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Spatial Patterns in Water Use Efficiency Created by Intensive Cultivation on Semi-arid Hillslopes

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ABSTRACT

The expansion of almond monocultures in southeast Spain has forced farmers to cultivate steep and rocky soils. The intensive cultivation of entire hillslopes from the crest to the valley bottom results in a redistribution of soil, leaving very thin soils on the convexities and thick soils in the valley bottoms. Previous research has indicated that apart from soil redistribution, tillage of stony soils also creates a lateral and vertical movement of rock fragments leading to a rock fragment armoring both on the convexities and in the valley bottoms. Frequent tillage of entire hillslopes has therefore resulted in a spatial pattern of soil properties such as soil thickness, rock fragment cover, rock fragment content, and porosity of the fine earth. These are key parameters in the water balance of marginal soils. A systematic sampling of soil depth, stoniness, fine earth bulk density and soil texture along cultivated hillslopes was carried out and the establishment of almond trees in plant pits with known soil depth was monitored. The water balance of selected pits along a transect through a first order valley was simulated for the hydrological year 1996/97 using the PATTERN eco-hydrological model. The model results for individual soil profiles indicate that the hydrological response of the thin, stony soils on the crests is more dynamic than that of the deeper soils in the valley bottoms. This spatial pattern is reflected by the poor establishment and small stem diameter of young almond trees on thin soils. This approach is a first step towards the understanding of the implications of intensive dryland farming on crop yield, runoff, and groundwater recharge.

INTRODUCTION

Almond monocultures in southeast Spain have expanded rapidly over the last decades (Grove, 1996). The increase of the acreage under almonds has forced farmers to expand into steep slopes with shallow and stony soils. To fully utilize the sparse and irregular rainfall, trees are widely spaced (c. 7 m) and the soil is kept bare by frequent and shallow tillage. These changes in the soil and land surface properties may be significant for the soil's response to drought and thus to desertification. In general, large plots are cultivated in a uniform manner covering entire hillslopes from the convex crest to the valley bottom. Initially a uniform man-made soil was created by ripping the bedrock to a depth of 20 to 40 cm. Now spatial variations in soil depth and stoniness can be observed. Poesen et al. (1997) have carried out tracer experiments demonstrating net downslope fluxes of fine earth and rock fragments by cultivation (tillage erosion). Apart from spatial patterns of increased denudation and accumulation, tillage also induces vertical movement of rock fragments within the plow layer resulting in rock fragment armoring (Oostwoud Wijdenes et al., 1997). Poesen et al. (1997 and 1998) and Boer et al. (1996) have shown that the spatial patterns in both rock fragment cover and soil thickness can be explained by a combination of topographic and land use factors. Rock fragment cover in almond plantations on slopes was shown to be highest on topographic convexities and in narrow valley bottoms (Poesen et al., 1997). This pattern was explained by intensive denudation because of tillage on the convexities dragging the rock fragments from the bedrock to the surface through kinetic sieving followed by a lateral flux down the slope depositing soil and rock fragments in the narrow valleys. A spatial analysis based on a 30 by 30 meter resolution digital elevation model of the upper Guadalentin drainage basin revealed that the relation between soil thickness and topography was strengthened by intensive tillage (Boer et al., 1996).

The modification of important hydrological properties by soil stoniness has been shown by several authors (see literature review by Poesen and Lavee, 1994). Among others, the following parameters are strongly influenced by rock fragment content: fine earth bulk density (Childs and Flint, 1990 and Torri et al., 1994), saturated hydraulic conductivity (Ravina and Magier, 1984) and water holding capacity (Childs and Flint, 1990, van Wesemael et al., 1995). The literature reveals that the impact of stoniness on individual parameters can be conflicting, and therefore there is a need to integrate the results of laboratory experiments addressing individual processes such as runoff (Poesen et al., 1990) or evaporation (Groenevelt et al., 1989; van Wesemael et al., 1996). Integration of individual processes into a water balance approach has been attempted using crop response surveys (Kosmas et al., 1993) and hydrological

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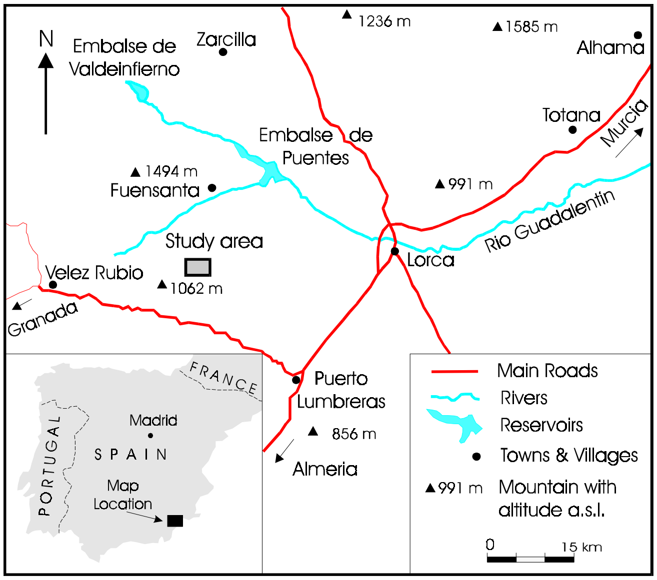

Figure 1. Location of the study area.

modeling (Mulligan, 1996).

The objective of this paper is to investigate the spatial patterns in soil properties on intensively cultivated hillslopes in a semiarid environment, and their impacts on the water balance and tree growth. We intend to show to what extent frequent tillage of stony soils can alter the subsurface characteristics of these soils and discuss some of the potential implications of these changes. In the present paper the PATTERN model will be used to investigate the potential impacts of measured within-field variation in stoniness and soil thickness on soil hydrology.

Study area

The study area is located in the upper part of the Guadalentin drainage basin (southeast Spain; Fig. 1). The area is part of the Sierra de Torecilla, which consists of slates, greywackes and conglomerates (IGME 1970). This hilly area contains a dense drainage network of steep V-shaped valleys. According to ICONA (1993), the soils are calcareous and contain a large proportion of rock fragments. The soils are classified as Eutric Regosols and Calcaric Cambisols. The climate is semiarid with average annual rainfall ranging from 270 mm in Puerto Lumbreras (465 m a.s.l) to 278 mm in Embalse de Puentes (450 m a.s.l). Mean annual temperature varies between 16.8 (Puerto Lumbreras) and 17.1ºC (Embalse de Puentes; Fig. 1). Information provided by local farmers and extracted from aerial photos reveals that traditional agriculture in the uplands of southeast Spain (i.e. before 1970) was much more diverse and small scale than at present. Barley and wheat were grown on the slopes and almond, olive and figs in the valley bottoms, which retained runoff and throughflow by a series of dams (cañadas). Large parts of the landscape consisted of scrubland (matorral 32%) and forest (21%). The introduction of crawler tractors and the low profitability of wheat and barley have changed the land use considerably: entire hillslopes are now planted with almonds (spacing 7 to 8 meters). Almond plantations are prepared by ripping open the soil and the bedrock to a depth of 20 to 40 cm in such a way that the trees are planted in a very stony 'man-made' soil. Thereafter, the fields are plowed at least twice a year depending on the rainfall distribution using a duckfoot chisel plow.

METHODS

In spring and summer 1997, a total of 50 soil pits were excavated along three transects. The following parameters have been determined in each pit for 10 cm depth increments: rock fragment content, bulk density (total soil and fine earth) and soil moisture content. Furthermore, overall soil thickness and rock fragment cover of the surface were also determined. Soil texture was determined for 14 samples from 4 profile pits. After the removal of organic matter with H_2O_2 the particle size distribution was determined using the hydrometer method (van Reeuwijk, 1992). Estimates of available water capacity (AWC) are based on the difference between gravimetric moisture contents selected from topsoil samples during summer representing wilting point (0.03 g g^{-1}) and one day after 31 mm rainfall representing field capacity field capacity (0.20 g g^{-1}) (Landon, 1991). The AWC was then calculated from the soil thickness, the rock fragment content by volume and the fine earth bulk density.

The PATTERN hydrology and plant growth model was developed to simulate hydrological processes and plant growth for semiarid areas, taking into account the peculiar characteristics of these areas, notably: infrequent and high intensity rainfall events, sparse plant canopies, shallow and stony, skeletal soils and high surface rock fragment covers (Mulligan, 1996, 1998). The PATTERN model is a bucket-type one-dimensional hydrological model. The model uses a tile approximation to represent up to four land cover classes, bare soil and three individually parameterized plant functional types along with a surface cover of rock fragments. The soil itself is represented as a three-phase medium consisting of pore space, the soil matrix and rock fragments (particles > 2mm). Water can only occupy the soil pore space. Rock fragments at the soil surface and within the soil profile have significant impacts on the surface and subsurface hydrology of the model. The growth model is based upon a production efficiency model (Monteith, 1983; Prince et al., 1994) in which growth is determined by the intercepted radiation and a radiation use efficiency (RUE), which is stress dependent. The fraction of radiation intercepted is measured by placing one tube solarimeter above and one below the canopy. In the PATTERN model, an unstressed RUE is used and combined with a water stress factor calculated by the hydrological model.

The PATTERN model is applied here to simulate the water balance in order to understand the hydrological implications of the variability in soil physical properties apparent from the field data. The model is applied in one-dimension and is parameterized for individual soil pit characteristics (soil thickness, rock fragment contents and rock fragment cover) of different parts of the slope. A uniform average value (n=14) for soil texture (sand 40%, clay 20%, and silt 40%) and organic matter content (4%) were used for all pits in the field. The high rock fragment contents of these soils explain the high SOM content and low fine earth bulk density (BDfe). Poesen and Lavee (1994) argue that increasing rock fragment content in a soil decreases the fine earth fraction but does not affect the input of organic matter, and hence SOM is concentrated in a smaller volume of fine earth. Bdfe is defined as mass of fine earth divided by the difference between the total volume and the volume of rock fragments. Poesen and Lavee (1994) and Torri et al (1994) have analyzed a large set of published density and stoniness data and demonstrated that BDfe decreases with increasing rock fragment content. The same trends were observed in the present study. Values for the various plant parameters were obtained from the literature (RUE; Prince et al., 1994) and from field measurements (Intercepted photosynthetically active radiation) obtained in central Spain. The model was integrated for the year 1996-1997, and output is generated at a daily time step. The model has been validated with respect to a number of its key results for stony soils under semi-natural vegetation (i.e. matorral) and a sunflower crop (*Helianthus annuus*) in central Spain (Mulligan, 1996). The predicted trends in soil moisture under three types of matorral cover (grass, dwarf shrubs and shrubs) corresponded very well to measured bi-weekly soil moisture values. Measurements of leaf area index and biomass for the three-matorral functional types and for Helianthus agree well with modeled values. Note that due to instability of the model for very shallow soils a thickness of 0.5 m was added to all soil profiles. This was considered the best way forward, since at this stage we are interested in relative differences between the typical soil profiles. Mulligan (1996) showed that the hydrological components of the PATTERN model are very sensitive to rock fragment content and fine earth bulk density and to some extent to soil depth. The instability of the model is probably due to the very rapid hydrological response to slight variations in inputs and outputs due to the low total pore volume of thin stony soils. The addition of 50 cm soil depth will influence the absolute results, but will have no impact on the relative differences.

In September 1994, soil thickness had been recorded in 167 plant pits spaced 7 meters apart along an entire hillslope. Almond trees were planted within the following months, and the hillslope has been plowed in a similar manner to the surrounding area. We will examine the relationship between soil thickness and crop growth. Stem diameter, canopy height and canopy diameter of the almond trees planted in these pits were recorded in September 1998. Stem diameters were measured at c. 50 cm above the surface, just below the grafting marks.

RESULTS AND DISCUSSION

Cross-slope patterns in soil properties

A survey of 167 plant pits spaced at 7 meter intervals across an entire south facing hillslope revealed that soils are shallow, ranging from 10 to 100 cm with an average of 32.9 cm and a standard deviation of 13.0 cm. Although almonds were directly planted in the pits on this particular hillslope, it is common practice to break up the bedrock to a depth of 20-40 cm before planting. Frequent tillage to a depth of 15 to 20 cm leads to a rather uniform soil thickness in a large part of the landscape, a thickness, which is greater than on most slopes under matorral. Exceptions to this uniform soil thickness occur where net denudation or accumulation can be expected. This explains the thinner soils on the topographic convexities (c. 10 cm) and thicker soils in the valley bottoms or at the foot of the slopes (> 50 cm) (Fig. 2). The rock fragment content by mass (Rm) of the individual samples (n=104) is generally very high with an average of 0.66 kg kg^{-1}. Clear lateral and vertical patterns in rock fragment content become apparent on hillslopes that have

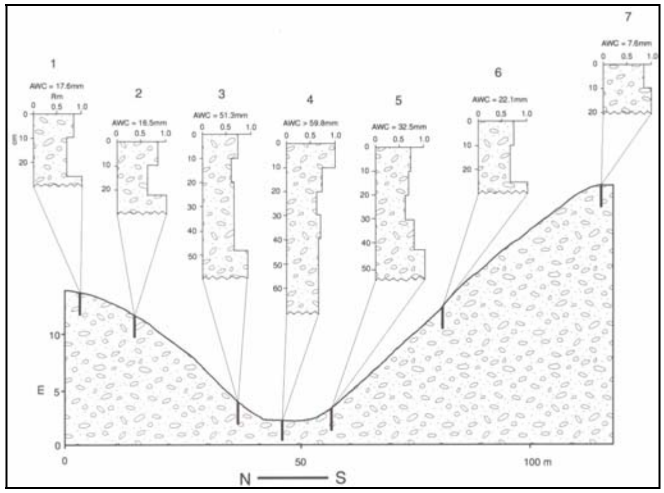

Figure 2. Stoniness (Rm) and available water capacity (AWC) along a north-south transect in a 20 year old almond plantation.

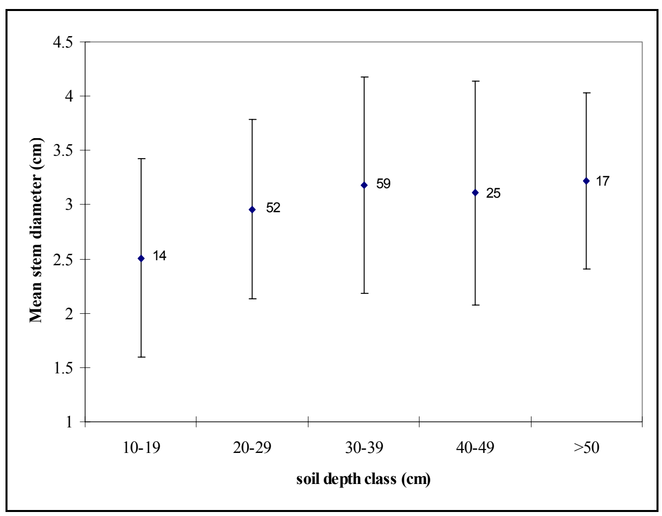

Figure 3. Stem diameter versus soil thickness class for 167 almond trees 4 years after planting on a south facing hillslope. Numbers refer to number of observations in each soil thickness class and error bars indicate standard deviation.

been cultivated for a longer period (Fig. 2). A rock fragment armoring appears and the rock fragment content decreases slightly with increasing soil thickness. In the valley bottom this rock fragment armoring results in a rock fragment mulch of 10 cm thickness.

It has been demonstrated in laboratory experiments using skeletal soils that in particular the macro porosity increases with increasing rock fragment content (van Wesemael et al., 1995). It is therefore reasonable to assume that the combined impact of soil thickness, rock fragment content and macro-porosity will lead to distinct patterns in available water capacity (AWC; see also Ingelmo et al., 1994; Landon, 1991). The AWC is generally very low compared to the ranges for temperate stone-free soils (AWC=80/200 mm per meter soil thickness; Landon, 1991). There is a downslope increase of AWC from the topographic convexities through the straight slopes to the foot slopes and the valley bottom which reflects downslope increase in soil thickness and decrease in rock fragment content (Fig. 2).

The cross-slope patterns in soil thickness and stoniness, which are reflected in the AWC, are in agreement with those expected as a result of tillage erosion. Poesen et al. (1997) argue that tillage erosion is strongest on topographic convexities explaining the shallow soils in which stoniness increases by raking up the bedrock. On the other hand, deposition of material translocated by tillage occurs at the foot of the slope leading to deep soils. The rock fragment armoring, in particular in the valley bottoms, can be explained by vertical movement because of kinetic sieving and preferential downslope dragging of large rock fragments by the tines of the chisel plow (Oostwoud-Wijdenes et al., 1997, Poesen et al., 1997). At a larger scale, using a spatial analysis of a 30 by 30 m DEM, the same patterns of thin soils on interfluves and upperslopes and thick soils have been reported by Boer et al. (1996). The strong correlation between landform and soil properties found in this study and confirmed by Boer et al. (1996) and Poesen et al. (1997, 1998) indicates that cultivation increases the topographic control on soil properties and soil moisture availability. Soil moisture availability is often very poor in semiarid environments under natural vegetation (Bergkamp et al., 1996; Mulligan and Thornes, submitted).

Cross-slope patterns in modeled water balance

The water balance of the two most contrasting profiles, which represent a hilltop (profile 7) and a valley bottom (profile 4), are examined in more detail here (Table 1). The hilltop profile is stony (Rv=0.44 compared with Rv=0.34 for the valley bottom), has a low fine earth bulk density (BDfe=796 kg m^{-3} compared with 1059 kg m^{-3} for the valley bottom) and is shallow. As mentioned above the BDfe reflects the density of the fine earth and pores in between the rock fragments and decreases with increasing rock fragment content. The hilltop also has a much higher saturated hydraulic conductivity (Ksat) (126 mm hr^{-1} compared with 11.4 mm hr^{-1} for the valley bottom) and has a relatively low surface rock fragment cover (Rc=0.46 compared with Rc=0.6 for the valley bottom). The variation in Ksat is generated by the pedotransfer functions of Campbel (1985) and, as soil texture and SOM are constant for the model runs, reflects the positive correlation with rock fragment content and the negative relation with BDfe. Fluxes of water into and out of the profile differ greatly between the two positions. Annual infiltration is 125 mm higher for the hilltop profile. This is due to the generally lower moisture of the hilltop profile (because of rapid drying) and because of the higher Ksat due to the lower fine earth bulk density. The shallow, skeletal hilltop profile shows higher evapo-transpiration than the valley bottom profile (371 mm compared with 330 mm). This is due to a combination of factors. On the one hand a lower runoff coefficient and a low pore space on the hilltops increases the soil moisture content after rainfall and therefore promotes evaporation from the bare soil. This effect of concentration of soil moisture in stony soils on evaporation rates was also observed in laboratory experiments (van Wesemael et al., 1996). On the other hand soil evaporation is higher on the hilltops because of the significantly lower surface rock fragment cover. Drainage from the base of the soil profiles is much higher on the hilltops (94 mm for the hilltop compared with 2.6 mm for the valley bottom). The hilltop profile has a much higher Ksat because of the lower fine earth bulk density and combined with the shallow soil depth this prevents large amounts of water to be stored in the soil profile to be lost subsequently to evapotranspiration. The

Table 1 Soil profile properties and water balance calculated with the PATTERN model for a north-south transect in a 20 year old almond plantation. The water balance was calculated for the hydrological year 1996-97 (P= 508 mm). Refer to Fig. 2 for the location of the soil profiles.

Profile		Rv (m^3 m^{-3})	BD_{fe} (kg m^{-3})	Ksat (mm h^{-1})	Infiltr. (mm)	Runoff (mm)	Evapotr (mm)	Drainage (mm)
1	N	0.45	759	188	508	0	386	88
2		0.44	796	126	488	21	409	55
3		0.37	999	19	410	98	380	9
4	Valley	0.34	1059	11	364	144	330	3
5		0.44	796	126	488	21	354	71
6		0.41	884	52	462	46	358	58
7	S	0.44	796	126	489	20	371	94

difference in Ksat between the two areas means that overland flow is much higher for the valley bottom site (144 mm compared with 20 mm). So we see that the tillage-induced soil characteristics of hilltops creates high infiltration, low overland flow, high evaporation and high recharge conditions whereas valley bottom soil characteristics generate ponding and overland flow with low evaporation and low recharge.

Implications of patterns in soil properties for hillslope hydrology

The one-dimensional modeling of one hydrological year pre-empts any firm conclusions on lateral redistribution of soil moisture. However, compared to evapotranspiration (76-93% of the infiltrated water) other fluxes in the water balance are small (Table 1). Runoff is constrained to those profiles on the footslopes and in the valley bottom where re-infiltration is likely to occur at short distances. These results indicate that even for a year with almost twice the average annual rainfall (508 mm) redistribution of moisture is limited to the valley bottoms and footslopes. This is in agreement with Mulligan and Thornes (subm.) who argue that on semiarid hillslopes hydrological processes operate in isolated cells rather than in catenal sequences as suggested for temperate hillslopes by Beven and Kirkby (1979) and Moore et al. (1991). During wet years, some redistribution of moisture could occur by drainage from the soil profiles and subsequent lateral flow over the bedding planes of the slates since drainage from the stony soil profiles accounts for a maximum of 20 % of the annual precipitation. However, drainage would be restricted to the steeper slopes and topographic convexities rather than in concave areas predicted by the wetness index (Beven and Kirkby, 1979). Therefore, although key soil parameters are related to topography and this pattern is exaggerated by intensive tillage, there is not enough rainfall even during wet years to generate continuous fluxes of water at the hillslope scale.

Crop response to variation in soil thickness

The results of the modeling exercise are strengthened by the outcome of the survey of 167 almond trees planted in 1994 in pits with known soil thickness (Fig. 3). Although there is no significant correlation between stem diameter and soil depth, the mean diameter value per depth class increases with increasing soil thickness until a value of 40 cm beyond which the stem diameters no longer react to soil thickness. The large variability observed in the measured results can be explained by a number of factors: i) interference of other soil properties strongly correlated to water availability as discussed in the previous sections, ii) variation in stem diameter of the plant material as produced by the nursery iii) differences in growth as a result of management (e.g. pruning, spraying of herbicides, weed control etc.).

CONCLUSIONS

Spatial patterns in soil physical properties like soil thickness, surface and subsurface rock fragment content, and fine earth bulk density can be explained by soil fluxes induced by tillage on hillslopes under almonds in southeast Spain. The break-up of bedrock during plowing leads to the production of thin stony soils and spatial redistribution of sorted particles. Mass movement processes accelerated by further plowing can redistribute these rock fragments in particular spatial patterns, which reflect slope morphology and plowing practice. A hydrological modeling exercise shows the impacts of the spatial pattern of soil physical properties on the water balance. Shallow and stony soils tend to occur near to hilltops and these show high rates of infiltration, low overland flow and high evaporation compared with valley bottoms which have deeper and less stony soils with higher surface rock fragment contents. As a result, valley bottoms tend to show lower infiltration, they tend to generate overland flow (though rapid re-infiltration is likely) and, as a result of high surface rock fragment contents they show low evaporation and thus higher and more stable soil moisture regimes. This suggests that, irrespective of catenal concepts of overland flow and throughflow, the spatial distribution of soil physical properties induced by plowing will produce preferential growth of almonds in valley bottom sites compared with hilltops.

Finally, deeper soils produce a more stable moisture regime than shallower soil, which tend to saturate and dry out quickly. For a *K*-strategist such as almond, if water resources from the bedrock are not available, growth and thus productivity tends to show a strong relationship with soil thickness, reaching an asymptote at a particular soil thickness determined by the regional water balance.

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