravel the multiple effects of location on farmer decisions on technology and land use.

Keywords: Spatial analysis; Geo-referenced farms; Technology adoption; Market access; Geographical information system

1. Introduction

The often-heard refrain as to what determines the value of a piece of residential or commercial land is "location, location, location" (Geoghegan et al., 1997). It follows then, that the technologies that are employed in association with that land as well, should be equally affected by its location in all its manifestations. It can be argued however, that the rich field of agricultural economics literature devoted to understanding the uptake of technology has not adequately incorporated locational effects in its analyses. This in spite of the fact that since von Thünen's time (Von Thünen, 1966), it has been clearly recognised that

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most economic activity has a strong spatial component (1966). The tools typically employed to capture locational and spatial effects in adoption analysis are dummy variables to differentiate regions, or approximate distances to urban or market centres. Dummy variables may capture a wide range of locational effects, from soil to climate to infrastructure, which can be impossible to differentiate and difficult to interpret. GIS tools provide new measures of location and spatially-differentiated variables that may be able to more explicitly quantify effects of spatial factors on technology uptake and land use. Further, while GIS-based land-use analysis has emphasised environmental and resource issues, more conventional issues of economic behaviour that also have spatial components may have been overlooked to date. It is the aim of this paper to demonstrate that GIS-derived measures of spatially-differentiated factors can be incorporated into the standard household adoption model, and can potentially differentiate the multiple aspects of location on choices of agricultural technology. The method is applied to a key farming system for east Africa, smallholder dairy farming. Dairy systems are particularly suitable to spatial analysis, given their heavy reliance on markets for a perishable product, and the role that agro-climate can play in driving productivity.

2. Location

As established in the literature, technology uptake is driven conceptually by a desire to maximise farmer utility in the context of individual and household resources, incentives presented by the external environment, and perceptions of the technology and of the risks associated with it (Feder et al., 1985; Kaliba et al., 1997; Sall et al., 2000). Location can play a role in several of these categories of determining factors, affecting either demand or supply of technology. Agro-climatic effects such as level of rainfall and its distribution, or soil and temperature, condition the household resources and determine the basic agricultural productivity of the land. Other spatial factors, such as market access, condition the incentives presented by the external environment at a certain location, whether through inputs, outputs, or other services. The demographic space is that related to neighbours and their land uses, the patterns and densities thereof, and resulting externalities. This concept has been employed in spatial studies of residential property value that measure neighbouring open space and its fragmentation (Geoghegan et al., 1997). In the context of developing country technology, neighbouring spaces and populations may affect transmission of knowledge, and access to common property. Even more abstract surfaces, related to the dynamic process of diffusion of information and technology, may be institutional structure surfaces (Bockstael, 1996). This may refer to social institutions that condition preferences and change gradually across ethnic or community boundaries, or perhaps organisational structures or policies that change abruptly with administrative boundaries.

3. Market access and its measurement

A focus of this paper is on market access and its measurement, largely because market-oriented dairy systems have traditionally been heavily dependent on infrastructure, and on spatial thresholds of milk surplus and deficit. Additionally, it is our contention that the environmental and land-use literature which most employs GIS tools has emphasised agro-climatic surfaces, while incorporating market access measures at a poorer, more coarse level of resolution. As we hope to demonstrate, high-resolution market access measures may yield significant inferences for the behaviour of farmers whose main means of transport may be a bicycle.

Generally, the concept of market access combines several elements: (1) distance between the point of observation and some market destination or combinations of destinations, (2) the utility of the market destinations, based on their supply or demand attributes, and (3) the impedance level or quality of the route, in terms of relative ease of movement for goods, services, people and perhaps even information. Combined, at the point of observation, these three elements condition prices observed at that location for inputs, outputs and services, their availability, and even their quality. Indeed, when prices cannot be observed, market access measures can serve as a proxy for price (Chomitz and Gray, 1996). Finally, in keeping with transaction cost theory (Williamson, 1985), it is useful to add another element to market access, (4) the individual capacity and resources of the agents at the point of observation. Differences in transactions costs faced at any point are partially a function of the individual characteristics of the market agents involved, including ability to use market information and to conduct exchanges, thus partially determining market access at that point.

In measuring market access, some or all of these elements can be used. The simplest measures may use only distances to destinations, or may differentiate those distances by level of impedance. A typical approach is to assume or estimate typical travel speeds for specific types of routes and surfaces, or to use their inverse ratios (Chomitz and Gray, 1996; Nelson and Hellerstein, 1997). In a GIS the access measures can be calculated using road networks connecting points with specific destinations yielding continuous measurement of access, or by creating buffers around points of a specific distance, creating categories of access (Serneels and Lambin, 2001). When the utility of market destination is added to these weighted distance, composite indices of market access are derived. These range from the classical gravity model of market access, to more flexible forms such as the negative exponential model (Deichmann, 1997), which allows flexibility in rate of decay. The composite potential measures may reflect a more complex interaction of market factors, but are unit less, and difficult to interpret. de Wolff et al. (2000) examine and test these various measures, and find that simple distance measures may be more useful in measuring market access, depending on the type of market and commodity being addressed. As will be described, in this study we employ combinations of relatively simple measures of distance to urban areas, differentiated by road type.

4. Measures of location in the literature

Given the multiple dimensions of location and market access, the measures of location used in traditional economic studies may be regarded as relatively crude proxies. They typically consist of dummy variables for location, represented by the administrative unit such as village or county, and simple farmer or researcher estimates of distance to an urban centre or road. 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. While some studies employ such locational dummy variables (Kaliba et al., 1997), others use a regional measure of productivity (Feder and Slade, 1984), or conduct separate estimates for different locations (Lapar and Pandey, 1999). At the end of the scale, many farm technology uptake studies include no explicit spatial variables at all (Rahm and Huffman, 1984; Polson and Spencer, 1991; Nkonya et al., 1997; Adesina et al., 2000; Sall et al., 2000). This may be because the economic agents are seen as discrete distinct decision-makers, but are not recognised to exist in an explicit spatial context (Anselin, 2001).

In contrast to the non-spatial approach usually taken by economic studies, environmental and land-use studies have explicitly treated the spatial dimensions, clearly because the focus on land requires attention to the wider landscape and to location. Many have also linked GIS-derived spatial information with socio-economic variables, typically using spatial grid data (de Koning, 1999; Verberg and Chen, 2000; Reid et al., 2000) or *field* data as described by Anselin in this issue. Two land-use studies in particular, Chomitz and Gray (1996) and Nelson and Hellerstein (1997), provide a method that can be adapted to the analysis of technology adoption. Both use an economic framework, and multinomial logit regression models similar to those used in household adoption analysis, but now applied to spatial grid data obtained by remote sensing along with GIS-derived market access measures. Nelson and Hellerstein (1997) also underline the importance of measuring route quality, by demonstrating that impedance-weighted road distances provide generally better market access measures than simple vector distances.

5. Integrated household and GIS based analysis of technology adoption

The above models of land-use change are aimed at identifying where or at what rate land-use change is taking place. From the technology adoption perspective, if we assume exogeniety of land resources and location to individual households, the question is *what* rather than *where*. Very similar approaches can be used for both sets of questions. The key is to more effectively integrate spatially-differentiated measures of the non-physical social and economic landscapes with the physical, regardless of whether addressing physical or behavioural outcomes.

The approach employed in this paper for dealing with this problem is to integrate spatially referenced household data (*objects*, Anselin in this issue) with point data derived from digital surfaces and infrastructure maps (*field* data). A key difference from the approach used in the above studies is the unit of observation, which is a household, rather than a spatial grid cell or administrative unit. As has been pointed out by others, a key to linking household and GIS data is to correctly define the spatial observation unit (Mertens et al., 2000; Geoghegan et al., 2001). Administrative units or grid cells are not individual economic agents, but simply aggregates of them (Anselin, 2001). Inferences as to outcomes in such units require simplifying assumptions about homogeneity of the decision-makers and the dynamics comprising that aggregate, a constraint that plagues land-use analysis in a systematic manner. Anselin (2001) indicates that proper inference of micro-level spatial behaviour is therefore more appropriately based on survey samples of individual agents, under the general principal of matching the spatial scale of the process under consideration and the scale at which measurement is carried out. The approach applied here does that, linking spatial measures to the perceived real decision-makers, thus matching the spatial and behavioural units. The related scale issue centres around the problem of optimally defining the spatial entities or regions for which a model should be calibrated, depending on the level of heterogeneity within units chosen: the greater the variability, or the smaller the spatial scale at which the process operates, the less accurate will be the aggregate as an estimate for the dependent variable (Anselin, 2001). For the small farmers with limited access to motorised transport under study here, we thus apply a high resolution road network.

While analysis of residential areas increasingly integrates GIS data (Geoghegan et al., 1997; Irwin and Bockstael, 2001), few studies have integrated household and GIS point data in this manner 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. They use a village level of analysis and so aggregate household and plot data to that level. In another livestock related study, Swallow et al. use GIS tools applied to household survey data to examine livestock disease control technology uptake in Ethiopia. They rely on GIS-derived "neighbourhood" variables to explain access to information and markets, although they also employ simple vector distances and locational dummy variables. At a minimum, GIS data make distance and other spatial measures more accurate or more easily computable (Anselin, 2001). More significantly though, integrating GIS data into household adoption analysis also offers the possibility of better differentiating the multiple effects of location, and also of predicting potential outcomes under different policy and infrastructure scenarios. This analysis attempts to demonstrate that in the case of several technologies employed by smallholder dairy farmers in Kenya.

6. Smallholder dairy production in Kenya

In Kenya smallholder dairy farmers produce some 56% of total milk and 80% of the total marketed milk nationally (Omore et al., 1999). In the study area, which comprises the main milk producing regions of the country (Fig. 1), about 87% of all households were farms, and of these 72% had dairy cattle. Most of the districts surveyed ranked dairy as the main source of farm income (Staal et al., 2001; Waithaka et al., 2000). Smallholder dairying has thrived on the good agro-climatic conditions in the temperate Kenyan highlands, most of which are located over 1500 m above m.s.l. Its success has also been due to several decades of government support through a dairy parastatal that until recently, acted as guaranteed buyer of milk output. In the study area, dairy production is typically conducted on a few acres, with a herd of crossbred cows ranging from 1 to 5 in size. Production is based on the close integration of dairy cattle into the mainly maize-based farms, and is sometimes accompanied by cash crops such as coffee, tea, or pyrethrum. The cattle are usually Friesian or Ayrshire crossed with local Zebu. An important element of this system is the use of the manure to fertilise food and cash crops, allowing sustained multiple cropping on the

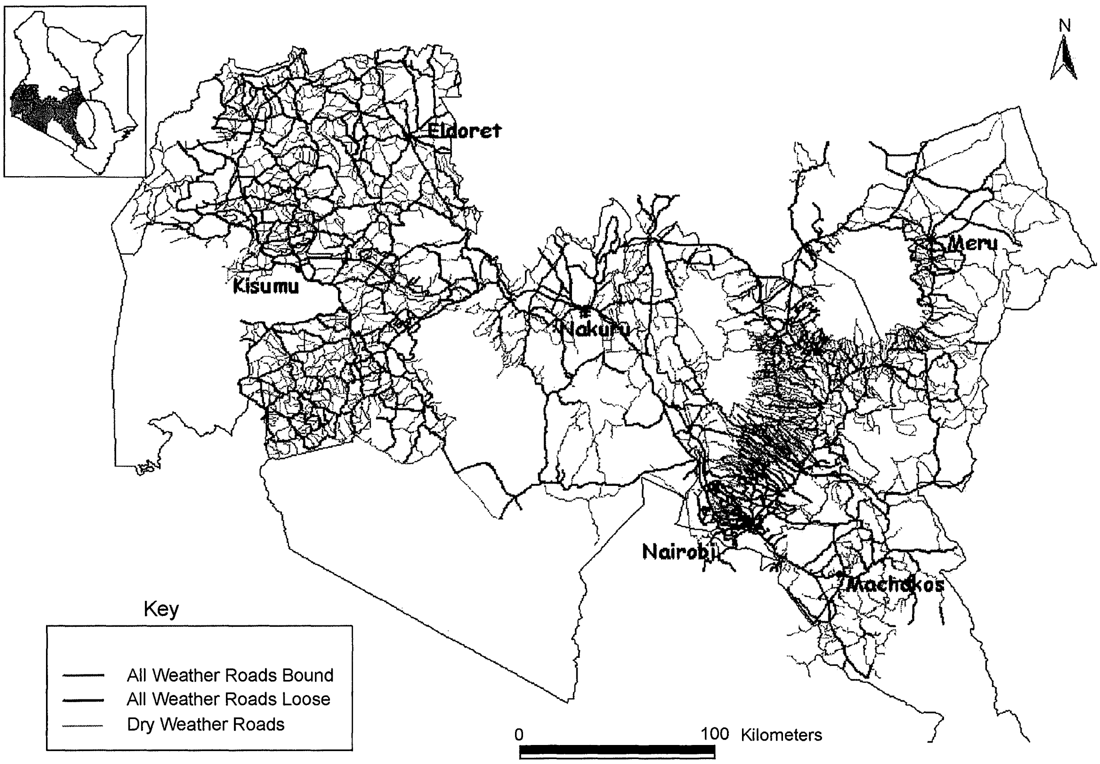

Fig. 1. Household survey area and road network map.

smallholdings. Cattle are fed planted fodder (*Pennisetum purpureum*, Napier grass), maize stover, weeds and grass, and sometimes supplemented with concentrate feeds such as grain millings or compounded dairy feeds. It is important to note that in some cases, a large proportion of fodder is gathered from public or common land or is purchased, so feed resources are by no means limited to those produced on farm. The main feeding systems in the area are stall-feeding based on cut- and carry of fodder in the case of some 32% of dairy farms, and only grazing for 39%, with the remainder employing some combination of the two. Milk production per animal is low, typically 4–7 l per day. The main cattle disease challenge is a tick-borne disease, east coast fever (ECF), which causes mortality particularly in herds that graze, whose exposure to ticks is greater.

Key to understanding milk production in Kenya is recognition of the role of the informal, or raw milk, market. It is estimated that about 80% of marketed milk is neither processed nor packaged, but is bought by the consumer in raw form (Omore et al., 1999), mainly due to traditional preferences for fresh raw milk, and to the unwillingness of resource-poor consumers to pay the costs of processing and packaging. Thus, the largest single market outlet for farmers, or 36% of marketed milk, consists of direct sales to nearby households, followed by small traders, who deliver 28% of the marketed milk to consumers or other retail outlets. Private formal dairy processors capture only some 19% (Omore et al., 1999).

On the input side, dairy farms are dependent on livestock services such as clinical veterinary services and artificial insemination (AI), critical to maintaining the health of susceptible cross-bred cattle and the genetic potential for higher milk yields. Since the early 1990s, however, the government has reduced support to AI and veterinary services. The expected replacement of these public services by private entrepreneurs has only partially occurred, and then only in high cattle density areas where demand is adequate to support them.

The important locational characteristics to smallholder dairy farming thus have to do with agro-climate, demographics, and access to both output markets and those for livestock services and feeds. Average levels of rainfall and temperature largely determine the feed production potential, not only of a farmer's own land, but of the public lands from which fodder is often gathered. The density of neighbouring households will partially determine the extent to which public lands are available for fodder gathering. For farmers with limited means of transport and communication, distance to livestock service centres will affect timeliness and thus effectiveness of such services, and the costs of accessing them. Finally, for a highly perishable product such as milk, failure to reach the market point in time may mean the loss of that day's revenues. The transfer and transaction costs associated with milk sales will generally be related to distance to consumer markets, distance to milk collecting and selling points, and the road infrastructure. Since many milk sales are to neighbours, local net demand and potentially, population density, will also be a determinant.

7. Data sources

7.1. Household surveys

Household data were obtained from three surveys conducted in central and western Kenya between 1996 and 2000, as part of an effort to characterise smallholder dairy systems by a collaborative team from the Ministry of Agriculture and Rural Development, the Kenya Agricultural Research Institute (KARI), and the International Livestock Research Institute (ILRI). Similar sampling methods were applied in each case, and each survey used a variant of the same data collection instrument, conducted in a single interview of each household. The survey collected a wide variety of data on household resources, land use and livestock management practices, livestock inventory, recall of feed and other input use, and use of livestock and extension services.

Prospective study districts were grouped according to agro-ecological production potential (high or medium) and market access (high, medium, or low). One to two districts were chosen within each combination, within which density classes were identified, from which two sub-locations, the smallest administrative unit, were randomly selected. Sample sizes were weighted by household estimates extrapolated from the 1989 census figures, and a sample size totalling 3330 was obtained. Random transects were then drawn in each sub-location, and every fifth household along the transect was selected until the desired samples were obtained, whether a farm household or not. Each household was geo-referenced using a GPS unit. All main milk processing and collecting centres in the study area were also geo-referenced. Mean values for the variables used in the analyses are shown in Table 1.

7.2. GIS layers

The primary new GIS coverage needed for the analysis was a detailed road network of the area, for which digitised maps at the level of resolution required were not available. Topographic map sheets at a scale of 1:50,000 were acquired from the Survey of Kenya to cover the study area and three classes of roads were digitised: (1) all-weather, paved surface (tarmac), (2) all-weather, loose surface, and (3) dry weather only (Table 2). Information was obtained from district-level road authorities on recent road renovation, and all main roads were visited to update the quality attributes in the GIS. GIS software (workstation ARC/INFO, ESRI, 1998) was then utilised to assign farm or facility information to the nearest node or intersection in the network, and major urban areas such as Nairobi and other towns were added as nodes, as were the milk market facilities. The resulting network contains a total of 10,199 nodes and 11,488 road sections. The road sections in the network were then assigned a quality variable that reflects assumed mean travel speeds, with values ranging from 30 km/h in the case of dry weather only roads (type 3) to 80 km/h for hard surface roads (type 1) (Table 2). The GIS was then used to calculate travel times based on each section's length and its associated travel speed, which then were used to identify least travel-time routes. To do this, the Arc/Info GIS-network module (ESRI, 1998) was used, and for each node on the network were obtained: (a) total distance to the largest city (Nairobi) by least travel-time path, (b) distance to the two nearest urban areas by least travel-time paths, separated by road type, and (c) distance to the nearest formal milk collection centres

Table 1
Description of independent variables included in household technology adoption model, source, expected sign and rationale for inclusion

Variable	Data source	Ho sign	Rationale
Sex of the household (hh) head	Survey	+	Male headed households are likely to have better access to information and services
Years of farming experience for the hh head	Survey	+	Longer farming experience predisposes farmer to better farming techniques through learning by doing
Years of formal education, hh head	Survey	+	More formal education is likely to increase farmer capacity for management and for utilising information
No. of adults in the hh	Survey	+	More adults implies more farm labour for the labour intensive dairy activity
Ratio of adult female to total adults in hh	Survey	+	Women contribute proportionately more labour to dairy and fodder production, and therefore a proportionately high number of women implies higher adoption
Ratio of hh members below 14 and above 65 to total family size	Survey	Uncertain	A higher proportion of dependents in the household implies less labour for dairy and fodder production. On the other hand, a higher dependency ratio gives incentives to produce more milk for consumption
Acreage under maize	Survey	(+) for dairy cows, (−) for Napier and concentrate	Higher maize acreage leads to greater fodder availability from crop residues
Hh landholding size in acres	Survey	(+) for dairy and Napier, (−) for concentrate	Large land size may mean there is more land available for cattle keeping and growing fodder, but may reduce need for concentrate feeding
Percentage of hh in the sub-location with stated access to animal health services	Survey	+	Availability of animal health provides support for the dairy enterprise in general, and all dairy-related technologies
Percentage of hh in the sub-location with stated access to formal milk outlets	Survey	+	Local availability of formal milk outlets implies reliable milk market, and support for dairy enterprise
Percentage of hh in the sub-location with stated access to extension services	Survey	+	Availability of extension services implies support for the dairy enterprise in general
Distance to the nearest formal milk collection centre by type 1 road (tarmac)	GIS	−	Distance to milk collection centre is expected to reduce formal milk price and market reliability
Total distance by road from homestead to Nairobi (km)	GIS	−	Nairobi is the largest milk market, particularly for the formal market. Greater distance to that market is expected to reduce price and market reliability
Mean human population density, 5 km radius	GIS	+	High population density is expected to correspond to higher local demand for milk, and thus favourable local market
Annual precipitation/potential evapo- transpiration (PPE)	GIS	+	Higher PPE corresponds to more favourable agro-climatic conditions for dairy production
Tarmac road distance along routes to two the nearest urban centres	GIS	−	Greater distance along main roads to nearby urban centres is expected to reduce prices in milk markets, and raise prices and reduce availability of inputs and services
All-weather earth road distance along routes to the nearest urban centres	GIS	−	Greater distance along secondary roads is expected to reduce milk prices and raise prices and reduce availability for inputs and services
Dry-weather only road distance along routes to two the nearest urban centres	GIS	−	Greater distance along seasonal roads to main roads will reduce access to input and output markets, and increase seasonal risks

Table 2
Description of household survey and GIS-derived variables included in the household models

Description	Cattle keeping households ($n = 2048$)		Agricultural households ($n = 2864$)	
	Mean	S.E.	Mean	S.E.
Dependent variables				
Cattle keeping: 1 if hh has any cross or grade cattle, 0 otherwise			0.62	0.49
Napier cultivation: 1 if Napier is planted, 0 otherwise	0.53	0.50		
Concentrate use: 1 if any concentrate is used, 0 otherwise	0.25	0.43		
Concentrate use intensity: Total kg of concentrates per year/total no. of cross + grade cows	157.63	491.95		
Household head characteristics (household survey)				
Sex of the hh head: 1 if male, 0 if female	0.79	0.41	0.78	0.41
Years of farming experience of the hh head	21.23	13.29	19.71	13.52
Years of education of the hh head	7.93	4.55	7.88	4.52
Household characteristics (household survey & GIS)				
No. of adults in the hh	3.84	2.11	3.59	2.03
Ratio of adult females to total adults in hh	0.53	0.21	0.53	0.21
Ratio of hh members below 14 and above 65 to total family size	0.41	0.25	0.42	0.25
Acreage under maize	0.87	1.13	0.78	1.03
Land size in acres	5.45	9.34	4.53	8.11
Annual precipitation/potential evapo-transpiration (PPE)	0.91	0.22	0.91	0.22
Neighbourhood characteristics (household survey)				
Percentage of hh in the sub-location with stated access to animal health services	92.31	11.83	92.02	12.57
Percentage of hh in the sub-location with stated access to formal milk outlets	16.86	28.98	14.86	27.57
Percentage of hh in the sub-location with stated access to extension services	90.13	18.69	89.66	19.54
Market infrastructure (GIS)				
Distance to the nearest formal milk collection centre by type 1 road (tarmac)	15.16	18.74	16.25	18.88
Total distance by road from homestead to Nairobi (km)	225.74	135.05	233.66	135.19
Mean human population density, 5 km radius	480.38	311.61	487.90	330.28
Tarmac road distance along routes to two the nearest urban centres	22.17	13.41	21.70	13.30
All-weather earth road distance along routes to the nearest urban centres	6.52	7.06	6.47	6.91
Dry-weather only road distance along routes to two the nearest urban centres	2.63	3.40	2.51	3.32

by least travel-time paths, by road type. Interpolation was used to produce smoothed accessibility surfaces for the whole study area. Arcview 3.1 Spatial Analyst (ESRI, 1999) was used to accomplish these interpolations, which utilises a simple inverse weighted distance algorithm.

The main agro-climatic variable used was precipitation/potential evapo-transpiration (PPE), which is an index that combines average effects of rainfall, altitude, and sun radiation, obtained from the Almanac Characterisation Tool (Corbett, 1999). The human population density layer was developed at ILRI and is based on the 1989 Kenya census, and is attached to sub-location boundaries. Using Arcview Spatial Analyst, focal neighbourhood functions were used to evaluate the mean population density within a 5 km radius for every point in the study area. Mean values for all of the above variables are shown in Table 2.

8. The integrated household model

8.1. Theoretical model

This analysis uses the same broad approach as used by many in this literature set; our emphasis here is on the empirical side, in introducing a new set of measures for spatial variables. Following Besley and Case (1993), the farmer i adopts the new technology if the derived benefits B_i are higher than a certain threshold

T. The decision to adopt can then be written as:

$$Y_i = 1 \text{ if } B_i > T \Rightarrow X_i\beta + \varepsilon_i > T$$

farmer i decides to adopt (1)

$$Y_i = 0 \text{ if } B_i < T \Rightarrow X_i\beta + \varepsilon_i < T$$

farmer i decides not to adopt (2)

where X_i is a vector of explanatory variables, β a vector of coefficients to be estimated and ε_i is an independently and identically distributed farm specific ex ante shocks. In the case of adoption of agricultural innovations in developing countries, Feder et al. (1985) identify key characteristics to be included in X_i farmer's characteristics, farm characteristics and external factors. Our addition to the model is simply to empirically express some farm characteristics and external factors using GIS-derived variables.

8.2. Empirical model

The model estimated is thus of the form:

$$Y_i = x_i\beta_1 + z_i\beta_2 + \varepsilon_i \quad (3)$$

where x_i is a vector of explanatory variables derived from household surveys, with β_1 as 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 household level.

As Anselin (2001) points out, however, the values of z_i are not actual observations, but are instead predicted values generated through the spatial interpolation described earlier. As such, z_i may have its own error structure, additional to ε_i, and potentially not independent from it. Correlation with ε_i would be more likely if there are similar spatial patterns in the two error terms. Anselin suggests that this should be addressed by means of instrumental variables, as employed by Chomitz and Gray (1996). In our case, no adequate variables were seen to be available to instrument the main spatial factors, weighted distances and agro-climate.

8.3. Spatial autocorrelation

Spatial autocorrelation refers to the "lack of independence which is often present among observations in cross-sectional data sets" (Anselin, 1988). In the case of adoption of dairy technologies, the farmer's individual decision may be a function of spill over effects arising from neighbourhood effects like local weather and agro-climatic conditions, common terrain features and soil types, common sources of demand for milk and patterns of information diffusion. In case of spatial autocorrelation, the information content of the sample is lowered, rendering it less efficient than uncorrelated counterparts, so parameter estimates are inefficient, although asymptotically unbiased. Moreover, the omission of a spatially correlated and important variable may result in biased estimates (Anselin in this issue).

The application of spatial econometrics to household data is relatively uncommon, potentially due to the unavailability of geo-referenced household data. Methods to test and control for spatial effects have been mainly developed for the linear regression case. Spatial econometrics for limited dependent variables is a developing field of research and the methods developed to incorporate spatial dependence in these models are not of general applicability (Anselin and Florax, 1995, Nelson and Geoghegan, this issue). As Bockstael (1996) indicates, no satisfactory methods are available for addressing spatial autocorrelation in logit models. Although a number of authors have incorporated spatial effects in probit models (for example Case, 1991, and Case, 1991), the estimation techniques has not yet been included in spatial econometrics packages (SpaceStat, 2002 Website; S+ manual). If autocorrelation arises because some spatial process is not taken into account in the model, one way to control for spatial dependence is to include variables that account for interactions among farmers (Cressie, 1991; Odland, 1988). In this analysis, GIS-derived distances have been introduced to take into account farmers' market access. Calculated at the farmer-level, these variables potentially control for the occurrence of spatial autocorrelation by capturing the interactions between neighbours and potentially controlling for neighbours' influence on adoption (Case, 1991). Distances between farmers and a common point (i.e. urban centre) can be considered as an indirect measure of potential spatial relationships between farmers. It is thus postulated that the distances variables control for the existence of spatial autocorrelation. There are two arguments to support this hypothesis. First, using a method similar to that of Besag (1974) reported in Nelson and Geoghegan in this issue, the occurrence of spatial autocorrelation was tested by performing a random sampling on the original set of observations with the rule that the sampled farmers do not live in the same area. By sampling non-neighbours, it is reasonable to assume that the observations are spatially independent. Results from 500 iterations of sub-samples of one observation taken randomly from each sub-location are relatively consistent with those using the whole set of observations. While the results based on sub-samples may be biased because the data spatial structure is destroyed, the consistency between the sub-sample results and the overall results seems to indicate that spatial autocorrelation does not affect the results significantly. Secondly, in another analysis the authors applied spatial econometrics techniques on the same dataset to analyse milk price formation (Staal et al., 2000) since in the case of linear regressions used in that case, these techniques are available. Neighbours were defined as those farmers within a radius of 5 km. To ensure that the results do not depend on a specific distribution of the residuals, three regressions were conducted using different covariance structures (conditional spatial autoregression, simultaneous spatial autoregression and moving average). Spatial autocorrelation was tested using the Moran's I statistics. Results showed that residuals do exhibit spatial autocorrelation when only survey variables are introduced in the analysis but do not when both survey and GIS-derived variables, including distances, are included in the analysis, as in the case of the analysis presented in this paper. These two arguments thus suggest a low likelihood of significant inefficiency in the estimation results presented here, at least for the examples that include GIS-derived variables. The comparison estimates using only survey-based data may indeed suffer from this problem.

8.4. Model specification

Three technological choices are analysed. The first is the decision by a farmer to keep improved dairy cattle, defined as some level of cross between local Zebu and exotic European dairy stock, or pure exotic animals. These animals can require significant management expertise and resources. Their large size, susceptibility to local animal diseases, and need for specialised reproductive services mean that small farmers must invest considerable time and resources in producing or obtaining feed of the quantity and quality needed, treating or otherwise protecting their stock from disease, and obtaining artificial insemination or suitable bull service. The dependent variable is expressed in binary form, with 1 for the presence on farm of any improved dairy cattle, 0 otherwise.

The second technology choice considered is whether or not to grow specialised planted fodder to feed these animals. The fodder of choice in highland Kenya is Napier grass, which is easily established from locally-available cuttings, and yields high biomass. Its cultivation often requires that land be diverted from food or cash crops. If however, milk market opportunities offer positive incentives compared to the alternative crops, Napier may be grown even when land is scarce, so that most food may need to be purchased. Indeed, Napier cultivation yields more fodder per land unit than is available through grazed pasture (Kariuki, 1998), so that smaller land holdings are expected to increase likelihood of Napier cultivation. If farmers choose to grow Napier instead of pasture, animals are generally stall-fed, sometimes exclusively (zero-grazed), with the Napier then cut and brought to them. The dependent variable is expressed in binary form, with 1 for the cultivation on farm of Napier grass, 0 otherwise. The analysis is conducted only for dairy farms.

Finally, a third technology choice is considered, that of the supplementary feeding of purchased concentrate feed to dairy cows, generally only those lactating. These concentrates may be either commercial dairy meal, or grain milling by products, such as maize bran. Again, the derived demand for this input will depend on relative incentives for producing more milk. The improved dairy cattle are bred to respond to higher concentrate use by significantly higher milk production, if an adequate base diet of fodder is supplied simultaneously. However, credit and risks associated with it are important constraints, and research in Kenya has shown that even though higher concentrate use consistently raises average returns, risk-adjusted returns may often be lower when farmers' levels of risk aversion are incorporated (Kaguongo et al., 1997). Use of concentrates, which requires cash expenditure, will thus depend on expected milk prices and their variability, as well as production risks. Greater fodder availability may lead farmers to forgo such risks by choosing not to buy concentrate. The dependent variable is expressed in binary form, with 1 for the stated use of concentrated feed on farm, 0 otherwise. The analysis is conducted only for dairy farms.

The independent variables are derived from both the household surveys and from the GIS, and are chosen to reflect technology adoption theory, as well as the specific characteristics of the technologies examined, both described earlier. The independent variables, their source, and rationale for inclusion in the models are described in Table 1. The same independent variables are used in all three models.

Given the potential complexity of managing improved dairy animals, greater levels of human capital on farm are expected to increase uptake of all three technologies. Human capital was introduced in the form of years of dairy farming experience, and years of formal education of the household head, which are assumed to proxy level of human capital in the household as a whole. Further, human capital of female-headed households may be constrained through social barriers to information and services, so this is proxied.

Household resources constraining the uptake decisions are expected to include labour, land and feed availability. Labour resources were represented by the number of adults and the proportion of female adults over total adults. Women are thought to supply the greatest proportion of labour for the dairy activities, but in many households the labour burden is shared (Maarse, 1995). The dependency ratio within the household may reduce labour availability, but may also increase demand for milk consumption. The total agricultural land held by the household is included in acres, a potential constraint to fodder production and cattle keeping. Additional feed resources are available from maize stover, so acres of maize cultivated is included. The measure of agro-climate, average annual PPE, although a GIS-derived spatial variable, should be seen as a measure of the quality of the land resources available to the household. However, it can also be expected to positively reflect availability of common property forage resources locally.

To measure market access, we employ combinations of relatively simple measures of distance to urban areas, differentiated by road type. These allow us to differentiate market effects of different types of infrastructure and destinations, which composite potential measures cannot do as easily. Also, as will be demonstrated, simple distance measures allow the testing of infrastructure policy scenarios. Further, the composite measures tend to be highly collinear with other measures of development or development potential, such as population density and agro-climate. Access to services is measured by two variables, derived from mean responses in the farm neighbourhood to farmers' stated access to animal health and extension services. Higher levels of both of these are expected to increase and sustain the level of adoption. Recognising the importance and multiplicity of milk markets, as well as markets for inputs and services, one survey variable and a set of GIS-derived variables are included to measure the different dimensions of market access. These are described in Table 1. Table 2 shows the mean values for the variables included in the models.

9. Results and discussion

9.1. Logit estimates of uptake of dairy cattle, Napier grass and concentrate feeding

The logit model results are shown in Table 3, under the columns for estimates using both survey and GIS-derived variables, in the form of marginal effects expressed as percent change in probability of uptake with the base change indicated for each variable. The estimates were made using a maximum likelihood procedure.

The results show reasonable explanatory power with percent of overall correct predictions ranging from 69% in the case of Napier grass adoption to 82% in the case of concentrate use. Adopters are more accurately predicted in the dairy cattle and Napier grass cases while non-adoption is better predicted in the concentrate case.

The effects of human capital measures on technology uptake are generally positive. Farming experience is positively significant only for dairy cattle uptake, and is not significantly associated with fodder cultivation or concentrate use. Improved cattle in these systems exhibit mortality rates of between 7 and 15% annually (Bebe et al., 2002), even among adult animals, and thus present significant risks. The positive role of experience in cattle keeping may be

Table 3
Estimated logit models for adoption of dairy cattle technology, Napier cultivation, and concentrate feeding[a]

	Dairy cattle				Napier				Concentrate feeding			
	Estimates using survey and GIS-derived data		Estimates using only survey data		Estimates using survey and GIS-derived data		Estimates using only survey data		Estimates using survey and GIS-derived data		Estimates using only survey data	
	Marginal effect (%)	Base change	Marginal effect (%)	Base change	Marginal effect (%)	Base change	Marginal effect (%)	Base change	Marginal effect (%)	Base change	Marginal effect (%)	Base change
n	2214		2178		1908		1843		908		1787	
No. of adopters	1391		1363		1028		1011		467		457	
Household head characteristics												
Sex (1 = male, 0 = female)	NS		NS		NS		NS		NS		NS	
Years of farming experience (unit)	0.26***	1	0.24**	1	NS		NS		NS		0.15*	1
Years of formal education (unit)	1.69***	1	1.60**	1	1.47***	1	1.53***	1	1.37***	1	1.65***	1
Household characteristics												
No. of adults	NS		NS		NS		NS		NS		NS	
Ratio of adult female to total adults (%)	1.00*	10	1.10*	10	NS		NS		−1.17**	10	−1.46***	10
Dependency ratio (%)	−1.37***	10	−1.36**	10	−1.22**	10	−1.19*	10	−0.82**	10	NS	
Acreage under maize (unit)	NS		3.16*	1	NS		NS		2.50***	1	2.18**	1
Land size in acres (unit)	0.46***	1	0.74***	1	NS		0.40**	1	NS		NS	
Average annual PPE	8.94***	0.1			7.31***	0.1			1.55**	0.1		
Neighbourhood characteristics												
Percentage of local hh with access to animal health services	2.05***	10	1.8*	10	NS		NS		5.54***	10	5.22***	10
Percentage of local hh with access to extension services	NS		NS		NS		2.04**	10	−1.00**	10	NS	
Percentage of local hh with access to formal milk outlets	1.62***	10	2.76***	10	1.40**	10	2.61***	10	1.54***	10	NS	
Market access												
Distance to nearest market centre (km)			5.00*	10			NS				NS	
Distance to the nearest formal milk collection centre on tarmac (unit)	−0.63***	1			NS				−0.26***	1		
Total distance by road to Nairobi in km	−0.74***	10			−0.57***	10			−1.01***	10		
Mean population density locally (hab/km^2)	NS				3.27***	100			0.90**	100		
Tarmac road distance to two the nearest urban centres	0.27**	1 unit			−0.30**	1 km			NS			
All-weather earth road distance to two the nearest urban centres	−0.90***	1 unit			−0.76***	1 km			−0.60***	1 unit		
Seasonal road distance to two the nearest urban centres (unit)	1.17***	1 unit			NS				NS			
District dummies (Kiambu = base district)												
Number of district dummies significant at minimum of 0.10 level			12				12				10	
Number of observations	2214		2178		1908		1843		1908		1787	
Log of likelihood function	−1253		−1130		−1154		−1019		−797		−751	
Overall percent correct prediction (%)	72.13		74.98		69.21		73.09		81.71		80.19	
Percent correct prediction: adopters	74.74		75.37		70.25		74.04		68.91		66.04	
Percent correct prediction: non-adopters	65.85		73.85		67.84		71.76		84.21		83.29	

Market access												
Distance to the nearest market centre (km)			5.00*	10			NS				NS	
Distance to the nearest formal milk collection centre on tarmac (unit)	−0.63***	1			NS				−0.26***	1		
Total distance by road to Nairobi in km	−0.74***	10			−0.57***	10			−1.01***	10		
Mean population density locally (hab/km^2)	NS				3.27***	100			0.90**	100		
Tarmac road distance to two the nearest urban centres	0.27**	1 unit			−0.30**	1 km			NS			
All-weather earth road distance to two the nearest urban centres	−0.90***	1 unit			−0.76***	1 km			−0.60***	1 unit		
Seasonal road distance to two the nearest urban centres	1.17***	1 unit			NS				NS			
District dummies (Kiambu = base district)												
Number of district dummies significant at minimum of 0.10 level			12				12				10	
Number of observations	2214		2178		1908		1843		1908		1787	
Log of likelihood function	−1253		−1130		−1154		−1019		−797		−751	
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Percent correct prediction: adopters	74.74		75.37		70.25		74.04		68.91		66.04	
Percent correct prediction: non-adopters	65.85		73.85		67.84		71.76		84.21		83.29	

[a] Regression with GIS-derived variables compared with regression using survey based distances and district dummies.
* Significant at 0.10 probability level.
** Significant at 0.05 level.
*** Significant at 0.01 level.

related to farmer ability to better control this risk. Years of education have very significant and positive association with all three technologies. An additional year of education raises the probability of adoption in each case by more than 1%. This is likely to be related to increased ability to manage the technologies and to use information. Sex of household head, however, is not significant in any case. This suggests that female-headed households are not differentially constrained from adoption of these technologies, in spite of the capital implications of cattle acquisition. This is a positive result for the promotion of dairy production in smallholder systems, at least in similar cultural settings.

The labour resource and constraint variables show mixed results. The number of adults in the household is not significant in any case. If some of these adults are not active in farming but instead are engaged in other occupations, then this variable may not be useful measure of labour availability. A higher proportion of women among the household adults is slightly significant and positive for the uptake of dairy cattle keeping, and is significantly negative for use of concentrate feeds. The former result is in keeping with the general view that women provide most of the labour for cattle keeping (Maarse, 1995). The latter result is not easily explained, but may be related to the fact that women tend to be the main gatherers of fodder from common land, which in this case may be substituted for concentrate feed. The dependency ratio is significant and negative in each case, suggesting that the constraints imposed on the household by having more dependents materially affect the labour availability. This affects apparently outweighs the increased demand for milk consumption that increased dependents implies.

Land resource effects are also mixed. Acreage under maize is only significant in the case of concentrate uptake. If higher acreage of maize is associated with lower acreage of Napier grass and pasture, then concentrates are possibly being used to substitute for the lower availability of fodder. The land size variable results are clearly reflective of the multiple sources of feed, and of farmer multiple objectives in keeping dairy cattle. Land size is significant only in the case of cattle keeping and is positive. The marginal effect of land size, however, is very small, with an additional acre only contributing about 0.5% to the probability of keeping dairy cattle, even though mean total acreage among the farms surveyed is only 4.5 acres (Table 2). Land is not apparently the constraint to dairy production that dairy development planners assume it to be, who often operate using the notion of recommended stocking rates. Feed and fodder can be purchased rather than grown, and importantly, demand for manure is likely to increase as land sizes decrease and food cultivation for subsistence becomes more intensive. By consuming feed imported from off-farm, with the manure applied on farm, the cattle become conduits for positive nutrient flow into the farm, critical for maintaining nutrient balances under heavy cultivation (Lekasi et al., 1998). Again, the low association with land size has significant positive implication for the promotion of smallholding dairying, as it appears to be an enterprise open for even those with very small landholdings, if market conditions are favourable. Even Napier cultivation is not associated with land holding size, again underlining the substitutability of purchased and farm-grown fodder.

The GIS-derived measure of rainfall and temperature (PPE) is highly significant and strongly positive in each case. An increase in PPE of 0.1, holding temperature constant, is approximately equivalent to an increase in rainfall of 143 mm annually. That level of increase is associated with an increase in the uptake of dairy cattle of nearly 9%, and of Napier grass of over 7%. This simply demonstrates the importance of underlying land productivity to dairying, including increased availability of fodder from common property. While significant, the effects of PPE on concentrate uptake are much smaller as expected, and may be a result of higher concentrate use generally with more market-oriented dairy production found in the higher potential areas.

Many of the neighbourhood measures of access to services and formal market are very significantly associated with uptake. Animal health service access is linked to the uptake of improved dairy cattle, and with the uptake of concentrates that are particularly associated with the highest grade of cattle, those at most threat from disease. Access to extension, however, is not significant with either dairy cattle or Napier uptake. Given the severe reductions in government support for extension services since the early 1990s, this result is not surprising. There is no apparent explanation, however, for the negative association of extension with concentrate use. Local formal milk market access, reflecting the density of formal market intermediary activity in the neighbourhood, is significant and positive for the uptake of all three technologies. Farmers report that while formal milk markets offer lower prices, they offer more reliable collection and payment (Ngigi, 2002). These results underline the importance of formal milk markets for the long-term success of smallholder dairy production.

The market access measures are significant and informative. Increased distance to the nearest formal milk collection centre by main road reduces the uptake of both dairy cattle and concentrate feed. An additional kilometre of road between farm and collection centre reduces probability of cattle uptake by 0.6%, so that the tens of additional kilometres that separate some farms from the centres can be expected to reduce uptake dramatically. This is likely to be an effect of both farm-gate prices received, and of market availability, since these routes are served by private intermediaries who charge farmers directly for transport costs. Concentrate use, associated with market-oriented dairy production, is also negatively affected. Similar effects are seen for total road distance to the largest formal market, Nairobi, for all three technologies. Again, the factors are likely to be price and availability, this time through differential milk prices paid by processors themselves to rural milk bulking agents, depending on distance to their plants, mostly located near Nairobi. The effects of distances to local urban markets, differentiated by road type and designed to proxy informal market access, are less consistent. Seasonal and main road distances to these centres are associated with an increase in the probability of dairy cattle uptake, which is not expected if these measures reflect market access. However, as seen in Table 2, these distances are relatively small, since there are some 16 urban centres of at least 50,000 inhabitants in the survey area. These measures may thus reflect some degree of urban and rural interface, so that locations quite close to local urban centres may offer greater opportunities for other enterprises such as horticulture, or non-agricultural enterprises, thus lowering the competitiveness of dairy production and reducing its uptake. The distance to nearest urban centres along all-weather earth roads produces the expected negative effect for all three technologies. The measure of local population density does not exhibit the characteristics of a market access measure. There is no associated affect on dairy cattle uptake with this variable. However, uptake of the improved feeding strategies, Napier and concentrates, is positively associated with local population density. This measure may thus be more reflective of the reduced availability of feed from common property expected with higher population densities. As a set of measures, these GIS-derived distances and densities can be seen when combined to reflect different facets of milk market access, rural versus urban location, and competition for local resources. Further, the demonstrated effects of even short distances of road underlines the need for high resolution measures of market access, particularly when the economic agents under study have limited means of transportation.

9.2. Comparisons with estimations using only survey data

In order to better assess the potential gains from integrating GIS-derived variables into such household models, estimations were made using only survey data for comparison. Instead of the GIS-derived measures of agro-climate, demographics and market access, variables were introduced that mirror those typically used in such studies. Market access was partially represented by farmer-reported distance to the nearest local market centre, obtained from the surveys. Market access and other locational factors were further represented by district dummy variables, with Kiambu, the district with the largest sample, as the base. The results are also shown in Table 3, in columns adjacent to those showing the integrated household-GIS model estimates. While the log likelihood results cannot be compared directly because of differing sample sizes, they along with the percent correct predictions suggest that the survey-only estimates have about the same or better explanatory power. However, much of that power seems to now lie in the 15 district dummy variables, 12 of which are significant at least at 0.10 probability level in the cases of dairy cattle and Napier, and 10 in the case of concentrate feeding. The farmer-reported distance to local market is significant only in the case of dairy cattle.

While overall explanatory power is not reduced by using only survey data, the ability to interpret and use the locational results is significantly impaired. Interpretation of the district dummy variables now requires detailed understanding of the differences between

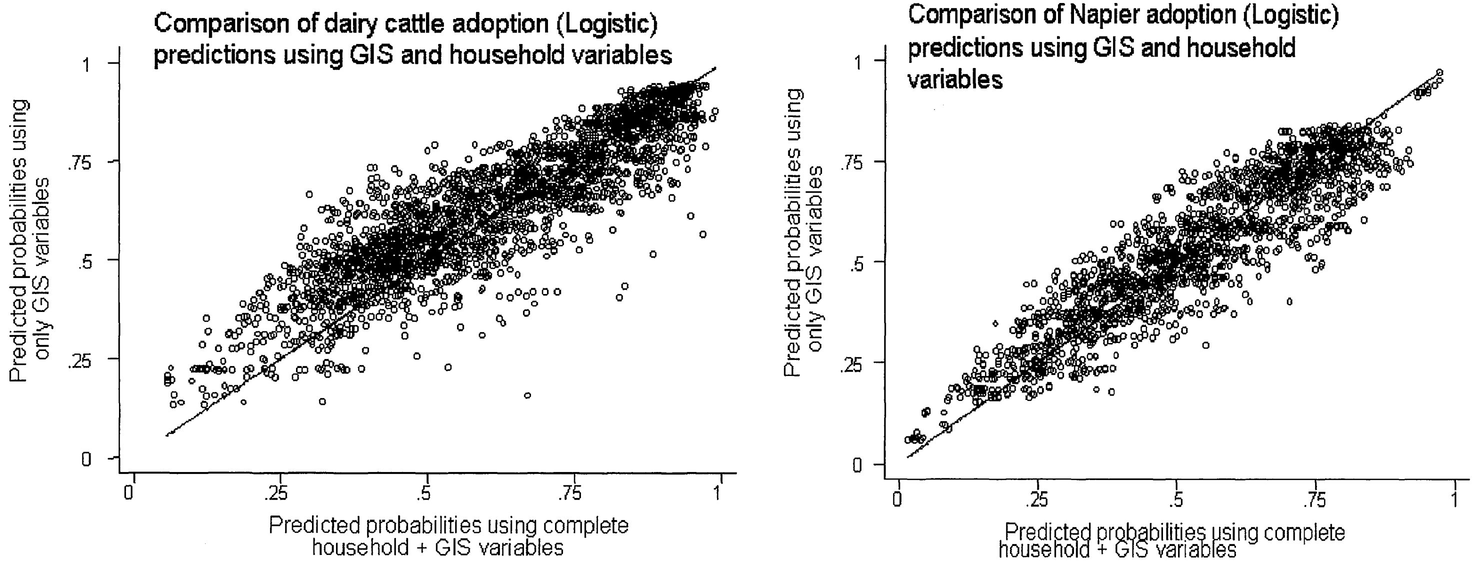

Fig. 2. Comparison of predicted values for uptake using full set of explanatory variables against using only GIS-derived variables.

districts, and speculation as to which of the factors associated with them, agro-climate, demographics or market, are associated with the observed outcomes. Further, these location proxies cannot easily be used to make useful spatial predictions.

9.3. Spatial predictions of technology uptake

The percent of correct predictions for the logit models, shown in Table 3, suggest satisfactory prediction levels of between 69 and 81%, with similar results for predictions of both adopters and non-adopters. However, to make spatial predictions, only the variables for which GIS surfaces are available can be used. We thus compared the levels of prediction when using the full set of variables, and those obtained when using only the GIS-derived variables. These are illustrated for two technology choices in the distribution graphs in Fig. 2.

Given the relatively good comparisons, spatial predictions of probability of uptake of the three technologies were made using only the significant GIS-derived variables, including PPE, population density and the distance measures, with all other variables held constant at their mean. The resulting probability of uptake maps are shown in Figs. 3–5, for dairy cattle, Napier, and concentrate uptake respectively. The spatial patterns of dairy cattle uptake show close correspondence with agro-climate potential, due to the strong effect of the PPE variable. Napier adoption demonstrates the combined effect of agro-climate and markets, with the highest probabilities in areas where both are favourable. Concentrate use, on the other hand, shows strong links to markets, with highest probability near large urban areas, particularly Nairobi, and very low probabilities elsewhere.

9.4. Spatial predictions of simulated infrastructure policy scenario

To further demonstrate the potential usefulness of the estimates of GIS-derived variables, a policy of upgrading some parts of the road infrastructure is

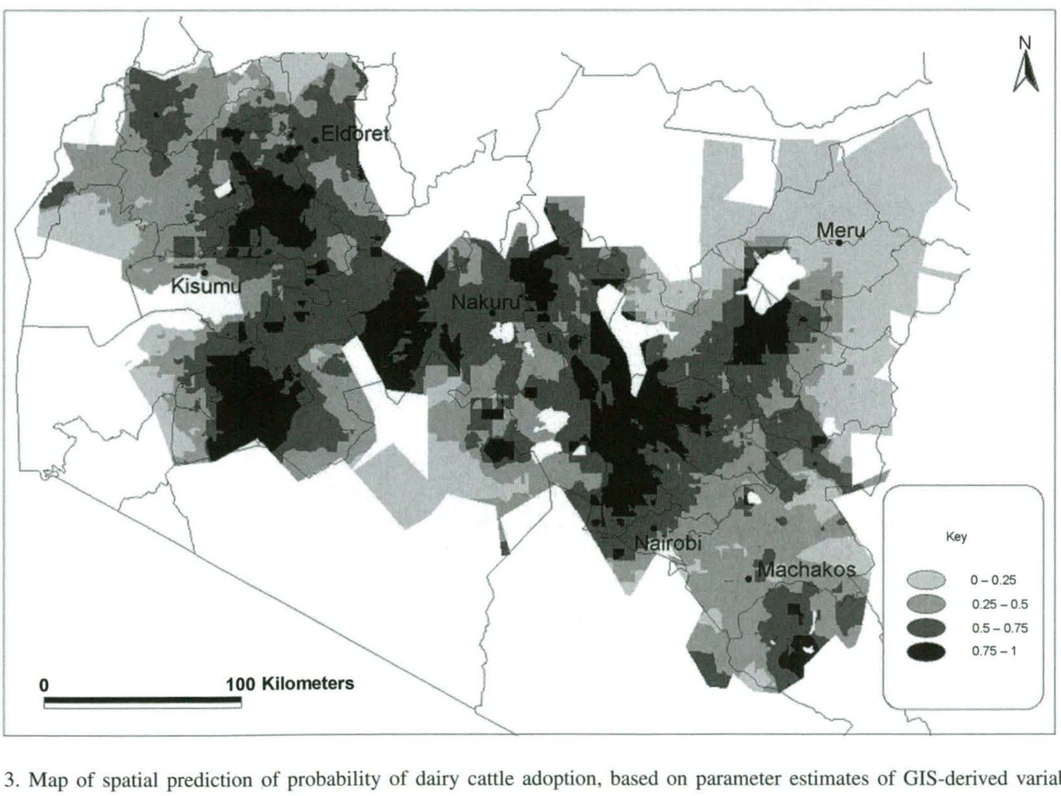

Fig. 3. Map of spatial prediction of probability of dairy cattle adoption, based on parameter estimates of GIS-derived variables.

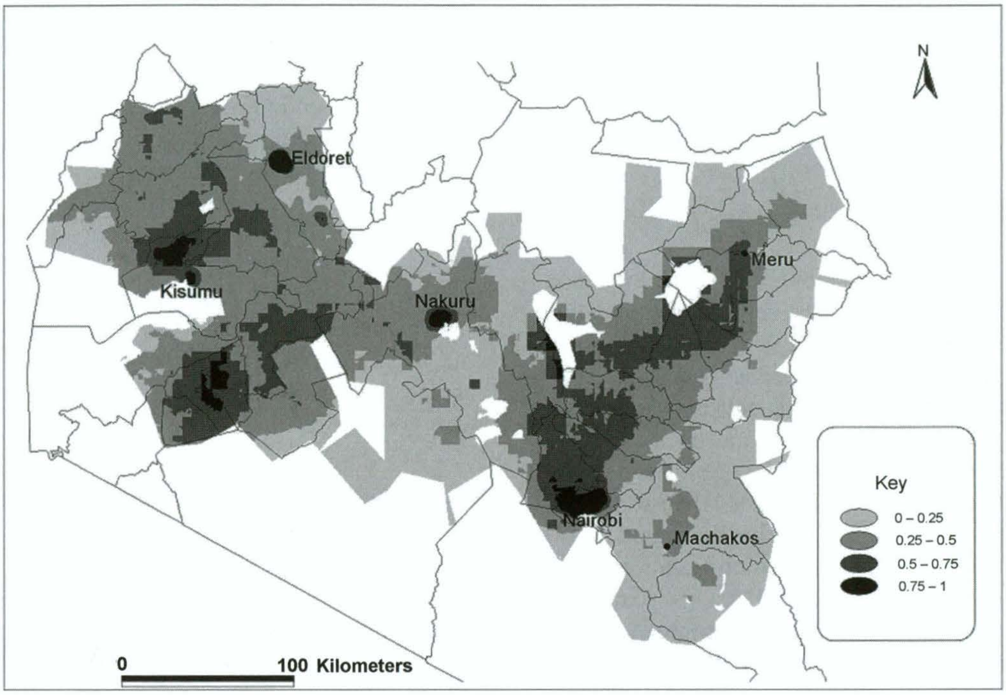

Fig. 4. Map of spatial prediction of probability of Napier adoption, based on parameter estimates of GIS-derived variables.

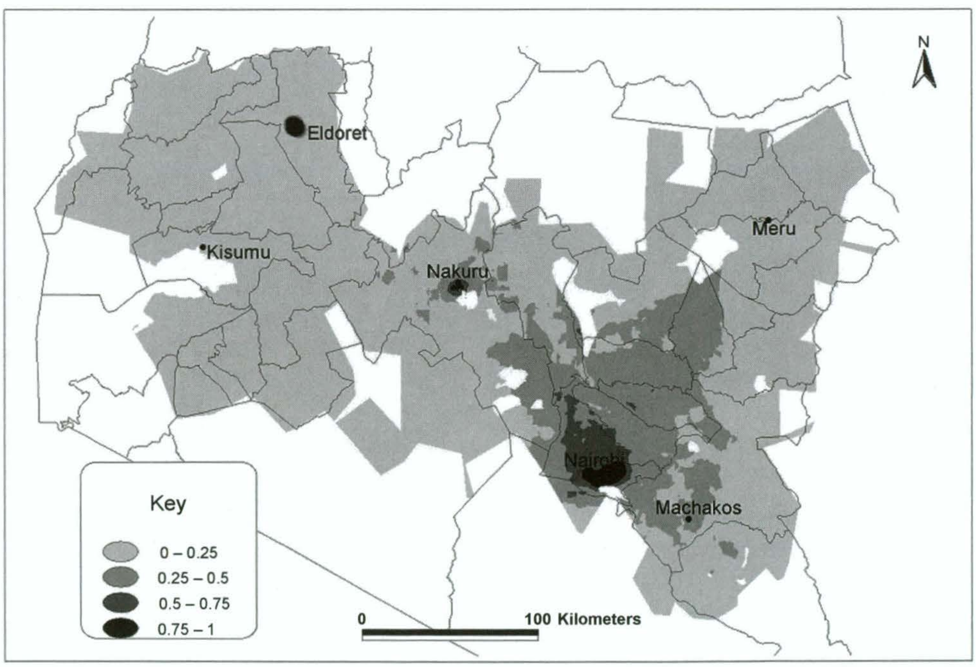

Fig. 5. Map of spatial prediction of probability of concentrate adoption, based on parameter estimates of GIS-derived variables.

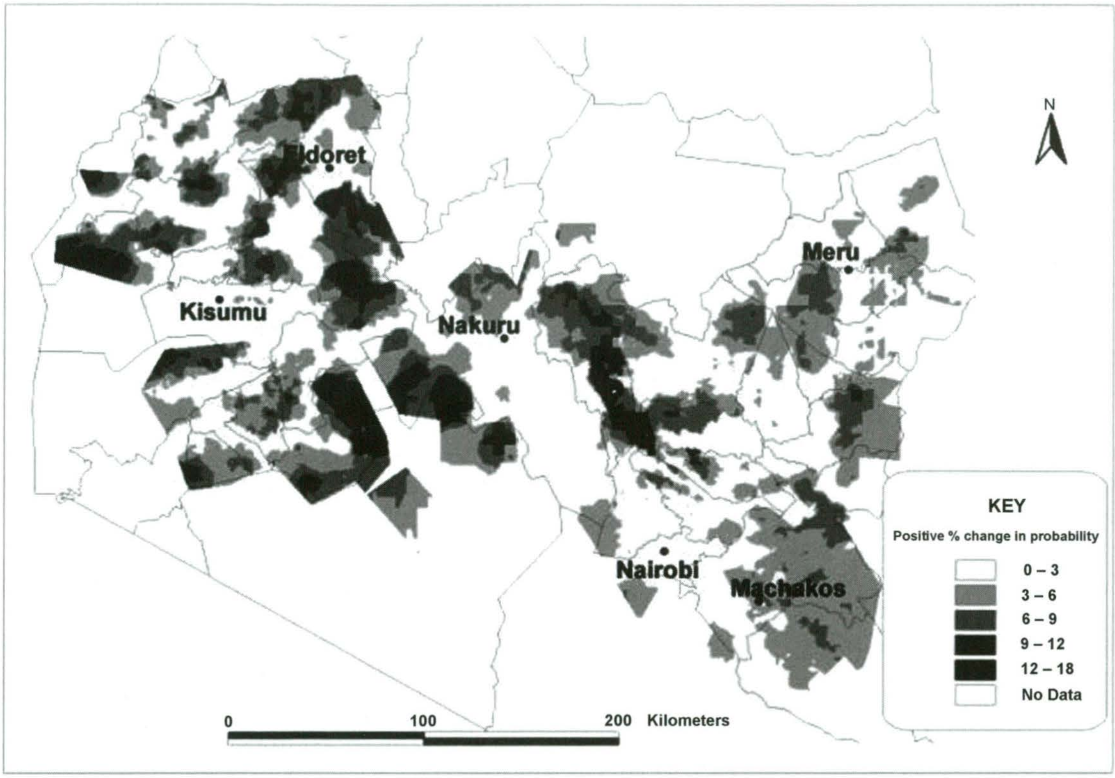

Fig. 6. Map of predicted positive change in probability of adoption of Napier cultivation with simulated upgrading of all-weather roads to tarmac roads, based on parameter estimates of GIS-derived variables.

simulated. The potential effect is examined, on the probability of uptake of Napier cultivation, of upgrading all sections of the "all-weather earth roads" to hard surface tarmac. To do this, the spatial predictions are adjusted to reflect the change in reduced probability of 1 km of all-weather road (−0.76) to that of 1 km of tarmac road (−0.30), measured along the routes to the two nearest urban centres. Such upgrading is thus expected to raise probability of uptake by 0.46 per km, the difference between the parameter estimates for the two roads type effects. Fig. 6 shows the change in probability of uptake that could potentially result from this upgrading of the infrastructure. The analysis highlights those areas that could potentially be most positively impacted by infrastructure development if smallholder dairy production is seen to be a strategic development strategy.

Generally, when the GIS-derived variables are significant, predictions could be made for a wide variety of policy scenarios, including location of collection centres, or location of livestock or extension services, and investment and impacts could be compared with cost-benefit analyses, etc. This could be used to target planning and investment to those areas where desired impacts would be greatest. Conversely, if changes in rainfall due to global climate change can be predicted, for example such an integrated model could predict potential changes in technology use. These spatial predictions demonstrate the ability of the integrated household model to provide better understanding of potential recommendation domains for sets of technologies. Since the spatial parameters are estimated in a household model and individual household characteristics are controlled for, the spatial estimates better reflect the locational effects themselves.

10. Conclusions

The well-established integration of spatial variables into models of land use and ecology is a tool equally available to economic analyses of technology uptake. As seen in these results, GIS-derived variables offer the potential to better differentiate the components of location, and to generate measures in units that can easily be used in spatial prediction and policy analysis. These results also illustrate the continued difficulty of creating close proxy variables for the types of access being targeted, as some variables aimed at market access instead appear to reflect other differences in rural and urban settings. More experience in application of GIS-derived variables in household models will no doubt improve the refinement of this technique, and our ability to select spatial proxies, including the use of both simple and composite access measures. The use in this case of relatively simple distance measures allowed per kilometre impacts to be assessed, which would not be possible if composite market access measures were employed. Bockstael notes that Von Thünen's model (Von Thünen, 1966) is of a system in which the landscape is a featureless plain. GIS-derived spatial measures help us to identify and differentiate the features that do exist, and integrating them into household models of economic behaviour may allow us to better understand how they affect farmer choices.

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