Integrating GIS-based field data and farm modeling in a watershed to assess the cost of erosion control measures: An example from southwest Germany

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Abstract: Policy measures regulating agricultural production are becoming increasingly important in the control of erosion and water runoff. In order to enable planners and other authorities to implement such measures efficiently, detailed information regarding the relevant costs and benefits is necessary. However, economic models to date have tended to utilize a spatial resolution that is insufficient to reveal the effects of such measures on a micro scale. Farming practices, like cross-slope cultivation, filter strips, or field divisions, exert varying impacts on small spatial structures. The benefits and costs of such measures depend to a large degree on local conditions, such as field size and slope. Environmental models as well as economic modeling must take these factors into account. This paper presents a novel approach called CULTIVASIM that directly incorporates field-level topographic and geometric data into a farm economic model. This allows researchers to gain insight into the cost structure of these tasks on a field level as well as a farm level when considering whole-farm adaptation possibilities. Results show that while filter strips lead to relatively uniform costs in relation to area, the costs of field division and cross-slope cultivation vary greatly depending on the field geometry. This information should be included when planning control measures and designing compensation schemes. This new model approach can be used to calculate the economic costs and benefits of using precision conservation practices across the landscape.

Key words: cost—CULTIVASIM—erosion control—field shape—geographical information system (GIS)—precision conservation

Economic models often neglect the field shape and size in evaluating the costs of erosion control measures.

They tend, in general, to work at a lower grain or spatial resolution than do models from landscape ecology (Vermaat et al. 2005), limiting the integration of the results between models from different disciplines. In research on issues related to multifunctionality, however, the establishment of links between the appropriate scales is critical (Zander et al. 2007). In the course of precision conservation, new technologies like geographical information systems (GIS), remote sensing, and precision farming allow measures to be implemented on a micro scale (Berry et al. 2003, 2005; Delgado and Berry 2008). Economic models using input data with low spatial resolution might disguise variation in economically relevant variables, such as the actual cost of certain agri-environmental measures. Thus, to evaluate the techniques of precision conservation economically, it is necessary to develop methods that use high-resolution information about the physical properties of the landscape for application to economic models, facilitating results that are more precise.

This paper presents an approach that transforms information about physical landscape properties taken directly from a GIS—such as maps of field shapes and a digital elevation model—into a suitable form that can be interpreted by a farm economic model. The lowest spatial unit we use within the farm economic model is the field. Many agri-environmental measures, such as those dealing with erosion, are typically implemented at the field level. For example, changes in cultivation technologies, like conservation tillage or the establishment of conservation practices like filter strips, are closely related to the topographic and geometric properties of a specific field. So far, there are no modeling procedures to assess these measures at this level while simultaneously relating them to the whole farm. Researchers should not simply assess measures at the field level alone because of the numerous linkages within the farming system; the implementation of specific measures in one field might have implications for other parts of the farm as well. The watershed level is of interest because from an ecological perspective, it is the unit that represents the ecological and physical links between the fields.

Why do we stress the field as the unit of analysis? From an economic point of view, different field shapes and sizes may have considerable impact on the cost of production, especially the cost of machinery and labor. In a number of European regions and elsewhere around the world, field sizes are on average quite small—often too small from the viewpoint of an optimizing farm manager. On the other hand, field sizes, shapes, and slopes are quite diverse, even within small areas such as villages and small watersheds. Under such circumstances, it matters from an ecological viewpoint where certain agri-environmental measures take place in the landscape (a point which we take as self-evident). Furthermore, the concrete location might also have important implications for the costs incurred. Note that, in spite of land consolidation programs and other possibilities, field sizes and shapes are in many cases fixed for the near future as well as the long term; current trends favor bigger units, often at the expense of erosion control. In most cases, the very small fields that exist in some parts of Germany have their origin in a long tradition of splitting the property for inheritance purposes, without consideration of erosion control.

There is considerable literature on the modeling of farms and watersheds (see, for example, the overview of Rossing et al. 2007); many studies use GIS for economic assessments (e.g., Bateman et al. 2002; Herrmann et al. 2003). However, these mod-

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els generally do not consider the economics of single fields. Most reports in the literature use either raster data or a set of sample fields to construct the economic model. For example, Rao et al. (2000) combine a GIS with management and economic modules in the Erosion Productivity Impact Calculator (EPIC) model in order to evaluate farm management practices with respect to erosion and nitrogen leaching. Since they work on a 50 m (164 ft) raster, they do not investigate the effect of different field shapes and sizes. Delgado and Bausch (2005) use precision conservation techniques such as remote sensing and modeling to evaluate how advanced management practices that accounted for soil variability increased nitrogen fertilizer use efficiencies and reduced nitrate leaching by 47%. Management zones that accounted for spatial variability in soil and crop yield also improved nitrogen-use efficiencies and reduced nitrate leaching by 27% (Delgado et al. 2005).

In a precision conservation setting, Kitchen et al. (2005) calculate farming profitability in a raster-based model, yet they do not consider field size and shape as an influencing factor for machinery cost. The spatial decision support system developed by Lant et al. (2005) includes spatial data in a linear programming model; however, it lacks sufficient spatial resolution to consider small structures like grass strips. Similar to Rossing et al. (2007), the work of Lant et al. is based on raster geometry and is consequently not designed to evaluate the economic effect of different field shapes.

Lehtonen et al. (2007) combined a sector model on a regional scale with a field-scale nutrient transport model to assess the ecological and economic effects of policy changes for two regions in Finland. However, they did not calculate the effects for each field but rather used averages for typical crop-field combinations that they then scaled up to obtain the effects on a regional level. A similar approach was used by Pacini et al. (2004), who used a set of representative field categories to assess the environmental impacts of policy scenarios. The RAUMIS (regionalized agricultural and environmental information system for Germany) model (Weingarten 1995) considers only the regional level.

Botterweg et al. (1998) evaluated various measures used to prevent erosion, like green cover or omitting plowing in autumn, but their assessment examined the catch-

ment area and not the individual field level. Gassman et al. (2002) modeled different cultivation practices using a combination of a farm-level economic model and two natural science models, but only one of the latter takes the individual field into account. Similarly, the NELUP (Natural Environment Research Council Economic and Social Research Council Land Use Programme) model (Oglethorpe and O'Callaghan 1995) considers only the farm level. Qiu (2005) uses a multi-criteria optimization model consisting of field-level economic calculations and a biophysical simulation model to assess the tradeoffs between income generation and environmental targets. However, he does not address the impact of different field shapes or sizes.

Van Wenum et al. (2004) optimized the allocation of biodiversity measures across fields of a representative farm using a mixed integer model. They distinguished several border regions and the center field, but their approach did not consider various field shapes. MODAM (Multi-Objective Decision support tool for Agro-ecosystem Management) (Kächele and Dabbert 2002) considers the economic effects of policy measures on different fields of farms but does not take their size and shape into account as influencing factors.

Some literature exists on the economics of field size and shape. This literature deals mainly with the evaluation of land consolidation programs (see Kapfer and Kantelhardt 2007 for an overview) and with compensation for worsened field structures due to infrastructure construction (Beckmann and Huth 1988). The latter focus, however, not on measures taken to prevent erosion but on a more general evaluation of the economic performance of different field structures. The most similar approach to the one presented in this paper was conducted by Kapfer (2007), who also used data from a GIS to calculate cultivation costs on a field level.

The motivation to develop the methodology for the current study emerged from a case study in southwestern Germany. The study area covers a watershed near the village of Massenbach that is situated in a loess landscape in the state of Baden-Württemberg, near the city of Heilbronn. The small watershed investigated here lies east of the village and comprises 237 ha (586 ac), 165 ha (408 ac) of which is arable land; the rest is forest, grassland, and settlements. Within the water-

shed, 115 fields are farmed by 17 farmers. All of the farmers also cultivate fields outside the watershed. Within the watershed, there have been severe erosion and runoff problems. Farmers and policymakers at different levels as well as scientists have developed an intense interest in how to best deal with these problems. This paper presents the results of the new methodology, which allows for the coupling of GIS-based field-scale modeling with farm modeling. This approach was used to examine the effects of three measures against water runoff and erosion. For cross-slope cultivation, cropping processes are carried out perpendicular to the slope to avoid creating furrows for water runoff. Field divisions split a field into two or more parts transverse to the slope to reduce the effective erosive field length. Finally, filter strips are created at the lower border of a field and sown with grass to retain effluent water and soil.

Materials and Methods

This section presents the modeling approach called CULTIVASIM (cultivation simulator) that has been set up at the Institute of Farm Management at the University of Hohenheim and involves a number of steps and elements. First, an overview of the necessary data is provided, and the data flow is represented. Then the different steps in generating gross margins, depending on field size and shape, are described. This description starts from a conceptual discussion of the factors that influence actual labor need in plant production and proceeds to the methods needed to generate a simplified field shape and working directions that can be used to calculate actual labor time needed. The integration of these data into a farm model is then discussed with reference to a nonlinear extension using maximum entropy and the erosion control measures that are implemented in the empirical application of the model.

Data Sources and Data Flow. Spatial data for the relevant fields are essential to this approach. We had access to a digital elevation model as well as a digital map containing real cropping units in the form of polygons. Information about the relationship of the fields to specific farms and about cropping limitations (e.g., if the field was occupied by a permanent crop) was obtained from the Integrated Administration and Control System, which was established to administer Eurpean Union agricultural policy and
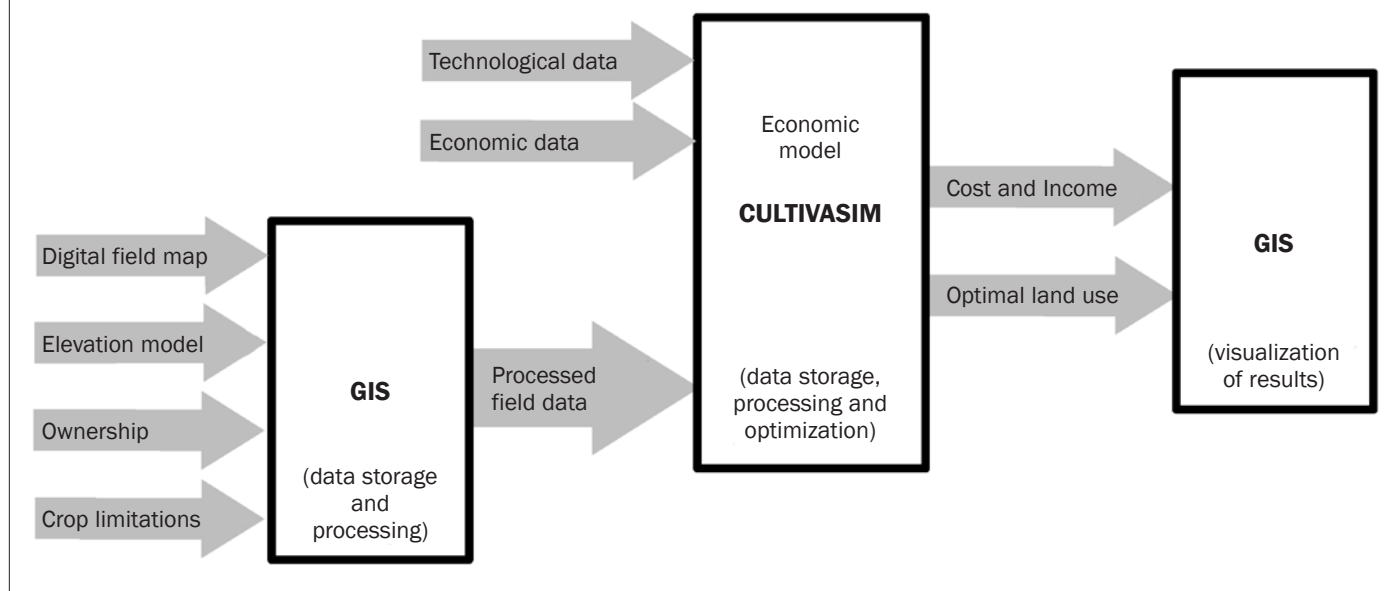
includes data obtained directly from farmer applications for EU payments.

Technical and economic data on cropping activities are needed to assess the use of the fields. Information about crops, prices, yields, number of cultivation passes, machinery size, and machinery costs were obtained by surveying the farms. This information set was expanded by standard farm management data: prices and the time required for machinery use were taken from Kuratorium für Technik und Bauwesen in der Landwirtschaft (KTBL) (2001), KTBL (2002), and KTBL (2004). Prices for hired machines and labor were fixed according to Landesverband der Maschinenringe in Baden-Württemberg e.V. (2003). Driving speed and turning time were obtained from Jäger (2000). Prices and quantity of pesticides were taken from WLZ-Raiffeisen AG (2002). Cropping procedure data were completed with the data available in Landesanstalt für Entwicklung der Landwirtschaft und der ländlichen Räume (LEL) (2001a), LEL (2001b), LEL (2003), and Regierungsbezirk Mittelfranken (2004). Some product prices were also taken from BW-agrar (2004).

The general data flow diagram is provided in figure 1. Spatial data on the field characteristics (field shape and digital elevation model, which is the basis for calculating field slopes) were stored and processed in a GIS. The aim of this processing was to produce polygon field shapes in a format suitable to calculate labor time needed for cultivation

and to determine the direction of cultivation. This processed field data was then transferred to the farm economic model named CULTIVASIM. In addition, technological and economic data from other sources were used in CULTIVASIM. The economic model first calculates gross margins for all cropping activities in each field, differentiated by the erosion control measures applied. Farm optimization was carried out within the model so that optimal land use and total gross margin were obtained for every farm. For the interpretation of the economic results, the data were again transferred to a GIS.

Gross Margins Determined by Field Shape and Size. The gross margin is defined as the difference between the returns and the variable costs of an activity; it serves as a good indicator for the relative profitability of a crop. In economic models of plant production, gross margins are often differentiated by land quality, which in turn influences yields and fertilization. Other data used in the calculations tend to be based on standard data and are often assumed to be uniform. In principle, the model offers the possibility to differentiate yields and revenues according to soil characteristics. The main soil types in the study area are calceric regosols, haplic luvisols, and terric anthrosols, all from loess. In all parts of the location, loess horizons are still at least 60 cm (2 ft) thick, so farmers did not encounter significant yield differences in different parts of their fields. Thus, from the farm survey, it was not possible to relate different
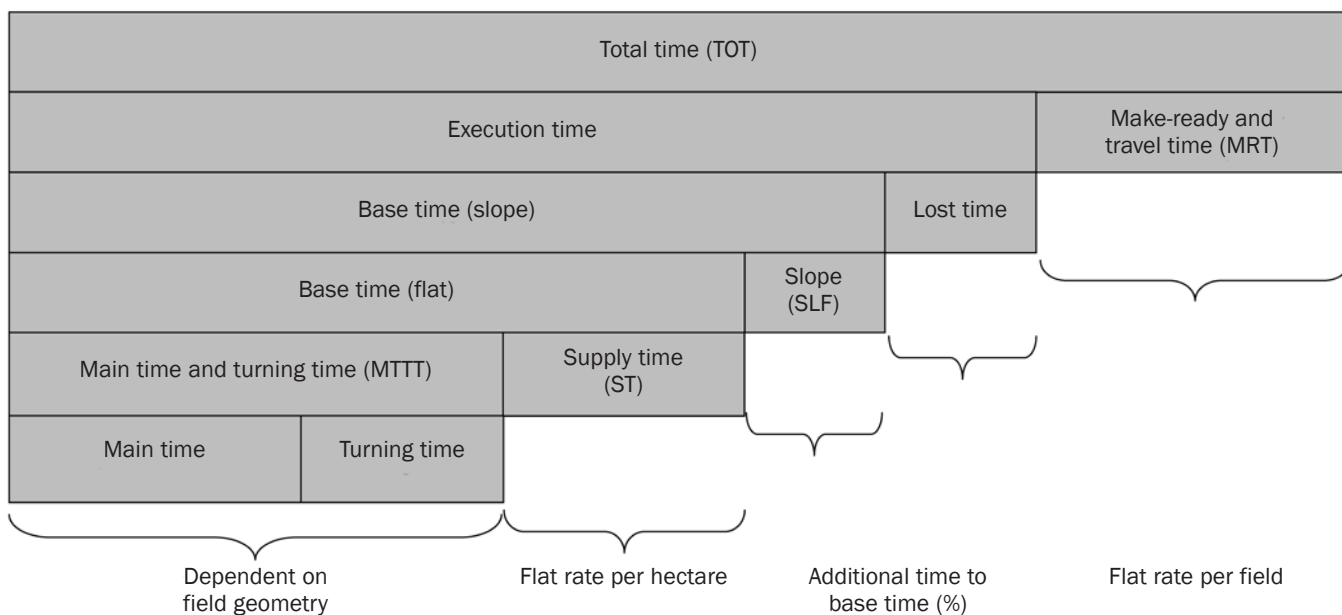
yields to soil quality, although such differentiation would have been desirable. However, this shortcoming has been accepted since the focus of the study was field sizes and shapes.

Field sizes and shapes were quite diverse within our study area. Field size ranged between 0.08 ha (0.2 ac) and 5.4 ha (13.3 ac). Field shapes varied from nearly square fields (with a length to width ratio of 1:1) to very long pieces of land (with a length to width ratio of 18:1). The empirical objective of this study was to evaluate measures within crop production contributing to lower runoff and less erosion. Such measures often depend on field topography, with respect to both the desired environmental effects and their economic implications. Measures that fall into this category include field divisions and cross-slope cultivation.

The most important influence that topographic factors have on the gross margin is via machinery costs. In addition, yield losses near the borders or on the headland play a role. The cost of machinery use was obtained by calculating the time needed for the processes; for example, fuel expenses depend largely on the time the tractor is in use. In addition to real productive working time (the so-called main time), other elements include turning time and supply time. Additional time is needed when the field is on a slope, and further time losses, such as those caused by jamming, have to be considered. The time scheme used in the model was adapted from KTBL (2002) and is shown in figure 2.

Figure 2

Time scheme for the calculation of cultivation costs.

Total time (TOT)				
Execution time				Make-ready and travel time (MRT)
Base time (slope)			Lost time	
Base time (flat)		Slope (SLF)		
Main time and turning time (MTTT)	Supply time (ST)			
Main time / Turning time				

Dependent on field geometry — Flat rate per hectare — Additional time to base time (%) — Flat rate per field

Note: This is a modified version of a figure from Kuratorium für Technik und Bauwesen in der Landwirtschaft page 79 (2002).

Jäger (2000) developed an interactive Web site to calculate main time and turning time of cultivation processes in relation to the field's corner coordinates. However, data have to be provided manually, and only a limited number of shapes are suitable. Our model uses an improved version of Jäger's algorithm, which has been adapted to different working directions and multiple shapes. Before we describe this, we must first discuss the data processing performed on the field data to generate information about the coordinates of the field that can be used for time calculation and to derive the working direction.

The first step is to simplify the shape of the field in order to minimize the probability of errors in detecting the direction of cultivation. Vertices, which exist on maps but do not influence machinery use on the field, can "disguise" the longest border, which is used to determine the working direction and would thus lead to unrealistic incorrect results.

As a rule, all corner points whose adjoining border directions differ by less than 8° are removed. In addition, many vertices that are very close to each other (mainly occurring to round off the corners) can hamper the detection of headlands (see the explanation below). These vertices are removed and replaced by their common center point. For fields larger than 0.5 ha (1.2 ac), a threshold of 8 m (26.25 ft) was chosen. If the vertices were closer than that, they were removed. For smaller fields, this value would have been too large because it caused regular headland borders to be erased. Thus, for fields smaller than 0.5 ha, the distance threshold of two vertices was set to

$$D_{min} = 0.1 \times A^{0.5} , \qquad (1)$$

with D_{min} denoting the minimum distance between remaining vertices (in meters) and A denoting the area of the field (in meters squared).

The new corner points were calculated as the mean of the Cartesian coordinates of the former points. The field sizes typically become a little smaller by the end of the cleaning process. Since the area of the field is calculated first and the final time calculation takes this correct value into account, the error is not severe.

Next, the direction of cultivation is needed in order to calculate cultivation time, where this is derived from the geometry of the field. It is assumed that the farmer cultivates the fields in the direction of greatest length because this usually minimizes the time needed and thus the costs incurred. The direction of the longest edge is a good proxy for the farmers' preferred working direction in the field (see figure 3). The previous section described how the borders were simplified in advance so that vertices that hardly influence the shape of the field do not prevent detection of the direction of cultivation.

The slope and the direction of the slope were calculated using a digital elevation model (DEM). For the eastern part of the area, a DEM with a 5 m (16.4 ft) resolution was available, while for the adjacent parts, only a less detailed model with a 50 m (164 ft) raster was at our disposal. Consequently, those parts for which we only had access to the less differentiated model were interpolated to a 5 m raster with the "spatial analyst" function of Environmental Systems Research Institute (ESRI) ArcMap. For this purpose, we used the "spline regularized" method within ArcMap with 12 neighboring points and a weight of 0.1. The slope could be derived from the resulting model for the entire area with the help of the "surface analysis − slope" function in the "percent" mode and a Z-factor of one. The average slope of each field was calculated as the mean of the slopes of all raster pixels belonging to this field by using the "zonal statistics" method.

Deriving the direction of the average slope was more complicated (see figure 4). Out of the interpolated DEM with the help of the "surface analysis − aspect" function, we calculated the slope direction of each raster

Figure 3

Cleaning the field borders and detecting the working direction. Border vertices on almost straight borders as well as very near points have been removed to ensure a correct detection of the working direction according to the longest border edge.

Eliminate straight line points

Eliminate near points

Detect direction of longest edge
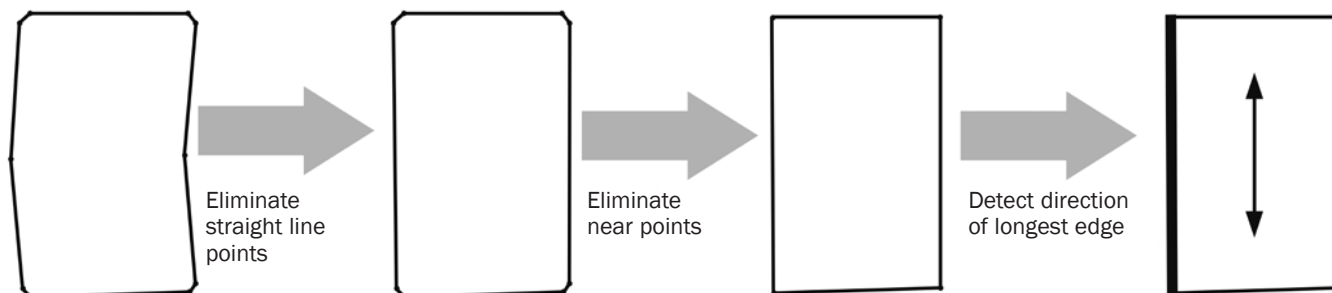
cell. These values were then brought into the interval of 0° to 180° by subtracting 180° if the value was >180° (modulo division by 180°). This was necessary to treat directions that differed by 180° as the same directions (a so-called semicircular direction range) because in agricultural practice, such cases are equivalent with respect to the calculation of the machinery time.

While these directions are meaningful in an agronomic sense, they pose a problem for computation. In order to derive field slopes from the slopes of raster cells, a vector addition must be performed. With a usual vector mean, the angles 0° and 180° would neutralize each other, although they should be considered as the same direction and aggregated. For this reason, the semicircular vector mean was calculated, which includes an intermediate step (Agterberg 1974). The direction values were multiplied by two, which again results in circular angles. On these modified angles, the method of vector addition

was then applied to calculate the average of the modified angles for each field. This was done by converting the angles to Cartesian coordinates, then calculating the sum of the x and y coordinates. The resulting vector was transferred back to polar coordinates, resulting in the predominant direction of field slope. Finally, the resulting angle was divided by two to compensate for the multiplication by two performed in the second step.
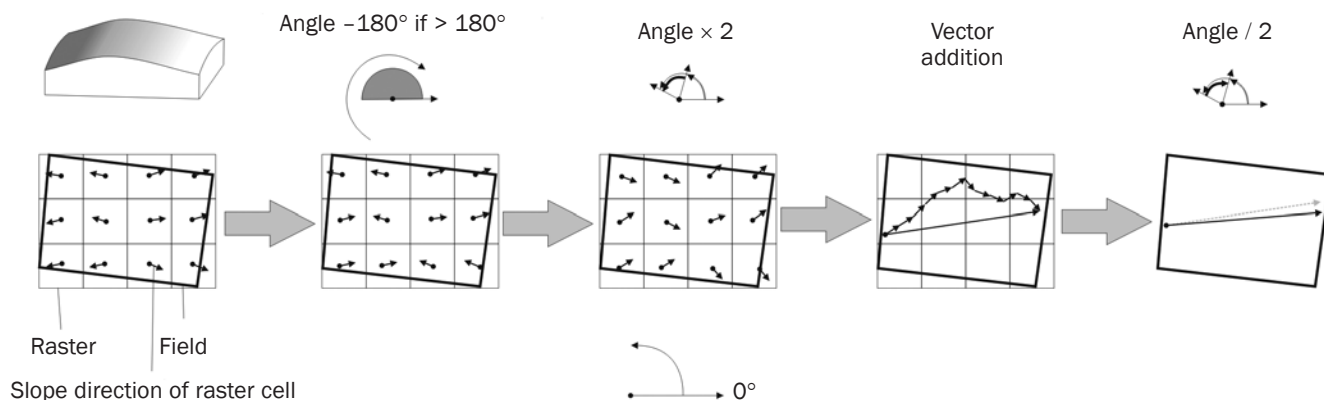
To obtain the cultivation cost, the time needed for cultivation has to be calculated. This is done using a script programmed in GAMS (General Algebraic Modeling System) based on the algorithm of Jäger (2000). The cultivation of headlands is especially time-consuming for farmers, so the algorithm used must detect headlands. The algorithm also has to be capable of detecting headlands of different field shapes, not only rectangles. The principle of the algorithm is to measure the angle between each field border and the working direction. If the angle is larger than

10°, it is assumed that this edge consists of a headland. If there are several headlands on adjoining edges whose angles differ by less than 30°, they are treated as one headland. Headlands are assumed to be 9 m (29.5 ft) wide for cereals or 12 m (39.4 ft) wide for sugar beets, maize, and potatoes.

The time needed for cultivation is then calculated depending on the occurrence of headlands and the size of the remaining main field and taking into account working widths, driving speeds, and turning times. The values from Jäger (2000) have been used as parameters for driving speeds and turning times. The lost time was set to zero as no information was available. However, the values for make-ready and travel time and supply time have been calibrated in a manner such that the total time fits the values given in KTBL (2002) for fields of 1 ha (2.47 ac) and 5 ha (12.4 ac). Therefore, the lost time is implicitly included in the supply and make-ready and
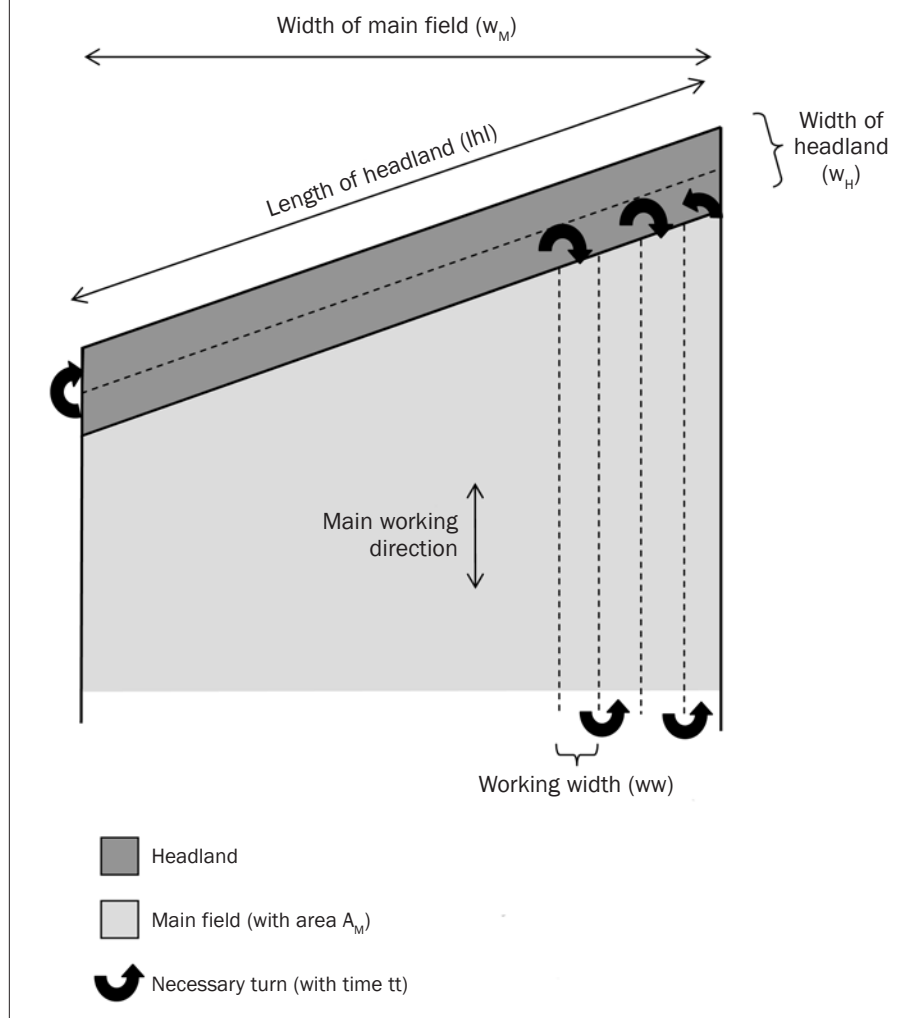
Figure 4

Method of aggregating slope directions for each field. The slope angles of the raster cells (obtained from a digital elevation model) had to be aggregated on field level. To obtain semicircular vector mean, the angles were brought to the range of 0° to 180° and multiplied by two before aggregation. Finally the result was divided by two.

Angle −180° if > 180°

Angle × 2

Vector addition

Angle / 2

Raster   Field

Slope direction of raster cell

0°

Figure 5

Size measures of a field used for time calculation.

Width of main field (w_M)

Width of headland (w_H)

Length of headland (lhl)

Main working direction

Working width (ww)

- Headland
- Main field (with area A_M)
- Necessary turn (with time tt)

travel times. A depiction of important field size measures is given in figure 5.

The mathematical expression for the time calculations is

$$MTTT = \left[\frac{A_M}{ww \times v_M} + \left\lceil \frac{w_M}{ww} \right\rceil tt + \sum_h \left(\frac{lhl}{v_H} \left\lceil \frac{w_H}{ww} \right\rceil + \left\lceil \frac{w_H}{ww} \right\rceil tt \right) \right] \times \frac{1}{A} , \quad (2)$$

with *MTTT* denoting the main time and turning time (s m⁻²), A_M as the main field area (m²), A as the total field area (m²), *lhl* as the headland length (m), *ww* as the working width (m), w_M as the main field width (m), w_H as the headland width (m), v_M as the speed on the main field (m/s), v_H as the speed on the headland (m s⁻¹), *tt* as the time for one turning process (s), *h* as the headland index, $\lceil \ \rceil$ is the ceiling function, and

$$TOT = (MTTT + ST) \times SLF \times A + MRT , \quad (3)$$

where *TOT* is the total time (s m⁻²), *ST* the supply time (s m⁻²), *SLF* the slope factor (dimensionless), and *MRT* the make-ready and travel time (s).

This calculation was performed for each field and each cultivation process. As the farmers in the study area use similar machines, it was only necessary to define each process once. If there were different machinery sizes in the region, an extension of the model would have been adequate.

Finally, the gross margins for every crop and every field can be calculated. The total time per hectare and field was then multiplied by the costs per hour for the tractor and added to the other per hectare costs for one pass of the field. Labor costs were not included here, as they were evaluated later with the farm economic model. A by-product of this type of time calculation is the fraction of land that belongs to the headland and to land that is

near the border. For border losses, an area of 2 m (6.6 ft) width along the borders, where a yield loss of 10% is assumed, is taken into account. On the headlands, a 20% yield loss is taken into account. Together with other flat-rate costs (such as costs for seed, fertilizer, or pesticides) and other revenues (such as public payments), the gross margins were calculated. Altogether, these calculations result in a sophisticated gross margin calculation for every crop on every field, forming the basis for the optimization model.

Optimization with an Extended Linear Programming Model. Linear programming (LP) is an established technique that allows for the optimization of an objective function that is subject to different constraints (see e.g., Hazell and Norton 1986). Numerous applications exist to simulate farmers' decision-making, resting on the assumptions that they maximize profits and comply with certain factor restrictions, such as limited labor capacity or limited farm land. While investment decisions can be taken into account in principle, our application, similar to many studies in the literature, focuses on the short- and medium-term adaptations of farmers. Time is not directly implemented, so the analysis is comparative static. We used this approach to model each farm within the watershed separately. The structure of the model was identical for all four scenarios modeled.

The LP model consists of production activities that the farm can perform. Each activity is characterized by a gross margin value and the technical coefficients associated with it. The technical coefficients describe the requirements of the production activities with regard to fixed factors and relate the production activities to field- and farm-level restrictions. An overview of the LP model structure is given in table 1. Effects on soil loss are not included here, as this model covers only the calculated cost of providing conservation measures. If one is also interested in the effects on erosion reduction, one could couple CULTIVASIM to an erosion model, which is the topic of a different publication (Aurbacher 2006). The endogenous variables (*X*) denote the optimal amount of each activity after optimization. For field-cropping activities, these values are long-term shares of the total available area of a field, presented in hectares.

The standard LP model described above may be underdetermined if several identical

Table 1

Structure of the linear programming (LP) model for one field and one farm. The columns represent the variable activities the farm can execute, and the rows show the capacities by which the farm is restricted.

		Activities of plant production (25)						Permanent crops (1)	Grassland (1)	Feeding animals (1)	Sale of fodder (1)	Activities of animal production (2)		Activities of agricultural policy (5)			Right-hand side
		Wheat	Wheat_cs*	Sugar beet	Sugar beet_cs†	Set aside	...					Dairy cow	Pig	Cereal payment	Small-scale producer	...†	
Gross margin		+‡	+	+	+	+	+	+	−	−	+	+	+	+			
Restrictions on field level (22)§	Arable land	+	+	+	+	+										+	+
	Grass-land								+							+	
	...																
Restrictions on farm level (19)‖	Labor	+	+	+	+	+	+				+	+	+			+	
	Sugar quota			+	+											+	
	Stable											+	+			+	
	Fodder								−	+	+						0
	...																

Note: These variables were included in the model: crop rotation activity, winter wheat, winter wheat (cross-slope), winter barley, winter barley (cross-slope), summer barley, summer barley (cross-slope), oats, oats (cross-slope), corn, corn (cross-slope), sugar beet, sugar beet (cross-slope), potatoes, potatoes (cross-slope), field pea, field pea (cross-slope), rapeseed, rapeseed (cross-slope), onion, onion (cross-slope), rapeseed as renewable resource, rapeseed as renewable resource (cross-slope), arable forage, filter strip, set aside, blackcurrant (permanent crop), grassland, feeding of animals, sale of fodder, dairy cows, pigs, cereal payment, corn payment, legume payment, and use of small-scale producer scheme.

* cs indicates two crops with cross-slope cultivation as examples for activities with erosion control measures.

† Dots indicate that some of the activities were omitted because there were too many to show.

‡ Plus signs (+) indicate a positive contribution to the gross margin, a positive demand for the factor or a positive factor endowment; minus signs (−) indicate the opposite. Zero or empty cells are given where no demand for that factor is needed or no initial endowment is provided.

§ Restrictions included on field level: Area, area in crop rotation, area grassland, area permanent crop, area filter strip, minimum use of area, activities not related to area, crop rotation limit cereals, crop rotation limit wheat, crop rotation limit winter barley, crop rotation limit summer barley, crop rotation limit oats, crop rotation limit row crops, crop rotation limit sugar beet, crop rotation limit potatoes, crop rotation limit onion, crop rotation limit sugar beets and rapeseed, crop rotation limit rapeseed, crop rotation limit legumes, obligation to cross-slope cultivation, obligation to parallel-slope cultivation, and obligation to measure.

‖ Restrictions included on farm level: labor (spring), labor (early summer), labor (late summer), labor (autumn), labor (total), stable places (cows), stable places (pigs), obligatory set-aside, yield limit for small-scale producer scheme, set-aside limit, potato quota, sugar beet quota, fodder, corn yield, cereal payment entitlements, corn payment entitlements, legume payment entitlements, and set-aside payment entitlements.

fields exist. In such a case, the model would imply an infinite number of solutions with equal target values that differ with respect to the values exhibited by the production activities. The results reported by the solver would depend unpredictably on rounding errors and chance. To counteract this, the model approach has been extended by a maximum entropy term, making the problem nonlinear.

The entropy equation is a measure of the uniformity of a distribution (Kapur 1989) and has the form

$$E = -\sum_i p_i \log p_i \quad , \qquad (4)$$

where *p* is a probability distribution over all possible cases, *i*. The principle of maximum entropy uses this measure as the target value and is often capable of finding reasonable solutions for ill-posed problems. It has recently been introduced into various economic applications (see Golan et al. 1996) and was used here to ensure a unique solution in all cases. This equation is multiplied by a weighting factor (β) and added to the target function (*TF*) (equation 5). In equation 5, the *TF* is being maximized. The weighting factor is small (0.03), so the maximization of the total gross margin remains dominant. As the total contribution of the maximum entropy term to the target function is marginal, it has no physical meaning despite ensuring a unique numerical solution. One could, however, interpret the model behavior as a preference of the farmers for an evenly distributed crop rotation on the fields. The system of equations for the model is as follows:

Objective function
max!

$$TF = \sum_u \sum_f \sum_a GM_{u,f,a} \times X_{u,f,a} - \beta \sum_u \sum_f \sum_{a_F} X_{u,f,a_F} \times \log X_{u,f,a_F} \quad , \qquad (5)$$

Restrictions on the field level

$$\sum_a D_{u,rf} \times X_{u,f,a} \leq LimF_{u,f,rf} \quad \text{for all } u,f,rf \quad , \qquad (6)$$

Restrictions on the farm level

$$\sum_f \sum_a D_{a,ru} \times X_{u,f,a} \leq LimU_{u,ru} \quad \text{for all } u, ru \quad , \qquad (7)$$

with *u* denoting the index for the farm units, *f* as the index for the fields, and *a* as the index for the activities. *D* is the demand of a production activity on a factor (the so-called technical coefficient), *X* the extent of activity, *GM* the gross margin of the activity, *rf* the factor restrictions on the field level, and *ru* the factor restrictions on the farm level. *LimF* is the factor limit per field and *LimU* is the factor limit per farm, while *TF* stands for target function, a_F for the activities with relation to area (These are the first 28 activities mentioned in the notes of table 1 [excluding crop rotation]) and β for the weighting factor.

The model endogenously prices the value of land and labor, as these factors, among others, are restricted to the farms. Depending on the farming possibilities, profitability of farming, and costs of complementary inputs,

Figure 6

Field-level costs of cross-slope cultivation in Massenbach.

Costs of cross-slope cultivation (on critical fields)

Cost in € ha⁻¹

- ≤ 0.00
- 0.01 to 100.00
- 100.01 to 200.00
- 200.01 to 300.00
- 300.01 to 400.00
- > 400.00

- Forest
- Settlement area
- Other (uncritical) field
- Direction of slope

N

0 125 250   500 m

shadow prices for the restricted factors are calculated.

Most crop production activities are modeled in several variations so that the effect of the measures against erosion can be studied. The model calculates the optimal extent of each activity and the total gross margins of all farms.

The modeling approach is presented here using the example of three measures that have been tested in practice during the research project. These measures are cross-slope cultivation, field divisions, and filter strips, all of which can be applied to all customary crops in the area. The latter two measures have been modeled in the GIS as scenarios regarding field shape and size, leading to differentially shaped files within the GIS.

Cross-slope cultivation was modeled as an extra activity in the LP model (see table 1). This was carried out by comparing the normal working direction with a cultivation perpendicular to the slope. In the reference run, fields were cultivated in the direction along the greatest length (see figure 3). For cross-slope cultivation, the working direction was rotated by 90° if the field was normally cultivated along the slope (or less than 45° transversely). This usually leads to higher

costs, since the number of turns and the border losses increase.

Generally, modeling was oriented toward the actual implementation of the real measures in the study area. For fields in which erosion has been identified as a pressing issue, but no measures have been implemented, scenarios for field divisions and filter strips have been worked out in the GIS. These critical fields account for 14% of the agricultural area cultivated by the farms included. On the basis of these, the model calculated different optimal farm adaptations.

For the reference run, normal field shapes were included. During the scenario runs, the modified field shapes (e.g., with field divisions) or the different activities (e.g., with cross-slope cultivation) were taken into account. The difference in the total gross margin between the runs provides the cost of the measure. These total costs are then divided by the area in which the measure was required, yielding the cost per area.

All measures could be evaluated twice: once at the field level and once at the farm level. The former includes no optimization of farm activities, as only the gross margins of the corresponding field activities are compared. The latter means that the farms adapt

their activities to the restrictions with the help of the optimization process.

Results and Discussion

The model provides results on two levels. First, gross margin calculations on the field level can be analyzed so that the costs of the measures can be displayed in relation to field size and shape. For farm income losses, however, optimization results are relevant; both types of results are presented below.

Results at the Field Level. The results at the field level contain gross margin calculations for every field. The resulting costs for the most important crops (winter wheat, winter barley, summer barley, maize, sugar beets, potatoes, onions, and rape [also as a renewable resource]), have been calculated and weighted by the crop shares in the reference scenario.

Figures 6, 7, and 8 show the field level costs as maps. The measures have been modeled on those fields that have been confirmed as especially vulnerable to erosion. They are colored white in the maps.

The most important data resulting from calculations on the field level are summarized in table 2. These results show that the costs of the measures differ strongly from

Figure 7
Field-level costs of field divisions in Massenbach.

Costs of field divisions (of critical fields)

Cost in € ha⁻¹
- ≤ 0.00
- 0.01 to 15.00
- 15.01 to 30.00
- 30.01 to 45.00
- 45.01 to 60.00
- > 60.00

- Forest
- Settlement area
- Other (uncritical) field

N

0 125 250   500 m

Figure 8
Field-level costs of filter strips in Massenbach.

Costs of filter strips (along critical fields)

Cost in € ha⁻¹
- ≤ 0.00
- 0.01 to 15.00
- 15.01 to 30.00
- 30.01 to 45.00
- 45.01 to 60.00
- > 60.00

- Filter strip
- Forest
- Settlement area
- Other (uncritical) field

N

0 125 250   500 m

Table 2

Field level costs of the policy measures cross-slope cultivation, field divisions, and filter strips for Massenbach. The unweighted average was calculated over all fields in the catchment. The histogram range stretches across the minimum and the maximum cost for each measure. The values refer to the number of fields in the given cost class.

	Cross-slope cultivation (€ ha^{-1})	Field divisions (€ ha^{-1})	Filter strips (€ ha^{-1})
Minimum	–5	7	10
Unweighted average	102	50	51
Maximum	642	156	170
Histogram of distribution			
0% to 20% of range	41 (77.4%)	18 (35.3%)	34 (64.2%)
20% to 40% of range	6 (11.3%)	17 (33.3%)	8 (15.1%)
40% to 60% of range	3 (5.7%)	13 (25.5%)	3 (5.7%)
60% to 80% of range	0 (0.0%)	2 (3.9%)	3 (5.7%)
80% to 100% of range	3 (5.7%)	1 (2.0%)	5 (9.4%)

field to field. For field divisions and filter strips, the average cost was about €50 ha^{-1} ($29 ac^{-1}) (note the exchange rate was from August 2009, €1 = $1.42). There were some fields with costs of only around €10 ha^{-1} ($6 ac^{-1}), and some costs were as high as €170 ha^{-1} ($98 ac^{-1}). For cross-slope cultivation, the variation was even greater: with an average of about €100 ha^{-1} ($57 ac^{-1}), costs ranged from slightly negative values to more than €600 ha^{-1} ($345 ac^{-1}). All distributions seem to be positively skewed. Thus, a large share of small values is opposed by a relatively small number of cases that exhibit strong upward deviation.

The costs of cross-slope cultivation are determined mainly by the orientation of the field toward the slope. If a field is perpendicular, like the field in the far southeast in figure 6, no costs are incurred. For the fields that are not perpendicular to the slope at the outset, the length to width ratio plays a role. The narrower the field is, the higher the costs. For example, the narrow fields in the north of the area lead to costs of more than €200 to €600 ha^{-1} ($114 to $345 ac^{-1}) and are shown in darker colors.

For field divisions, the size of the field is the controlling factor for cost. The smaller the field, the higher the costs, as the shares of unproductive turning, make-ready, and travel time progressively increase. In figure 7, for example, the field in the southeastern corner had an area of 4.6 ha (11.3 ac) and

is divided into two parts of 3.4 (8.4 ac) and 1.1 ha (2.7 ac). The costs are rather low, measuring about €16 ha^{-1} ($9 ac^{-1}) and €23 ha^{-1} ($13 ac^{-1}). In contrast, the very small field directly adjacent on the western side had an original size of 1.6 ha (4.0 ac) and has been divided into two parts of 0.8 ha (2.4 ac) each. The costs are much higher, €67 ha^{-1} ($39 ac^{-1}) and €59 ha^{-1} ($34 ac^{-1}). The example of the 1.1 ha field shows that not only the size but also the narrowness influences the cost increase. Although the area is only 40% bigger, it is about five times as long as the adjacent western field. As such, it is still rather easy to cultivate, and the cost increase due to the division is rather low.

Finally, the costs of the filter strips are determined mainly by the share of the field that is taken out of production. Fields with relatively large filter strips are burdened with higher costs per hectare of field area, mainly because of the forgone crop yield and the cost of establishing and maintaining the strip. The field in the southeastern corner in figure 8 in this case is an example of a field with huge filter strips (15% of the area); it is thus burdened with about €150 ha^{-1} ($86 ac^{-1}). The fields with smaller filter strips (1% of area) at the southern border of the area incur costs of about €10 ha^{-1} ($6 ac^{-1}).

Results at the Farm Level. After optimizing the farms with the LP model and taking the required measures into account, the actual income losses of the farms were obtained. In contrast to the costs at the field level, the farm structure and possible adaptations of crop rotation and other farm activities play a role at the farm level. Thus, additional information about changes in total farm income can be obtained. For a more effective comparison, these income losses have been expressed in relation to the area considered, where table 3 shows the results.

The income losses on the farm level (for convenience we will call them also "costs") are usually lower than on a field level, as the ability of farms to adapt is taken into account. For example, if cross-slope cultivation is required on sloping fields, crops for which this measure is comparatively costly will be placed primarily on other fields. This is also true for field divisions. With filter strips, the additional time consumption necessary for their maintenance, which has not been included in the gross margin calculation, outweighs the benefits of adaptation. As costs for cross-slope cultivation and field divi-

Table 3

Average income losses for the policy measures of cross-slope cultivation, field divisions, and filter strips for Massenbach at farm level (in € ha^{-1}). The average was calculated over all farms. The histogram range stretches across the minimum and the maximum income loss for each measure. The values refer to the number of farms in the given income loss class.

	Cross-slope cultivation (€ ha^{-1})	Field divisions (€ ha^{-1})	Filter strips (€ ha^{-1})
Minimum	10	15	12
Average income loss	42	44	57
Maximum	114	79	137
Histogram of distribution			
0% to 20% of range	4 (36.4%)	4 (36.4%)	5 (45.5%)
20% to 40% of range	5 (45.5%)	4 (36.4%)	4 (36.4%)
40% to 60% of range	1 (9.1%)	2 (18.2%)	1 (9.1%)
60% to 80% of range	0 (0.0%)	0 (0.0%)	0 (0.0%)
80% to 100% of range	1 (9.1%)	1 (9.1%)	1 (9.1%)

sions are higher for small fields, their effect on the gross margin average is overestimated as they have not been weighted by area in field-level calculations. In the farm-level calculations, however, the model weighted the costs endogenously by the size of the fields, so the average costs of these measures appear to be lower than on the field level. There is a certain leveling out of the costs at farm level, as one farm usually has more than one field under examination. Nonetheless, the range of costs per hectare among the farms is quite high. As can be seen from the histogram in table 3, the distribution of the costs among the farms is positively skewed, which means that most farms encounter income losses below average, while some have to face costs far above average.

Discussion of the Methods. The methods presented go beyond approaches that are already well-known. In the field of agricultural economics, there are different models aimed at calculating the economic effects of cultivation changes due to agri-environmental factors, such as MODAM (Kächele and Dabbert 2002), RAUMIS (Weingarten 1995), or the NELUP (Oglethorpe and O'Callaghan 1995) economic model. While RAUMIS works on a district level, MODAM and Kapfer (2007) consider individual fields. With the exception of the latter, none of these models can calculate cultivation costs directly according to the field geometry. Even Kapfer's (2007) model does not calculate farming time and costs directly with respect to an irregular field shape; instead, it merely transforms the fields into rectangles with the same area and the same share of headlands as before. Since this modifies the assessed number of turns on the headland as well as on the main field, the approach is assumed to be less accurate than the one presented here.

This novel mechanism offers the possibility to evaluate measures that have been designed for precision conservation. All measures that are endogenously linked to field topography, such as cross-slope cultivation, field divisions, or filter strips, can be evaluated for their economic effects as experienced by the farmers, even if they are implemented differently from field to field. For example, differentially sized filter strips, as proposed by Dosskey et al. (2005), can easily be calculated by accessing their characteristics via a GIS. The same is true if the shape of the field is changed (e.g., when grassed waterways or retention ponds are established). This allows us to evaluate

precision conservation measures that have been designed for optimal effectiveness with regard to their costs for the farmers and thus facilitates a balanced optimization according to costs and benefits.

However, there are still some challenges. The field shapes following the application of measures that change the borders of the fields still must be worked out manually in the GIS. For measures other than "geometric" measures (those where the geometry of the field changes), like mulch seeding (not presented in this paper), inclusion in the model is easier; these can be modeled as distinct activities so that the above shortcomings are not relevant. An important topic not yet discussed here is the investigation of various combinations of measures. This can be accomplished with the presented approach by setting up the appropriate field structures in the GIS or by adding activities for combined "nongeometric" measures. Depending on the number of possible combinations for each field, this could become a complex task. However, initial attempts by Aurbacher (2006) show that there is substantial potential for decreasing costs when the most suitable and least expensive measures are selected for each field.

A further step could be the inclusion of field neighbor relations when evaluating headlands in order to examine the cost effects if an adjacent street or meadow can be used to turn the tractor instead of a headland. There is also the possibility of coupling the model results to models from other disciplines, such as erosion models, which is the topic of a different publication (Aurbacher 2006). This offers the opportunity to evaluate some measures with regard to benefits as well as costs.

Evaluation of Measures and Policies. This novel modeling approach allows for the possibility of systematically assessing agricultural measures in the area of erosion and runoff prevention but may also be extended to other topics. Results are obtained at field as well as farm levels.

As the farm level approach takes the adaptation possibilities of the farms into account and includes the opportunity costs of factors utilized, it renders the most realistic measurement of the income forgone by the farms. This figure can be taken as a measurement of costs. The field-level assessment neglects these factors but gives additional insight into the distribution of costs over various fields as well as other influencing factors.

For example, the costs of cross-slope cultivation vary over a much wider range than field divisions, although their average costs are about the same on the farm level. The costs of filter strips also vary in relation to field size, but they are relatively uniform if related to a square meter of filter strip, resulting in costs of ~€0.105 m^{-2} ($0.0139 ft^{-2}).

The costs of erosion-reducing measures are, of course, also dependent on other parameters like machinery costs, crop prices, and crop yield. As the measures lead to an increase in machinery utilization on the fields, an increase in fuel prices or machinery costs raises the costs of these measures. Further, as border losses are increased by field division and cross-slope cultivation and land is taken out of production for the filter strips, a higher yield or crop price level also increases the costs of the measures described. A detailed investigation of these factors, however, is beyond the scope of this paper.

These investigations show that agricultural measures for reducing erosion and runoff lead, in this case, to moderate costs. However, each measure has its own individual profile. This is important for designing agricultural and environmental programs.

Most schemes currently offer flat-rate payments for certain land use restrictions. Our investigations show that this approach is not appropriate for certain measures to prevent surface runoff. If these payment schemes are applied, some farmers would be overcompensated and some undercompensated, resulting in poor acceptance on the one hand and a waste of money on the other. The costs of different fields are not, to a large extent, leveled out with regard to the farm-level. Even if that were the case, flat rate payments would not be appropriate in the case of voluntary participation, as adverse selection on a field-by-field basis could still occur. This leads to the conclusion that new methods beyond flat-rate payments are needed to distribute public payments to farmers. One way could be to calculate the necessary compensation on a field-by-field basis as in the approach shown above. The transaction costs, however, would be very high, as extensive data is required. To overcome this obstacle, we could calculate the typical costs for various sites and farming conditions and differentiate payments according to a set of indicators like field size, slope, width to length ratio, or crop rotation. Furthermore, even novel mechanisms like auctions would be justified

when the distribution of cost rates exhibited high heterogeneity. Thus, this new modeling approach can be a valuable tool for designing new agri-environmental programs not only by calculating the necessary amount of compensation, but also by identifying appropriate compensation mechanisms. It can even be used to estimate the adoption of new programs by farmers.

Summary and Conclusions

This paper presents a novel modeling approach in the field of economic-ecological modeling of policy measures. Specific geographical information, such as slope and field shape, can be included directly in farm models at the field level. Costs and revenues of crop production can be calculated for every field with respect to field size, shape, and slope. The gross margins for every field are used to optimize the farm as a whole. Thus, the costs of measures like cross-slope cultivation or field divisions can be obtained on both the field and farm levels. This facilitates the evaluation of policy measures for each distinct parcel. Beyond that, this model optimizes farms as a whole and takes various adaptation options into account. The resulting land use can be coupled to models from different disciplines in the natural sciences.

This comprehensive modeling system has been tested in the field of erosion control in arable areas. Thus, it has provided many important insights about the size and structure of agricultural income losses due to measures against erosion. This modeling system can, of course, be used for all kinds of agri-ecological questions regarding, biodiversity or groundwater quality. It bridges the gap between economic modeling, used to evaluate larger aggregates, and the view of landscape ecology, which is focused on local structures.

This model can be used as a powerful tool for designing and evaluating measures that affect farmers and whose effectiveness has to be tested on off-farm targets such as ecological features. This can be of practical use for all kinds of policy recommendations, not only for the design of agri-environmental programs at the national level, but also for spatial planning at the regional or local levels. Such approaches could help solve conflicts between agricultural and other stakeholders within the sector or region. This new model approach can help apply and evaluate viable precision conservation practices across the landscape.

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