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Multi-scale system approaches in agronomic research at the landscape level

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Abstract

Spatial multi-scale analyses of actual land use system performance as determined by spatial yield variability reveals the need for landscape research in agronomy. Main 'drivers' of spatial yield variability for five different crops in Honduras, Costa Rica and Ecuador were identified. It is demonstrated how they vary with spatial scales and that landscape-related factors often play a large and significant role in when the variability in yield is determined. These results indicate that landscape experiments in agronomy are relevant. Apart from empirical analysis, spatial–temporal explicit modeling of landscape process dynamics such as water and soil redistribution within a landscape can give insight in the performance of agronomic systems within a dynamic landscape context. For a case study in the South of Spain it is demonstrated how within a landscape this type of research can determine the on- and off-site effects of water and soil redistribution in agro-ecosystems. Only after a spatially explicit multi-scale system analysis and explorative landscape process modeling is completed, relevant agronomic landscape experiments can be designed.

Keywords: Landscape; Agro-ecosystem; Scales; Erosion; Deposition; Modeling

1. Introduction

Traditionally agronomic research is focussed on well-controlled field experiments. The majority of these experiments are fertilizer trials aimed at the construction of dose response relationships of ideally managed crop systems. In the real-world many other growth limiting factors reduce yields far below the 'ideal' yields obtained under such experimental conditions. In the last decades, considerable disciplinary research has put emphasis on solutions aimed at eliminating growth limitations. Agronomists, e.g., have among other issues focused on improving crops and their management (through weed control, fertilizer gifts and their timing, etc.), while soil scientists have tried to improve soil tillage techniques and introduced soil-related site-specific management practices or precision farming (Bouma, 1997). All these techniques have in common that they focus on a subsystem of the complex land use system and are all aimed at the plant or field level.

More recently, there is a tendency towards a more holistic system description aimed at understanding complex land use systems managed by man, i.e., agro-ecosystems (Fresco, 1995; De Ridder et al., 1996). This system approach raises also new research questions, which cannot be easily answered by standard well-controlled agronomic research designs. One of the main questions involves the determination of the system boundaries, the key processes affecting the

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system and their driving forces. It is essential to answer these questions before starting any experiment with or within such systems. Natural ecosystems are complex systems with many non-linear relationships and feedbacks causing apparent unpredictable behavior and responses. Agro-ecosystems are inherently more complex than natural ecosystems because the human factor adds a second source of complexity. When the system functioning is better understood, land management and its impact on the environment can be determined more accurately. Only an increase in knowledge will help in the design of more sustainable agro-ecosystems.

1.1. Scales and agro-ecosystems

Agro-ecosystems are multi-dimensional entities with a distinct spatial distribution. Apart from the spatial dimensions, agro-ecosystems are known to be able to change significantly within decades. These changes may be linked to, human-induced land use/cover change (Pennock and van Kessel, 1997), landscape processes (Veldkamp and Bouma, 2001) or to management (Droogers and Bouma, 1997). When dealing with such multi-dimensional systems the issue of scale becomes relevant too. A scale can be defined as a range of spatial and temporal frequencies. Actors and processes that operate at the same scale interact strongly with another, but the organization and context of these interactions are determined by the cross-scale organization of the system (Peterson et al., 1998). In general, processes operate at characteristic periodicities and spatial scales (Holling, 1992; Peterson and Parker, 1998). Biophysical processes that control plant physiology and morphology often dominate detailed and fast scales. At coarser and often more slower scales (fields and catchments) the competition for nutrients, light and water by crop and weed on different soils dominate. At the largest (less detailed) landscape scale, climate and geomorphologic processes determine the structure and dynamics of agro-ecosystems (O'Neill et al., 1991). This scale dependency implies that characterizing agro-ecosystems might need different parameters/factors (data) for the different spatial and temporal scales.

All interacting processes within agro-ecosystems produce scale-specific patterns, which are self-organizing in nature. This self-organizing behavior is caused by the non-linearity of processes and the many feedback mechanisms that act within the system (Rigon et al., 1994). Complex systems can be found in different steady states, which can reorganize into new states. These state changes often happen quickly when considerable pressure is put on the system. These reorganizations are often perceived as catastrophes. Examples of these steady states are the observed relations between climate and vegetation zones for continents and soil vegetation landscape niches within these zones. Only large climatic or man-induced vegetation changes will change this apparent equilibrium.

1.2. Yield determining factors in agro-ecosystems

Agro-ecosystems are usually characterized by their yields. An analysis of the causes of spatial yield variability can give insight into the limiting factors that determine the spatial variability of yield. When certain factors are found to limit yield they should be subjected to more in-depth analysis and characterization. Actual yields can be used as a measure of agro-ecosystem output. The problem with actual yields is that many socio-economic and biophysical factors cause the actual yield to be usually far below the theoretical biophysical production potential, the so-called yield-gap.

In order to unravel possible scale effects in actual spatial variability of yield, a system analysis can be made for different spatial scales by changing the resolution of the spatial units but by keeping the studied area constant.

When the scale-dependent analysis of the yield gap reveals landscape-related yield limiting factors, it is relevant to carry out a more in-depth research at the landscape level which can be done by landscape measurements or modeling experiments. The design of such a modeling experiment requires more insight in how the landscape system and its processes might affect crop performance and vice versa.

1.3. Dynamic landscape concept

The most dynamic interactions between and within agro-ecosystems in landscapes involve water-related processes. Precipitation is partly intercepted and taken up by the vegetation. The remaining water is released into the landscape through infiltration or run-off. The migrating water has the potential to change a landscape by weathering (infiltrated water), by erosion/sedimentation (run-off and run-on water) and other denudation processes. These landscape-changing processes are thus directly influenced by the existing agro-ecosystems through water uptake or by slowing down the surface water, and hence stimulating infiltration. Land use, therefore, has an effect on landscape processes, which, in turn, determine soil and crop functioning (Veldkamp and Bouma, 2001). If we consider a temporal scale of 1–100 years, weathering processes can safely be ignored, and we can focus our attention on water redistribution and related processes. It is well known from erosion studies that landscape processes can have a large impact in sloping areas (Lal, 1998; Laflen and Roose, 1998). These studies, however, mainly focus on the erosion aspects of the landscape processes, while deposition can have an equally large impact.

Typical aspects of landscape processes are the apparent threshold effects. Because non-linear landscape processes tend to self-organize into stable domains, they do not immediately respond to a shift in one or a few of its many controlling factors (Rigon et al., 1994). When many controlling factors are changing or if the magnitude of change is large, the whole system will reorganize itself into a new stable domain (Milne, 1991). The sensitivity for such reorganizations depends on the resilience of the system. Such reorganizations often happen suddenly and are viewed by farmers as disastrous events. An apparent small change in one variable that controls the agro-ecosystem, like a precipitation event, may trigger such a catastrophic event. It is as if the system is pushed over a threshold (Holling, 1992). It can take years of small events and changes in the landscape to bring it to the brink of such reorganization. Examples of such catastrophic events are landslides, mudflows, large erosion and deposition events, but also fire, pests and diseases represent natural causes for ecosystem reorganization.

Agro-ecosystems at the landscape level should thus be evaluated within a dynamic landscape concept incorporating both on- and off-site effects. Such an approach should aim at exploring natural soil and landscape processes in such a way that they can be linked to crop productivity. We will demonstrate a landscape modeling approach which allow assessments of possible on- and off-site effects as a result of agronomic decisions and measures at the landscape level.

Summarizing, it is the goal of this paper to illustrate that agronomic research at the landscape level is relevant. A two-step top–down methodology will be demonstrated to support the design of relevant agronomic landscape research at the correct regions and sites. The first step consists of a spatially explicit analysis of factors that control the variability in yield in order to determine relevant regions and scales for landscape research. The second step involves regional exploration of the potential effects of landscape processes on water and soil redistribution, allowing the selection of relevant research transects or sites. Only when the relevant regions and sites are known can the question be addressed which agronomic measures to study.

2. Materials and methods

2.1. Spatial explicit yield variability analysis as a function of biophysical and socio-economic factors

Recently, more emphasis of global change research has been placed on land use/cover change (LUCC) (Turner et al., 1995; Lambin et al., 1999). As a result, high quality geo-referenced databases have become available. One of these research projects, CLUE (conversion of land use and its effects, URL: http://hello.to/clue) (Veldkamp and Fresco, 1996) has yielded a wealth of agronomic data for a series of tropical countries. These data are all derived from original agronomic census data based on interviews. They have only been used to establish relationships between the land use patterns and their potential drivers leaving the spatial yield data unexplored. For three of these countries, Costa Rica (1984), Ecuador (1991) and Honduras (1993) (Veldkamp and Fresco, 1997; De Koning et al., 1998; Kok et al., 1999; Kok and Veldkamp, 2001), the spatial explicit yield data for coffee, banana, maize, rice and bean and potential controlling factors are available.

A grid-based data format is adopted, as data from many different sources have to be harmonized. Census data have administrative units as spatial units, while soil, climate and topographical maps have different spatial units. Instead of using uniform grid cells with one dominant value, sub-grid information is present for most of the potential driving forces of spatial yield variability. In every cell we use, e.g., the percentage of fertile soils, percentage of a well-drained soils, among other variables. Using this approach, no information is available when gridding the basic data and by scaling (aggregation) of data to coarser resolutions. In addition to the basic grid ($7.5 \times 7.5\,\mathrm{km}^2$ for Costa Rica and Honduras and $9.25 \times 9.25\,\mathrm{km}^2$ for Ecuador), we created a coarser resolution ($37.5 \times 37.5\,\mathrm{km}^2$ for Costa Rica and Honduras and $37 \times 37\,\mathrm{km}^2$ for Ecuador).

We analyzed yield data with multiple regression analyses at two different spatial resolutions. Potential independent factors affecting yield variability were selected from both socio-economic (f.e., infrastructure, population, education, etc.) and biophysical (f.e., climate, geomorphology, soil) data. Before executing the multiple regression analysis, steps were taken to quantify and minimize the correlation between variables (multi-collinearity effects) and between neighboring grid cells (spatial auto-correlation).

2.2. Modeling water and soil redistribution within landscapes

For the simulation of the landscape dynamics the LAPSUS model is used (Schoorl et al., 2000). LAPSUS (LandscApe ProcesS modeling at mUlti dimensions and scaleS) is a basic surface erosion/deposition model based on the continuity equation for sediment movement (Kirkby, 1971, 1986; Foster and Meyer, 1975). After integration and under the assumption that the transport capacity C and the detachment capacity D or settlement capacity T remain constant within one finite element, the sediment transport rate is evaluated as follows:

$$S = C + (S_0 - C)\,\mathrm{e}^{-\mathrm{d}x/h} \tag{1}$$

where the rate of sediment transport S (m^3/s) along dx (m) length of a finite element is calculated as a function of transport capacity C (m^3/s) compared with the amount of sediment already in transport S_0 (m^3/s). The term h (m) refers to the transport capacity divided by the detachment capacity D (m^2/s) or to the transport capacity in proportion to the settlement capacity T ($-1\,\mathrm{m}^2/\mathrm{s}$). Calculated sediment shortage results in erosion while calculated excess of sediment in transport compared to the local transport capacity results in deposition (settlement).

This model evaluates the rates of sediment transport by calculating the transport capacity of water flowing down slope from one grid cell to another as a function of the discharge and the gradient of the slope. Surplus of capacity is filled by the detachment of sediment, which depends on the erodibility K_{es} (m^{-1}) of the surface. This detachment of sediment causes lowering of the surface or erosion. However, when the rate of sediment in transport exceeds the local capacity, the surplus of sediment in transport will be deposited by settlement causing a higher surface or sedimentation. The routing of the overland flow and the resulting model calculations were done with a multiple flow algorithm to allow for a better representation of divergent properties of convex topography (e.g., Freeman, 1991; Quinn et al., 1991; Holmgren, 1994). This modeling framework was tested elaborately for the effects of changing flow algorithms, spatial resolution and temporal resolution (Schoorl et al., 2000). LAPSUS was validated by field observations. It displayed a realistic erosion and sedimentation patterns which closely matched with real-world erosion and sedimentation patterns at the same spatial resolution ($25 \times 25\,\mathrm{m}^2$) (Schoorl and Veldkamp, 2001).

Main input parameters for the grid-based LAPSUS model were the topographical potentials (slope gradients) calculated from our digital elevation model (DEM) and regional precipitation and evaporation. The calculated rainfall surplus generated the overland flow. Within each grid cell we assumed uniform conditions for all parameters involved. The model evaluated all parameters on an annual basis. As a consequence, the model updated all parameters (also DEM and soil data) calculated each year and simulated different rates of erosion and sedimentation during the next time step. The current situation in the study area was reflected in a base scenario, which assumed that infiltration and erodibility was dependent on land use and underlying soil properties (e.g., Bonachela et al., 1999; Cerda, 1999). The infiltration (I) combined with the calculated rainfall surplus determines the amount of overland flow of water. The infiltration (I) for each grid cell was calculated as a function of soil depth d_{s} (m^1), available water capacity AWC (vol.%) and management practices IF (–):

$$I = \mathrm{IF}\,\mathrm{AWC}\,d_{\mathrm{s}} \quad (2)$$

Detachment of surface particles D (m^2/s) depends on the erodibility of the parent material K_{es} (m^{-1}), management EF (–), discharge Q (m^3/s) and slope angle Λ (–):

$$D = K_{\mathrm{es}}\,\mathrm{EF}\,Q\Lambda \quad (3)$$

To evaluate the off-site effects of agro-ecosystems, we used a simple indicator of flooding risk. For this case study the yearly flooding risk for each grid cell was calculated as a function of the distance to a channel, the discharge within that channel, and the height difference between the cell and channel bed.

2.3. LAPSUS case study

A DEM with a spatial resolution of 25 m was the starting point for this grid-based case study. For this uni-scale experiment, we chose an area of 17.12 km^2 (approximately 27 500 grids) in the South of Spain near Álora in the province of Málaga (Andalusia, Fig. 1). The relief for the study area showed altitudes ranging from 100 to 625 m above sea level. In this region, the general climatic conditions are dry Mediterranean summer (Csa) with decreasing precipitation from west to east. The study area has a mean annual temperature of 17.5°C and receives a mean annual rainfall of 534 mm, mainly from October to April. Fieldwork, aerial photographs, satellite images and expert knowledge provide the base for building the base maps for the study area. The resulting soil depth map (Fig. 1b) represents the underlying geology, slope gradients and topographical position (De Bruin and Stein, 1998; Wielemaker et al., 2001). The main land use were divided into five major classes (Fig. 1c): annual crops (mainly wheat and chickpea), citrus, olive with some almond, semi-natural vegetation and a rest group (urban, bare, riverbed). Soil types and properties of the area are described by Ruiz et al. (1993).

3. Results and discussion

3.1. Crop yields as a function of biophysical and socio-economic factors

3.1.1. Costa Rica

We analyzed the spatial yield variability of coffee, banana, maize, rice and bean within Costa Rica in 1984 based on spatially explicit agronomic census

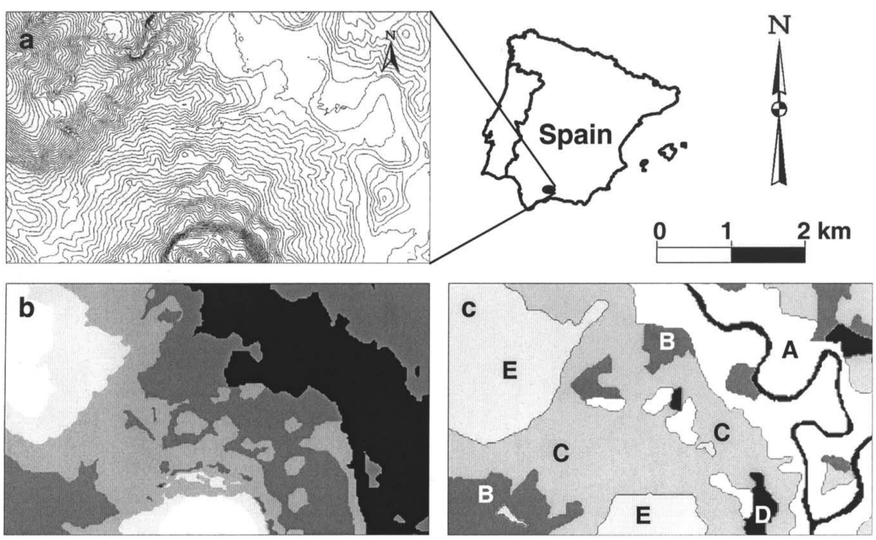

Fig. 1. Location of the study area in southern Spain including: (a) the 20 m contour line map; (b) soil depth from deeper than 1.50 m (shaded black) to less than 0.30 m (shaded white); (c) main land use with capital letters indicating: A — citrus, B — annuals, C — olive, D — other land uses, and E — nature.

Table 1
Regression models (significant at the 0.05 level) for the explanation of yield variability in Costa Rica, 1984, for selected crops at $7.5 \times 7.5\,\mathrm{km}^2$ scale[a]

Spatial resolution ($7.5 \times 7.5\,\mathrm{km}^2$)	Coffee yield (%)	Banana yield (%)	Maize yield (%)	Rice yield (%)	Bean yield (%)
Overall model fit (R^2)[b]	13.1	14.2	29.2	37.1	26.3
Socio-economic factors[c]	10.5 (0.80)	5.7 (0.40)	13.7 (0.47)	2.5 (0.07)	16.5 (0.63)
Biophysical factors[c]	2.6 (0.20)	8.5 (0.60)	15.5 (0.53)	34.6 (0.93)	9.8 (0.37)
Climate	1.8 (0.14)	8.5 (0.60)	9.8 (0.34)	31.1 (0.84)	0.6 (0.02)
Landscape	0.8 (0.06)	–	5.7 (0.19)	3.5 (0.09)	9.2 (0.35)

[a] Between brackets are the relative factor weights within the regression model.
[b] The partial R^2 values of the independent factors are listed.
[c] Factors are subdivided into socio-economic and biophysical main groups, and the biophysical group is further subdivided into climate- and landscape-related factors.

data (Veldkamp and Fresco, 1997). Potential independent factors that affected the variability of yield were selected. Both socio-economic (infrastructure, population, education) and biophysical (climate, geomorphology, soil) factors were taken into account. Table 1 gives the results from multiple regression analysis valid for a spatial resolution of $7.5 \times 7.5\,\mathrm{km}^2$. All crops yielded significant models (at the $P = 0.05$ level of probability) with significant contributions from both two main factor groups. Model fits (coefficients of determination, R^2) were relatively poor (around 13–14% for coffee and banana yields) to fair (ranging from 29 to 37% for the yields of maize, rice and bean). The relative contribution of the land- and climate-related factors within the model ranged from 0.20 for coffee yield to 0.93 for rice yields, illustrating the complex interactions within land use systems (Turner et al., 1995).

The exercise was repeated for the same data set but aggregated to coarser spatial units ($37.5 \times 37.5\,\mathrm{km}^2$) different results emerge (Table 2). With the exception of the yield for coffee and banana, a considerable increase in model performance was observed. The coefficients of determination ranged from 52.9% for bean, 63.8% for maize and 72.3% for the spatial variability of rice yield. When analyzing the relative contributions of the main explaining factors within the regression models the biophysical contribution had generally increased, with the exception of coffee yield.

Landscape (geomorphologic and soils factors) continues to play a significant role (between 0.09 and 0.35) at both spatial scales for maize, rice and bean. For the yield of coffee and banana, the landscape is less of a dominant factor. When a similar spatially explicit analysis was made for the Atlantic Zone region in Costa Rica at a $2 \times 2\,\mathrm{km}^2$ resolution

Table 2
Regression models (significant at the 0.05 level) for the explanation of yield variability in Costa Rica, 1984, for selected crops at $37.5 \times 37.5\,\mathrm{km}^2$ scale[a]

Spatial resolution ($37.5 \times 37.5\,\mathrm{km}^2$)	Coffee yield (%)	Banana yield (%)	Maize yield (%)	Rice yield (%)	Bean yield (%)
Overall model fit (R^2)[b]	14.7	11.6	63.8	72.3	52.9
Socio-economic factors[c]	14.7 (1.00)	–	18.7 (0.29)	–	29.5 (0.56)
Biophysical factors[c]	–	11.6 (1.00)	45.1 (0.71)	72.3 (1.00)	23.4 (0.44)
Climate	–	11.6 (1.00)	26.3 (0.41)	58.7 (0.81)	–
Landscape	–	–	18.8 (0.30)	13.6 (0.19)	23.4 (0.44)

[a] Between brackets are the relative factor weights within the regression model.
[b] The partial R^2 values of the independent factors are listed.
[c] Factors are subdivided into socio-economic and biophysical main groups, and the biophysical group is further subdivided into climate- and landscape-related factors.

Table 3
Regression models (significant at the 0.05 level) for the explanation of yield variability in Ecuador, 1991, for selected crops at $9.25 \times 9.25\,km^2$ scale[a]

Spatial resolution ($9.25 \times 9.25\,km^2$)	Coffee yield (%)	Banana yield (%)	Maize yield (%)	Rice yield (%)	Bean yield (%)
Overall model fit (R^2)[b]	8.9	7.7	17.1	14.3	21.4
Socio-economic factors[c]	1.3 (0.15)	5.5 (0.71)	7.4 (0.43)	5.0 (0.35)	17.0 (0.30)
Biophysical factors[c]	7.6 (0.85)	2.2 (0.29)	9.7 (0.57)	9.3 (0.65)	4.4 (0.70)
Climate	–	–	2.4 (0.14)	5.7 (0.40)	1.0 (0.05)
Landscape	7.6 (0.85)	2.2 (0.29)	7.3 (0.43)	3.6 (0.15)	3.4 (0.16)

[a] Between brackets are the relative factor weights within the regression model.
[b] The partial R^2 values of the independent factors are listed.
[c] Factors are subdivided into socio-economic and biophysical main groups, and the biophysical group is further subdivided into climate- and landscape-related factors.

landscape properties turned out to be the most dominant factor in explaining the current distribution of land use (Kok and Veldkamp, 2000).

3.1.2. *Ecuador*

We also analyzed the spatial yield variability of coffee, banana, maize, rice and bean in Ecuador in 1991 based on spatial explicit agronomic census data (De Koning et al., 1998). Table 3 gives the results from multiple regression analysis valid for a spatial resolution $9.25 \times 9.25\,km^2$. A similar procedure as for Costa Rica was applied. Independent socio-economic and biophysical factors that control yield variability were selected. All crops yielded significant models (at the 0.05 level) with significant contributions from both main factor groups. Model fits (coefficients of determination) were relatively poor, ranging from 8.9% for the yield of coffee yields to 21.4% for the yield of bean. The relative contribution of the land and climate-related factors were usually more than 0.50 with the exception for banana yields, which had a biophysical contribution of only 0.29. These empirical relations change somewhat at the higher aggregated level ($37 \times 37\,km^2$) (Table 4). Model fits increased significantly with the exception of the yield model for bean. Furthermore, a considerable decrease in the relative contribution of the biophysical factors can be observed. The rice and bean spatial yield variability were only explained by socio-economic factors while their relative contribution to the variability of the yield of coffee, banana and maize decreased to 0.64, 0.28 and 0.14, respectively. Apparently, landscape components only played a significant role in determining the variability of the yield of banana and maize at the scales studied in Ecuador.

Table 4
Regression models (significant at the 0.05 level) for the explanation of yield variability in Ecuador, 1991, for selected crops at $37 \times 37\,km^2$ scale[a]

Spatial resolution ($37 \times 37\,km^2$)	Coffee yield (%)	Banana yield (%)	Maize yield (%)	Rice yield (%)	Bean yield (%)
Overall model fit (R^2)[b]	39.5	46.1	36.0	39.5	12.2
Socio-economic factors[c]	14.2 (0.36)	33.3 (0.72)	30.8 (0.86)	39.5 (1.00)	12.2 (1.00)
Biophysical factors[c]	25.3 (0.64)	12.8 (0.28)	5.2 (0.14)	–	–
Climate	4.1 (0.10)	5.8 (0.13)	–	–	–
Landscape	21.2 (0.54)	7.0 (0.15)	5.2 (0.14)	–	–

[a] Between brackets are the relative factor weights within the regression model.
[b] The partial R^2 values of the independent factors are listed.
[c] Factors are subdivided into socio-economic and biophysical main groups, and the biophysical group is further subdivided into climate- and landscape-related factors.

Table 5
Regression models (significant at the 0.05 level) for the explanation of yield variability in Honduras, 1993, for selected crops at 7.5 × 7.5 km² scale[a]

Spatial resolution (7.5 × 7.5 km²)	Coffee yield (%)	Banana yield (%)	Maize yield (%)	Rice yield (%)	Bean yield (%)
Overall model fit (R^2)[b]	36.9	33.3	45.9	32.5	68.9
Socio-economic factors[c]	0.0 (0.00)	5.6 (0.17)	12.1 (0.26)	3.8 (0.12)	4.4 (0.06)
Biophysical factors[c]	36.9 (1.00)	27.7 (0.83)	33.8 (0.74)	28.7 (0.88)	64.5 (0.94)
Climate	22.8 (0.62)	19.0 (0.57)	28.8 (0.63)	21.5 (0.66)	59.4 (0.86)
Landscape	14.1 (0.38)	8.7 (0.26)	5.0 (0.11)	7.2 (0.22)	5.1 (0.08)

[a] Between brackets are the relative factor weights within the regression model.
[b] The partial R^2 values of the independent factors are listed.
[c] Factors are subdivided into socio-economic and biophysical main groups, and the biophysical group is further subdivided into climate- and landscape-related factors.

3.1.3. Honduras

Finally, we analyzed the yield variability of the same five crops (coffee, banana, maize, rice and bean) in Honduras in 1993 based on the agronomic census data (Kok et al., 1999). Table 5 gives the results from multiple regression analysis valid for a spatial resolution 7.5 × 7.5 km² and Table 6 gives the results at a resolution of 37.5 × 37.5 km². Similar potential independent factors affecting yield variability were selected as with the other two case studies. All five studied crops yielded significant models (at the $P = 0.05$ level of significance) with usually significant contributions from both main factor groups.

At the relatively detailed 7.5 × 7.5 km² resolution crop yield models showed a fair to reasonably R^2 ranging from 33.3% for the yield of banana to 68.9% for the yield of bean. Again the model fits increased when the data were reanalyzed at the coarser resolution of 37.5 × 37.5 km² level. Model fits increased to high values ranging from 51.3% for rice to 90.2% for bean yields. For both spatial scales the biophysical factors, dominated by climate, were the main determining factors for variability of yield. Landscape properties usually had a significant contribution in explaining the variability in yield and within the model their contribution was often in the range 0.27–0.77.

The Costa Rica, Honduras and Ecuador examples clearly illustrated the scale dependence of the spatial yield regression models. The general tendency at the scale levels used is that at higher aggregated spatial scales the overall model performance increased combined with an increase of the contribution of the climate component. Ecuador is a case where the socio-economic factors dominate the spatial yield

Table 6
Regression models (significant at the 0.05 level) for the explanation of yield variability in Honduras, 1993, for selected crops at 37.5 × 37.5 km² scale[a]

Spatial resolution (37.5 × 37.5 km²)	Coffee yield (%)	Banana yield (%)	Maize yield (%)	Rice yield (%)	Bean yield (%)
Overall model fit (R^2)[b]	71.8	61.1	67.0	51.3	90.2
Socio-economic factors[c]	1.9 (0.03)	17.5 (0.29)	3.6 (0.05)	–	2.9 (0.03)
Biophysical factors[c]	69.9 (0.97)	43.6 (0.71)	63.4 (0.95)	51.3 (1.00)	87.3 (0.97)
Climate	45.5 (0.64)	18.7 (0.31)	11.8 (0.18)	37.3 (0.73)	70.6 (0.78)
Landscape	24.4 (0.34)	24.9 (0.40)	51.6 (0.77)	13.9 (0.27)	16.7 (0.19)

[a] Between brackets are the relative factor weights within the regression model.
[b] The partial R^2 values of the independent factors are listed.
[c] Factors are subdivided into socio-economic and biophysical main groups, and the biophysical group is further subdivided into climate- and landscape-related factors.

variability, while Honduras demonstrates the opposite, i.e., a mainly biophysical dominated system. Costa Rica plays an intermediate role with an alternating dominance of both groups of factors.

The differences of the three countries were related to the spatial pattern of the different land uses within the countries. In Costa Rica, e.g., coffee is grown near the capital San José, accounting for the high socio-economic drive while coffee is grown in more remote but biophysical optimal areas in Ecuador and Honduras. A similar pattern can be observed for bananas. In Ecuador, banana is mainly grown near a large urban center with a harbor, while Costa Rica and Honduras have their banana production in the remote Caribbean coastal zones. The different results for rice, bean and maize is related to the different food preferences in the three countries and whether the crops are grown by local farmers or by larger commercial enterprises (Kok and Veldkamp, 2001).

It is also shown that if one wants to understand actual agronomic production, a distinct quantification of all factors is required to quantify the relative contribution of landscape- and climate-related properties. It is obvious from the three cases that landscape properties tend to contribute significantly but almost never dominate the actual spatial variability in yield.

This type of spatial explicit analysis can help to determine regions where landscape factors dominate yield variability. Especially, if landscape factors are thought to reduce actual yield levels it will be worthwhile to investigate in more detail the specific landscape agro-ecosystem. A first exploratory assessment of the interactions between landscape and current agro-ecosystems can be obtained by landscape process modeling as demonstrated below.

3.2. Modeling water and soil redistribution within landscapes

The model settings of the demonstrated baseline scenario of LAPSUS are given in Table 7, while the inputs are illustrated in Fig. 1. The values in Table 7 are based on published data and a systematic scale-dependent calibration exercise (Schoorl and Veldkamp, 2001). Water redistribution is illustrated with the run-off map of Fig. 2a, where areas of flow concentration and flow divergence are clearly visible. The river valley has deeper soils (Fig. 1) and shows limited run-off because of high infiltration rates. Local erosion and sedimentation rates for each grid cell and their spatial distribution are presented in Fig. 2b. Erosion rates throughout the area varied from 0 to more than 700 t ha^{-1} yr^{-1}, with a mean of 11.1 t ha^{-1} yr^{-1} for this baseline scenario. In general, erosion rates were higher in down slope areas, on the steeper slopes and in areas where the run-off was concentrated in channels. Sedimentation was mainly concentrated within specific points in the main channels and on the transition from the steep slopes to the more flat areas in the main valley, forming small alluvial fans. Sedimentation rates varied from 0 to more than 1·7 t ha^{-1} yr^{-1}. Natural vegetation areas showed the highest erosion rates followed by annuals and olive just above the mean rates for the whole area. Citrus and the rest group showed much lower erosion rates. Overall, the smallest amounts of re-sedimentation events were found in the areas under olive and annuals. At the locations where citrus is grown, the valley floor, a large number of re-sedimentation events occurred.

The general impression of the overall pattern of the erosion and sedimentation rates in Fig. 2b is

Table 7
Parent material and land use-related main input parameters: surface erodibility (K_{es}), water retention capacity (AWC), surface erodibility factor (EF) and infiltration factor (IF)

Parent material	K_{es} (m^{-1})	AWC (vol.%)	Land use	EF (–)	IF (–)
Colluvium	7.4×10^{-5}	0.161	Citrus	0.5	1.0
Marls	11.1×10^{-5}	0.105	Annuals	1.3	1.2
Sand/gravel	7.4×10^{-5}	0.151	Olive A	0.75	1.5
Schist	6.7×10^{-5}	0.135	Nature	1.2	0.75
Gneiss	5.2×10^{-5}	0.066	Rest	0.01	0
Conglomerate	3.7×10^{-5}	0.055			
Serpentinite	2.2×10^{-5}	0.044			

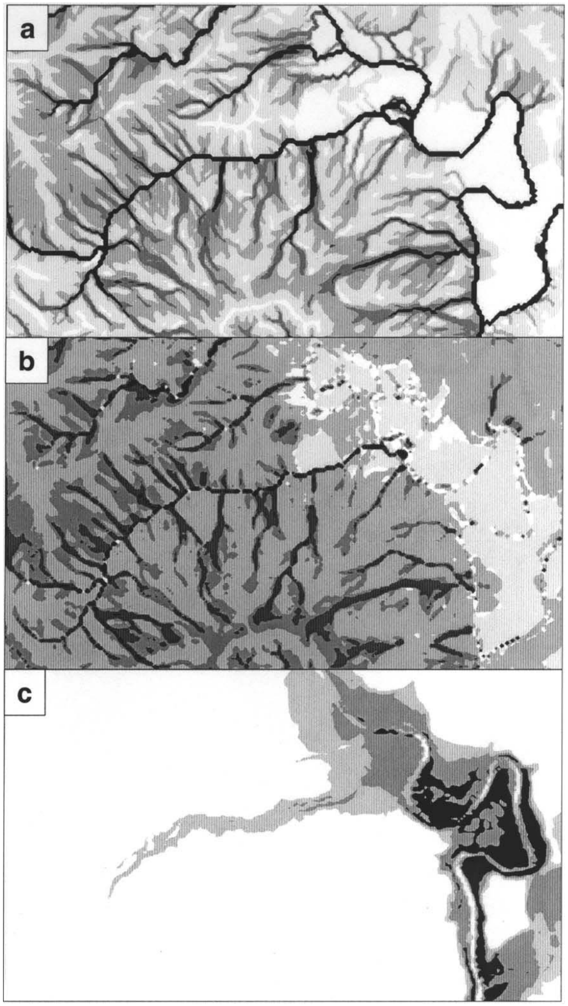

Fig. 2. Spatial distribution of current conditions in the case study area for: (a) water redistribution with scaling from white (low discharge) to black (high discharge); (b) soil redistribution, erosion (light gray (low) to black (high)) and sedimentation (white); (c) flood hazard map for the study area, gray scale indicating increasing flooding hazard from white (low) to black (high).

that the patterns was determined by the underlying topography and the resulting drainage network, but the patterns are also clearly related to the parent material and land use. This observation has been made before in other studies in Spain (e.g., Cerda, 1998, 1999).

As an example of an off-site effect, a flooding risk indicator is given (Fig. 2c). This simple assessment is based on distance to a channel, the discharge within that channel and the height difference between a specific site and the adjacent channel bed. The areas in Fig. 2c which are most prone to flooding are also the areas affected by off-site effects. Increasing amounts of run-off from the slopes are diverted into the channels, which continue to collect all extra run-off downstream. Especially, vulnerable areas are the sharp river bends, inner terraces and the alluvial fan area where the simulated catchment drains into the main river valley. In our case study area all these vulnerable positions are planted with citrus, which consequently have high risk of flood damage. Local farmers, who marked these areas as prone to flooding, confirm this outcome.

In this case study we demonstrated that in the landscape system the on-site consequences of land use change can result in major off-site effects. Concerning the simulated landscape processes the most important indirect changing parameters are run-off/run-on, infiltration, erosion and re-sedimentation both on-site and off-site. The effects will not be limited to the case study area alone. For example, the increased run-off and sediment transport will eventually enter and possibly alter the downstream part of the whole river drainage system.

The model presented in this paper can be used as a tool to explore possible effects of certain land use changes within a dynamic landscape context. All types of changes that affect the infiltration and erodibility can be evaluated within the model, including management practices. If one would try to design an agronomic experiment based on the demonstrated scenario, measurements should be made in fields situated on the eroding sloping areas as well as on the re-sedimentation sites in the lower valley. The within field measurements should be aimed at on-site effects of land management as illustrated by some relevant examples in a special issue on "Tillage erosion and tillage translocation" (Govers et al., 1999).

The current LAPSUS model is far from complete since it only calculates the effects of water erosion and re-sedimentation. Other relevant regional processes like landsliding, slumping and related mass movements are not included. But despite these limitations the model is able to predict the dynamics of overall landscape system well.

4. Conclusions and recommendations

Our holistic spatial- and scale-dependent agro-ecosystem analysis confirmed that landscape properties and processes can determine the variability of yield of many crops. We propose the application of a top–down approach. First a national to regional empirical analysis about the role of landscape factors in determining spatial variability of yields, followed by a process modeling approach at those regions where landscape dominance in yield variability is known.

Systematic national and regional analyses will allow for the identification of areas or hotspots where landscape processes dominate agro-ecosystem performances. For such areas explorative modeling of the landscape system for its on- and off-site effects in respect to water and soil redistribution can give insight into the selection of relevant transects or chain of sites for designing agronomic landscape research. One should always study simultaneously the supplying and receiving sites. Emphasis should be on interconnected sites: the 'winners' and 'losers' in the landscape in respect to water, soil and nutrients should be studied in concert. The methodology propagated here advocates to view farmers more in a landscape context than in a field context. As farmers not only farm fields but also landscapes agronomic landscape experiments are essential.

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