Coupling the Tradeoff Analysis Model with a market equilibrium model to analyze economic and environmental outcomes of agricultural production systems

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ABSTRACT

Analysis of the economic and environmental outcomes of agricultural systems requires a bottom-up linkage from the farm to market, as well as a top-down linkage from market to farm. This study develops this two-way linkage between the Tradeoff Analysis Model of agricultural systems and a partial equilibrium market model. The resulting model can determine the effects of technology and policy interventions on the spatial distribution of environmental and economic outcomes at market equilibrium quantities and prices. The approach is demonstrated with a case study of tradeoffs between poverty and nutrient depletion in a semi-subsistence agricultural system (Machakos, Kenya). The results suggest that the linkage of market equilibrium analysis to farm level Integrated Assessment Models can be important in the analysis of agriculture–environment interactions.

1. Introduction

Integrated Assessment Models (IAMs) are used in agricultural research to assess policy impacts on economic and environmental sustainability of agricultural production systems. Assessing the spatial distribution of economic outcomes (e.g., poverty), and environmental impacts (e.g., nutrient depletion) requires the use of spatially explicit data and models. Some farm-level IAMs have been developed to represent the heterogeneity of the physical environment and economic behavior of farmers by integrating site-specific biophysical and economic models. These models typically use spatially-explicit data to model agriculture–environment interactions but treat prices as exogenous (see Goddard et al., 1996; Fleming and Adams, 1997; Brown, 2000; Antle and Capalbo, 2001; Mathur, 2003; Oxley and Apsimon, 2007; Uthes et al., 2010). However, when a policy or a technological change affects many farms, the aggregate responses may impact market equilibrium agricultural prices. Consequently, farm-level IAMs may need to be coupled to market equilibrium models to account for price endogeneity and market interactions in the assessment of agricultural production systems (Kayser, 1999; Verburg and Veldkamp, 2005; Pérez Dominguez et al., 2009).

The goal of this study is to link the Tradeoff Analysis (TOA) Model (Antle et al., 1998; Stoorvogel et al., 2004), to a price-endogenous (partial) market equilibrium (ME) model. The TOA model is an IAM that links site-specific bio-physical process models and economic decision models, and aggregates economic and environmental outcomes to a regional scale, but treats prices as exogenous. The linkage between the TOA model and the ME model allows the effects of site-specific interactions at the farm scale to be aggregated and used to determine market equilibrium. The resulting market equilibrium in turn can be used in the TOA model to determine spatially explicit economic and environmental outcomes. The linkage is illustrated in a case study of the semi-subsistence agricultural production system of Machakos, Kenya. Poverty and sustainability issues are critical in this region where technology or policy interventions are likely to affect the market for maize, a key commodity in Machakos. The case study illustrates the differences in the analysis with and without market equilibrium and the importance of feedbacks in the assessment of tradeoffs between nutrient depletion and poverty in the semi-subsistence agricultural system of Machakos, Kenya. The next section presents the linkage between the TOA model and the ME model. The third section presents the application of the linked models for Machakos, Kenya. The results are discussed in section four followed by general conclusions in the last section.

2. Coupling the TOA and ME model

2.1. The Tradeoff Analysis Model

The TOA model (Fig. 1) incorporates crop models to assess land quality and economic models to simulate land management...
decisions. Subsequently, those decisions are input in environmental process models to simulate the associated environmental outcomes. These simulations are executed for a statistically representative sample of the farmer population in a region. The site-specific economic and environmental outcomes can then be aggregated to the regional level to create economic and environmental indicators of interest to stakeholders. The simulations can be repeated for alternative parameter settings to quantify the inter-relationships (i.e., tradeoffs) among the indicators.

At the farm level, the effects of site-specific soil and climate conditions on productivity potential, or inherent productivity, are estimated using crop simulation models. Then an econometric-process model (an empirical econometric production model developed by Antle and Capalbo (2001) and later adapted by Antle et al. (2010a)) simulates site-specific land management decisions using econometric production models (input demand and output supply) that are functions of inherent productivity, prices, farm characteristics, and policy parameters.

Environmental impacts of these management decisions are then simulated using environmental process models. As a result, management decisions and resulting environmental outcomes on each unit of land in production are functions of site-specific environmental conditions, prices, policies, technology and other farm-specific variables. The distributions of these site-specific and farm-specific characteristics in the population generate a joint distribution of economic and environmental outcomes in the population that are functions of the underlying environmental and economic parameters.

With this joint distribution the outcomes can be statistically aggregated into economic and environmental indicators that represent the population. By varying model parameters, such as prices, different environmental and economic outcomes are generated. The aggregate relationships between economic and environmental indicators generated in this way are referred to as tradeoff curves. Thus, tradeoff curves represent the supply side of the agricultural system. Here we use the fact that when tradeoff curves are
generated by varying output or input prices, they represent the output supply and input demand behavior of farms (Stoorvogel et al., 2004).

Fig. 2 shows graphically how price-based tradeoff curves can be constructed by aggregating farm-level outcomes. Suppose that the simulated farm-level outcomes (e.g., soil quality and crop production) associated with a given set of crop and input prices, is point A in Fig. 2a. Repeating this simulation for a statistically representative sample of farms in a region generates a distribution of points representing the population of farms in the region as in Fig. 2b. Different distributions of outcomes can be generated by changing a parameter, such as the mean of the distribution of a crop price (see Fig. 2c). The data can then be aggregated to obtain a tradeoff curve (see Fig. 2d). When the tradeoff curve is generated by varying a price, it can be interpreted as a set of possible equilibrium points associated with these prices. Each point along the tradeoff curve are referred to as tradeoff points.

2.2. Linking the TOA model to a market model

The tradeoff curve derived in Fig. 2 illustrates, besides the relation between environmental quality and crop production, the relationship between the market price and the aggregate quantity of an output. This forms the basis for linking a tradeoff analysis to a market equilibrium analysis. This linkage is portrayed in Fig. 3 which shows a tradeoff between an environmental quality indicator $E$ (e.g., an indicator of sustainability such as nutrient depletion) and aggregate output $Q$ represented by the curve $T$. That tradeoff curve is generated by varying a price $P$ (e.g., price of $Q$ or an input price). Each point along $T$ is a possible equilibrium, and corresponds to a point on the supply curve $S$. If we add to this system a demand curve such as $D$, we obtain a market equilibrium point $a$ which in turn defines the point $b$ on the tradeoff curve as the equilibrium. Since point $b$ is associated with a specific spatial distribution, the correspondence between points $a$ and $b$ allows the market equilibrium to be linked to the associated spatial distribution of outcomes (map in the figure). If market conditions change (e.g., a shift in the demand due to a policy intervention) then a new market equilibrium point $a'$ is attained. Point $a'$ corresponds to a different equilibrium crop price, so producers respond by changing production decisions, resulting in a different spatial distribution of economic and environmental outcomes (map) associated with the corresponding equilibrium point $b'$ in the tradeoff curve. Thus, the linkage between the TOA analysis and market equilibrium analysis allows us to associate the spatial distribution of economic and environmental outcomes with each possible market equilibrium.

Market equilibrium can change in response to factors affecting market demand, as in Fig. 3, as well as changes in the factors determining market supply. As the discussion above showed, the market supply of a crop is derived by aggregating the individual quantities produced at each price. Consequently, a change in any of the factors that determine this farm-level supply decision will shift the market supply curve. To illustrate this point, let the market supply be defined as $S = f(P, \theta)$ where $P$ is a crop price and $\theta$ is a vector that defines the distribution of individual farm characteristics in the population, including other output and input prices, and farm characteristics such as farm size and technologies in use. The market demand is defined as $D = f(P, \psi)$ where $\psi$ is a vector that defines parameters that may influence the demand such as aggregate income or the distribution of income and household characteristics.

Fig. 4a shows the supply $S^0(P, \theta)$ and demand $D^0(P, \psi)$ schedules of a crop in the market and $A(P_0, Q_0|\theta, \psi)$ is the initial equilibrium point implying that $P_0$ is the initial price equilibrium and $Q_0$ the initial equilibrium quantity of the system given the parameters $\theta, \psi$. Changes in factors determining either demand or supply result in a change in market equilibrium price, and thus will lead to a different spatial distribution of economic and environmental

![Fig. 2. Derivation of the tradeoff curves of two environmental and economic indicators (e.g., environmental quality and crop production) by changing the mean of the distribution of crop prices.](image-url)
Fig. 3. Theoretical framework to link environmental and economic outcomes, market equilibrium and underlying spatial distributions.

Fig. 4. Market equilibrium: shifts on supply and demand schedules due to changes on their parameters.
outcomes. For example, a reduction in production costs will result in a rightward shift in the supply curve from \( S^0(P, h) \) to \( S^1(P, h) \). Given that the demand curve has a negative slope, the market equilibrium point moves to point \( B(P_1, Q_1| h, \psi) \). Consumers benefit from the increased consumption (from \( Q_0 \) to \( Q_1 \)) at a reduced price (from \( P_0 \) to \( P_1 \)). In contrast, if there is a change in demand, caused for example by an increase in consumer income leading to a new value \( \psi^1 \), then the demand curve shifts to the right (Fig. 4b). In this case, the equilibrium point moves from point \( A_0(P_0, Q_0| h, \psi) \) to \( B(P_1, Q_1| h, \psi^1) \). As in the previous case, the equilibrium quantity changes from \( Q_0 \) to \( Q_1 \), but this time there is an increase on the price from \( P_0 \) to \( P_1 \). Alternatively, there is the case when both market supply and market demand shift. Fig. 4c shows a shift of the demand curve to the right, from \( D_0(P, \psi) \) to \( D_1(P, \psi^1) \) and a shift of the supply curve from \( S^0(P, \theta) \) to \( S^1(P, \theta) \). The new equilibrium point \( C(P_3, Q_3| h, \psi^1) \) implies a decrease in the equilibrium price from \( P_0 \) to \( P_3 \) and a new equilibrium quantity \( Q_3 \) given the conditions \( \theta^1, \psi^1 \). Any change in market demand or supply results in a change in market equilibrium price. The change moves the system to a different point along the tradeoff curve shown in Fig. 3 associated with a different spatial distribution of economic and environmental outcomes. It is important to note that changes in the structure of the farm or changes induced by a technological change or policy (e.g., a change of \( \theta \) on the supply side) could lead to different price responsiveness (elasticities). The latter will influence the magnitude of shifts in supply/demand on the equilibrium price and quantity in the market. For example, Fig. 4d shows the effects of a shift from the supply curve \( S^2 \) to a new supply curve \( S^3 \) and to another more elastic supply curve \( S^4 \). Although the new equilibrium values obtained from the shift of the supply curve to \( S^1 \) and \( S^2 \) both have the same effect (e.g., consumers benefit from an increased consumption and lower prices in both cases) the magnitude of the effect is larger (\( Q_0 Q_2 > Q_0 Q_1 \) and \( P_0 P_2 > P_0 P_1 \)) when a supply curve such as \( S^2 \) is more elastic. The market analysis shown above can be done in a similar manner in terms of input demand and supply.

2.3. Implementation: The TOA–ME

The linkage of the TOA model with a market equilibrium model has been implemented in the TOA software (Stoorvogel et al., 2004). The TOA software integrates spatially explicit GIS-based soils and climate data with the DSSAT crop growth simulation models (Tsuji et al., 1994; Jones et al., 2003), econometric-process simulation models of land use and management decisions (Antle and Capalbo, 2001), and a suite of environmental process models. The software can be used to create two-dimensional tradeoff graphs, such as illustrated in Fig. 2, as well as maps of the spatial distributions of outcomes illustrated in Fig. 3. The TOA software and documentation are publicly available at www.tradeoffs.nl.

In order to link the TOA model to a market equilibrium model, an additional module was created within the TOA software (Fig. 5). The TOA–ME module reads the output data from the TOA simulation. As noted above, either output supply functions or input demand functions can be derived from the TOA analysis. Here we discuss the case of output supply. The user chooses a functional

![Fig. 5. General structure of the TOA–ME.](image-url)
form for the output supply function (e.g., the supply function for maize) and the program estimates the corresponding parameters using ordinary least squares. It is assumed that the initial market equilibrium is at the base prices, so the program reads the user-defined demand parameters (price elasticity or slope) to calibrate the demand function’s intercept corresponding to the initial equilibrium. Once the parameters are estimated and calibrated, the program solves the equations simultaneously for the equilibrium price and supply. The resulting market equilibrium price and supply represent the tradeoff point associated with the equilibrium values. The user can then re-run the TOA model using the equilibrium values and generate the spatial distribution of outcomes associated with this equilibrium point. This process can be repeated for different policy or technology scenarios to get the new equilibrium values and measure the effects of these policies on the underlying spatial distributions of the economic and environmental indicators.

For the single market setting, the aggregate output supply function for a specific crop can be defined as:

\[ Q_s = \frac{a_0 P^{a_1}}{P^{a_1}} \]  

(1)

The output supply parameters \(a_0 \) and \( a_1 \) are estimated using ordinary least squares. A constant elasticity demand curve for the same crop is specified as:

\[ Q_d = \frac{P^{\beta_0}}{P^{\beta_1}} \]  

(2)

The condition for market equilibrium is then defined as:

\[ Q_s = Q_d \]  

(3)

Eqs. (1–3) are solved simultaneously in order to obtain the equilibrium quantity and price \( Q_s \) and \( P \). The equilibrium price is then used to define a new tradeoff point by setting the mean of the price distribution of the corresponding crop to the equilibrium value. The econometric production model and the environmental process models are run again using this price. The results from this process will show the tradeoffs between environmental outcomes and economic outcomes at the equilibrium price. Different technology or policy scenarios can be run in order to measure their effects under a market equilibrium condition.

As noted above, the TOA–ME can estimate equilibrium for input markets in a similar manner. Input demand equations (e.g., for fertilizer) can be derived from the TOA output, and together with a corresponding input supply equation, the TOA–ME can solve for input market equilibrium.

In order to specify the market output demand or input supply functions we can follow two approaches. One is to use data to estimate statistically the needed demand or supply function parameters. Alternatively, parameters from the literature can be used. Sensitivity analysis of these parameters can be used to assess the effects of parameters on the model. The TOA–ME is also capable of conducting multiple market analysis (two or more outputs or two or more inputs or a combination of outputs and inputs). However, there are some additional issues that must be addressed in the multiple market case such as how the multiple prices are jointly varied for parameter estimation.

3. TOA–ME application for the semi-subsistence agricultural system in Machakos, Kenya

In this section we consider a case study of the semi-subsistence agricultural system in Machakos, where maize is an important part of the system. We use this example to illustrate the differences of the analysis with and without considering market equilibrium analysis in the assessment of policies designed to reduce poverty and soil degradation.

3.1. Study area

Kenya is one of the world’s poorest countries with about half of the population living on an income of less than US$1 per day. Agriculture in Kenya is the most important sector in the economy, representing about 30% of the GDP (Karanja et al., 2002). Most of the agriculture is semi-subsistence where intercropping, small farm size (<2.5 ha), high rates of crop failure (>50% during dry years) and lack of an established capital market are typical (Kamau, 2000; Antle et al., 2010a). In many regions of Kenya, rapid population growth and limited access to land has led to farm sizes so small that it is difficult for farmers to climb out of poverty by relying solely on growth in farm productivity. All these conditions plus the highly variable and changing climate make farms in this region highly vulnerable. Thus, investment in the rural non-farm sector that creates opportunities for non-farm employment, and investment in education and training programs in addition to investment in market infrastructure, would be necessary to increase rural income growth (Marenya et al., 2003). These issues are the core of the policy scenarios analyzed in this study, which are in line with proposed policy interventions set by the Government of Kenya (Government of Kenya, 2004).

The Machakos region is located southeast of Nairobi between 0°7’ and 3°00’ southern latitude and between 36°87’ and 38°51’ eastern latitude. The area of the region is approximately 14,000 km² with an altitude range between 340 and 1710 m.a.s.l. The main crops grown in the Machakos region are maize, pigeon pea, sorghum, beans, horticultural crops and fruit trees. Maize production is an important subsistence crop and a cash crop for larger farms. Despite several efforts of the government and research programs to increase maize yields, average yields are far below the potential contributing to serious food deficits in many regions of Kenya. Soil nutrient depletion is one of the major constraints to increasing crop productivity. In order to reverse the declining trends in per capita food production and negative nutrient balances, soil fertility management on farms must be improved (e.g., Donovan and Casey, 1998). Despite research showing that fertilizer could be a profitable option to increase yields and income, fertilizer use in Sub-Saharan Africa is low, and it is even lower in semi-arid areas. According to the UNDP (2001), average consumption of fertilizer in 1998 was 13.8 kg of nutrients per hectare of arable and permanently cropped land. The low use of fertilizer has been attributed to high prices caused by high transport costs and import tariffs, high levels of risk associated with low and highly variable rainfall patterns, inefficient input distribution and availability, financial constraints and difficulty of farmers in assessing returns to fertilizer (Freeman and Omiti, 2003). Marenya and Barrett (2009) show that low rates of fertilizer use in Kenya are also associated with low soil fertility due to severe nutrient depletion that results in low fertilizer response.

3.2. Data

This study uses data from two farm-level surveys from 6 villages in Machakos and Makueni District carried out between 1997 and 2001, (De Jager et al., 1998). Table 1 shows summary statistics for the six villages. The main cropping systems in the region can be grouped as:

- maize and beans grown as monocrop or intercrop and sold in the market or used for home consumption;
- complex intercrop systems which are mostly used for home consumption. A large number of crops are planted together and frequently diverse combinations and proportions are found in different farms;
study we use an own price elasticity of demand for maize of 3.3. The TOA model application for Machakos and scenarios elasticity of demand for maize is about
Nzuma and Sarker (2008) estimated that the short-run own price
literature. There are few studies that have actually estimated the
8 persons.

in each field. These crop-specific outputs, inputs and returns at the
returns by choosing the activity with the highest expected returns
and livestock production in the current season. Cost of production,
accumulated in a previous season become inputs available for crop
availability. Manure and organic fertilizer as well as crop residues
model simulates milk and manure production as functions of feed
inputs and returns at the

• vegetables are primarily cash crops but are limited to the areas
that have access to irrigation; and
• grass used for livestock feeding.

The data show that farm size varies across the region but most
farms are very small relative to the average household size of about
8 persons.

Data for the demand side of the analysis were obtained from the
literature. There are few studies that have actually estimated the
price elasticities of demand for maize and other crops in Kenya.

Nzuma and Sarker (2008) estimated that the short-run own price
elasticity of demand for maize is about –0.53 while the long-run
own price elasticity of maize was about –0.80. Other studies sur-
veyed by Nzuma and Sarker reported elasticities of demand for
maize ranging from –0.45 to –0.90 (see Table 2). In the present
study we use an own price elasticity of demand for maize of –0.50.

3.3. The TOA model application for Machakos and scenarios

In the application of the TOA model for Machakos, Antle et al.
(2010a) defined the farm according to its characteristics (location,
size, number of family members, age and education of household
head, availability of off-farm income, number of Tropical Livestock
Units (TLUs), and family labor) (Fig. 6). For each growing season the
model simulates milk and manure production as functions of feed
availability. Manure and organic fertilizer as well as crop residues
accumulated in a previous season become inputs available for crop
and livestock production in the current season. Cost of production,
expected revenue and expected returns of each activity for each
field on the farm are computed by simulating crop input use and
input demand functions, crop failure probabilities and crop and
byproduct equations. The model assumes that farmers maximize
returns by choosing the activity with the highest expected returns
in each field. These crop-specific outputs, inputs and returns at the
field level are aggregated to the farm level.

Antle et al. (2010a) analyzed two policy issues: the loss of soil
nutrients with the resulting loss in crop productivity, and the
increasing dependence of a growing population on small farms for
their livelihoods. To deal with these two policy issues, Antle
et al. (2010a) constructed three scenarios to be analyzed. The first
scenario assumes that there is an increase in fertilizer availability
due to investments in market infrastructure and reductions in im-
port tariffs which lower farm-gate cost of fertilizer. This fertilizer
scenario assumes that these interventions reduce the price of fer-
tilizer by 50% and assumes all farmers use fertilizer (the quantity
is estimated by the fertilizer demand at those lower prices). The second scenario, called rural development, represents the conse-
quences of a policy that stimulates investments in the rural sector,
which in turn increases off-farm employment opportunities and
farm consolidation. This scenario assumes that household size is
reduced by 25% and farm size is increased from the regional aver-
age of about 3–6 ha. A third scenario is a combination of the fertil-
izer and the rural development scenarios.

These three policy scenarios are compared to the base scenario.
The indicators used to analyze the system are the poverty rate
(headcount poverty index, HPI with a poverty line equals to $1/
day), and the average soil nutrient depletion rate (nitrogen loss),
estimated by incorporating the NUTMON model into the TOA anal-
ysis. As mentioned before, maize is an important food crop in Ken-
ya, making the price of maize a key variable for policymakers. For
this reason, the mean of the maize price distribution was varied in
order to construct the tradeoffs between poverty and nutrient
depletion indicators.

3.4. Results

3.4.1. Results from TOA

Fig. 7 shows the tradeoff curves between the poverty and sus-
tainability indicators for the base scenario and for the three policy
scenarios. For the base scenario, at the base maize price, $P_{maize}^b$, the re-
sults show that the poverty rate is about 76% and the soil nitrogen
depletion averages about 32 kg/ha. The rural development scenario
shows a reduction in poverty from the base value of 51 to an
average of 51 (point $P_{maize}^d$ in the figure), and a reduction in the
nitrogen depletion rate to 27 kg/ha from the 32 kg/ha of the base
scenario. The fertilizer scenario shows that at the base price $P_{maize}^b$
the soil nitrogen depletion is about 29 kg/ha and the headcount
poverty rate is about 68%. The combined rural development and
fertilizer scenarios yielded the largest changes in poverty rate and
nutrient depletion, with a headcount poverty rate at the base
price $P_{maize}^b$ of about 42%, and an average nitrogen depletion rate of
about 25 kg/ha. In all cases there is a negative relationship be-
 tween poverty and nitrogen depletion as the price of maize is var-
ied. As expected, an increase in maize price leads to an increase in
farm income and a reduction in poverty. Note that the poverty
measure in this analysis is income based, therefore it does not take

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<th>Table 1</th>
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<td>Summary statistics by village, Machakos NUTMON data. Source: Antle et al. (2010a, 2010b).</td>
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<tr>
<td>Variable</td>
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<tr>
<td>Output price, complex intercrop (ksh/kg)</td>
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<td>Maize price (ksh/kg)</td>
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<td>Bean price (ksh/kg)</td>
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<td>Mineral fertilizer price (ksh/kg)</td>
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Note: Means with standard deviations in parentheses.
into account changes in consumption (e.g. the effects of maize price changes on consumption). Conversely, an increase in maize price causes an increase in soil nutrient depletion. Fig. 6 shows that the alternative scenarios shift the tradeoff curve inwards relative to the base scenario. In this case, an inward shifting of the tradeoff curve is good because both poverty and nutrient depletion are reduced. The effect of maize price on soil nutrient losses is explained by the fact that farmers increase the amount of land allocated to maize as the maize price increases, but do not increase fertilizer use enough to prevent a net loss of nutrients in the harvested grain.

3.4.2. Results from TOA–ME

The TOA analysis presented above is the first step in the market equilibrium analysis, as indicated in Fig. 5. Using these simulation outputs, the maize supply elasticities were estimated, assuming a constant-elasticity supply function (Table 3). These elasticities for Machakos are larger than some reported in the literature (see for example, Lubulwa et al., 1995; Thorne et al., 2002; Karanja, 2003; and Mghenyi, 2006). This difference may be explained by the explicit representation of the discrete land use decision embedded in the econometric-process model described in Section 2.1, which can produce a more price-responsive supply function than estimates based on aggregated data (for more details see Antle and Capalbo, 2001). On the demand side, the intercept of the constant elasticity demand function was calibrated using the base price of maize (15.7 ksh/kg) as the initial equilibrium price. The supply and demand parameters are used to determine the market equilibrium price and quantity which allow us to identify the point on the tradeoff curve associated to those equilibrium values for the three scenarios.

Fig. 7 shows the relationship between poverty and output quantity (maize production) and the link to the market supply and demand curve. The poverty-maize production tradeoff curve is, as mentioned before, a set of possible equilibrium points associated with different prices. The implied supply curve $S_b$ for the base scenario is drawn in the bottom part of the figure. The demand schedule $D$ results in a market equilibrium point $E_b$ which in turn defines the point $T_b$ on the tradeoff curve. Using this point we can map the spatial distribution of the outcomes (e.g., poverty) as it is shown in the figure (map).

Each scenario generates a different tradeoff curve and a new supply curve. Consequently, new equilibrium points are estimated for each scenario. In this presentation the demand curve is fixed. We assume that the income that drives the demand is more than just farm income (e.g. farmers have other sources of income such as off-farm income and remittances). Consequently, changes in farm income due to changes in the price of maize are not large enough to shift the demand. However, demand effects could also be
estimated and incorporated into the market equilibrium analysis. More generally, demand may also respond to policies that increase crop production or stimulate rural development and thus raise incomes. Fig. 8 also shows the tradeoff curve for the combined scenario of rural development and fertilizer availability, the derived supply curve (SR+C) and the equilibrium point (ER+C) at the equilibrium price (PR+E) which determines the point (TR+C) along the tradeoff curve. This point allows us to determine the spatial distribution of impacts on the disaggregate outcomes. In the figure a new map of the distribution of poverty for the district of Machakos is obtained (see map1 in Fig. 8).

The goal of this analysis is to estimate the effect of policy scenarios in moving along the tradeoff curve. Without the ME analysis, an analyst would not know the impact of the scenario on the market equilibrium price, so the analyst might compare the simulation results at the base prices. To illustrate the implications of not considering a ME analysis, we analyze the effects of the combined rural development and fertilizer scenarios. The results suggest that at the base price this policy would decrease the poverty rate from 76% to 42% (which implies a 45% reduction in poverty). However, the results at the market equilibrium prices suggest that the poverty rate is reduced to about 53% (implying a 31% reduction in poverty). This means that the difference between the results at the base and market prices is about 14%.

Table 4 shows that the spatial distribution of outcomes is different at the base prices and at the market equilibrium prices. The effects of market equilibrium on aggregate outcomes are presented in Fig. 7. The market equilibrium points estimated for each scenario are labeled as PB for the base scenario, PF for the fertilizer scenario, PR for the rural development scenario, and PR+F for the combined rural and fertilizer scenario. The figure shows that the market equilibrium points are different than the base prices for each scenario. To illustrate the implications of not considering a ME analysis, we analyze the effects of the combined rural development and fertilizer scenarios. The results suggest that at the base price this policy would decrease the poverty rate from 76% to 42% (which implies a 45% reduction in poverty). However, the results at the market equilibrium prices suggest that the poverty rate is reduced to about 53% (implying a 31% reduction in poverty). This means that the difference between the results at the base and market prices is about 14%. Likewise, the model suggests that at the base price this policy reduces the nitrogen depletion rate from 32 kg/ha to about 25 kg/ha. The model shows that at the market equilibrium price this policy would reduce the nitrogen depletion to about 19 kg/ha, implying that the difference between the two models is about 21%. The difference between the impacts on poverty and nitrogen depletion measured at the base price and at the market equilibrium price may be explained by the fact that the policy intervention leads to new socio-economic conditions in the population (larger farm size, smaller household size and fertilizer availability). These changed conditions in turn, cause an outward shift of the maize supply curve (i.e., the supply curve shifts to the right) resulting in a lower (equilibrium) price of maize (this is equivalent to the shift of the supply curve shown in Fig. 4a. Fig. 8 also provides a graphical illustration of the impacts on poverty...
and nitrogen depletion measured at the base and equilibrium prices). As result, land allocated to maize is reduced (recall from above that price of maize drives land use decisions) and farm income is decreased. Thus, compared to the base price, the impacts on poverty are smaller at the market equilibrium and the impacts on nitrogen depletion are larger.

Table 5 shows a comparison of the aggregate results for both cases, at the base and market prices, in terms of the changes on poverty and nutrient depletion due to the policy interventions (the three scenarios under analysis). In conclusion, Tables 4 and 5 show that linking an ME analysis to the TOA has quantitatively important effects on the assessment of agriculture–environment interactions and policy making in cases where market conditions determine prices (i.e. existence of local or regional markets).

4. Discussion

Market equilibrium is likely to be important in the analysis of agricultural systems in developing countries where product and input markets are not well integrated, and therefore, local supply determines local prices (e.g., high transport costs may cause farm-gate prices be set locally). Also, changes in the market supply schedules are driven not only by prices but also by changes in farm characteristics in response to policy changes, environmental conditions or socio-economic conditions. For example, in developing countries, urban and rural development policies such as infrastructure investment can affect rural–urban migration and off-farm employment, and thus change farm characteristics such as farm size, household composition, and farm family members’ health and education (Reardon et al., 1998). These policy-induced changes in the distribution of farm characteristics affect market supply, which together with market demand determines the equilibrium market price. This equilibrium price in turn determines farm-level land management decisions and thus determines the spatial distribution of economic and environmental outcomes as shown in Fig. 3. Linking the ME results back to the spatial distribution of economic and environmental impacts (e.g., poverty, land quality, etc.) allows us to understand the magnitude of these impacts at the disaggregate level (i.e. site-specific economic and environmental outcomes). The fact that the TOA model is a spatially explicit model that incorporate the effects of farm characteristics on land use and management decisions, provides an opportunity to fill that gap by linking spatially explicit production systems to ME models. The model allows us to assess the interaction between socio-economic and environmental indicators and the effects at the market.
level and vice versa (i.e. interaction across scales). In fact, several studies have recognized the need to link farm-level agricultural systems models to the aggregate, regional scales that are the principal concern of policy makers (Easterling, 1997; Ewert et al., 2006; Van Ittersum et al., 2008). Most methods and modeling tools that link micro and macro-scales use either a bottom-up or a top-down approach. The gap between micro-level (e.g., field or farm) and macro-level (e.g., region or market) and their interactions has barely been bridged by the few models designed for multi-scale assessments (Laborte et al., 2007). The TOA–ME described in this paper achieves the micro–macro-linkage using a multi-scale approach that includes both bottom-up (e.g., farm to market) and top-down (e.g., market to farm) analyses.

Another example of a multi-scale model is the System for Environmental and Agricultural Modeling; Linking European Science and Society – Integrated Framework (SEAMLESS-IF, Van Ittersum et al., 2008). The SEAMLESS-IF couples bio-physical models (e.g., APES), bio-economic farm-level models (e.g., FSSIM) and market level models (e.g., SEAMCAP, CAPRI). The SEAMLESS-IF is based on simulation of representative farm types derived from the EU’s Farm Accountancy Data Network (FADN). Land-based differences in agricultural production systems are defined in land capability classes. A statistical procedure is used to allocate non-spatial farm types to land capability classes (polygons). These results are up-scaled to the regional scale based on area-weighted aggregation or further aggregated to the whole EU (Uthes et al., 2010).

SEAMLESS-IF has a coarse representation of farm-level decision-making and which scope of analysis is the whole EU or its NUTS (EU nomenclature of territorial Units for Statistics.). In contrast, the TOA–ME uses spatially-explicit data that represents the heterogeneity of the farm population, which enables the assessment of distributional impacts of policy or technology interventions. While the TOA–ME’s scope of analysis is a region such a watershed, a key feature is that the TOA–ME provides a transparent framework that can be applied to any system in any region of the world. However, a frequent limitation for the application of the TOA–ME, particularly in developing countries, is the availability of data. Spatially-explicit IAM, such as the TOA, require highly detailed data that are generally available only from special purpose surveys. In order to deal with this limitation, Antle and Valdivia (2006) developed a minimum-data (MD) approach to agricultural system modeling which can be implemented using data that are usually available from secondary sources (e.g., previous studies, census, etc.) to characterize the distribution of returns for competing land use and management activities in the farm population. They applied the MD approach to the analysis of ecosystem service supply.

Fig. 9. Spatial distribution of effects on poverty for the base scenario and combined rural development and fertilizer scenario, at the base and market equilibrium prices for Machakos, Kenya (excludes non-agricultural area).
and concluded that this approach could provide information to policy makers within the degree of accuracy necessary for policy making. The MD has been applied to the analysis of ecosystem services supply, technology adoption and technology impact assessment. The MD has been applied to the analysis of ecosystem services supply, technology adoption and technology impact assessment. The MD has been applied to the analysis of ecosystem services supply, technology adoption and technology impact assessment. The MD has been applied to the analysis of ecosystem services supply, technology adoption and technology impact assessment. The MD has been applied to the analysis of ecosystem services supply, technology adoption and technology impact assessment. The MD has been applied to the analysis of ecosystem services supply, technology adoption and technology impact assessment. The MD has been applied to the analysis of ecosystem services supply, technology adoption and technology impact assessment. The MD has been applied to the analysis of ecosystem services supply, technology adoption and technology impact assessment.

Table 4
Spatial distribution of poverty (headcount poverty index, %) and nutrient depletion (N loss kg/ha/season) disaggregated by village and aggregated at regional level for the base and the combined rural development and fertilizer scenarios at the base prices and at the market equilibrium prices for Machakos, Kenya.

<table>
<thead>
<tr>
<th>Village</th>
<th>Headcount HPI (%)</th>
<th>Rural Development + Fertilizer Scenario</th>
<th>At base prices</th>
<th>At market equilibrium Prices</th>
<th>Nutrient Depletion Base Scenario</th>
<th>Rural Development + Fertilizer Scenario</th>
<th>At base prices</th>
<th>At market equilibrium prices</th>
</tr>
</thead>
<tbody>
<tr>
<td>Machakos</td>
<td>88.04</td>
<td>55.43</td>
<td>–37.04</td>
<td>66.30</td>
<td>24.69</td>
<td>12.35</td>
<td>36.70</td>
<td>29.13</td>
</tr>
<tr>
<td>Kononyweni</td>
<td>89.58</td>
<td>64.12</td>
<td>–28.42</td>
<td>73.38</td>
<td>18.09</td>
<td>10.34</td>
<td>34.78</td>
<td>26.12</td>
</tr>
<tr>
<td>Kasikeu</td>
<td>83.38</td>
<td>47.50</td>
<td>–43.03</td>
<td>63.38</td>
<td>23.99</td>
<td>19.04</td>
<td>31.49</td>
<td>24.40</td>
</tr>
<tr>
<td>Kiamo</td>
<td>81.03</td>
<td>41.38</td>
<td>–48.94</td>
<td>53.45</td>
<td>34.04</td>
<td>14.89</td>
<td>23.13</td>
<td>18.75</td>
</tr>
<tr>
<td>Matuu</td>
<td>45.91</td>
<td>10.23</td>
<td>–77.72</td>
<td>12.95</td>
<td>71.78</td>
<td>5.94</td>
<td>32.43</td>
<td>28.07</td>
</tr>
<tr>
<td>Kibwesi</td>
<td>75.83</td>
<td>33.33</td>
<td>–56.04</td>
<td>39.17</td>
<td>48.35</td>
<td>7.69</td>
<td>29.12</td>
<td>22.96</td>
</tr>
<tr>
<td>Region</td>
<td>76.10</td>
<td>42.05</td>
<td>–44.74</td>
<td>52.55</td>
<td>30.95</td>
<td>13.80</td>
<td>32.01</td>
<td>25.38</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Scenario</th>
<th>At base pricesa</th>
<th>At equilibrium pricesb</th>
<th>Differenceb</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>% Change poverty</td>
<td>% Change nutrient dep.</td>
<td>% Change poverty</td>
</tr>
<tr>
<td>Rural dev. + fert.</td>
<td>–44.74</td>
<td>–20.73</td>
<td>–30.95</td>
</tr>
</tbody>
</table>

Note: Standard deviations in parenthesis.

Table 5
Effects of policy scenarios on poverty and nutrient depletion at the base and market equilibrium prices for the region of Machakos (aggregate results).

<table>
<thead>
<tr>
<th>Scenario</th>
<th>At base prices</th>
<th>At equilibrium prices</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>% Change poverty</td>
<td>% Change nutrient dep.</td>
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<tr>
<td>Rural dev. + fert.</td>
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<td>–30.95</td>
</tr>
</tbody>
</table>

References