COST Action ES1306

Short Term Scientific Mission Report

CONNECTIVITY IN HIGHLY MANAGED MEDITERRANEAN MOUNTAIN LANDSCAPES: A MODEL-BASED STUDY

Beneficiary: João Pedro Nunes, University of Aveiro, Portugal (jpcn@ua.pt)

Host: Saskia Keesstra, Wageningen University and Research centre, Netherlands (saskia.keesstra@wur.nl)

Period: 19/10/2015 to 15/04/2016

Reference code: COST-STSM-ECOST-STSM-ES1306-191015-063626

1. Purpose of the STSM

Traditional agricultural practices in the mountains of the NW Iberian Peninsula involve intricate networks of terraces and irrigation channels, whose effects on water and sediment connectivity are not completely understood. On the other hand, large-scale afforestation with commercial short rotation coppices in the last decades has often replaced this heterogeneous landscape with large homogenous monoculture patches. These suffer irregular but large-scale disturbances, due to clear-cutting or forest fires, which greatly enhance water and sediment connectivity and lead to increased soil loss during short periods of time.

The complexity of both systems has so far prevented an assessment of the long-term sediment yield in each, and therefore also an estimate of the impacts of afforestation on soil degradation in this region. It is, however, possible that modern forestry management practices actually lead to enhanced soil erosion rates when compared with traditional agriculture management.

The main objective of this STSM was to estimate erosion in terraced agricultural fields and eucalypt and pine forest plantations in the Macieira de Alcôba mountain catchment (1 Km^2; Figure 1), central Portugal, between 2004 and 2013. This catchment is representative of the traditional agricultural system which used to dominate this region, but also includes planted forest hillslopes with eucalypt and maritime pines. The analysis took advantage of measured data for runoff, erosion, streamflow and sediment yield between 2010 and 2013, which include data immediately after a large wildfire which occurred in 2011.

Figure 1. Left: the Macieira de Alcôba catchment, including terraced agriculture in the valley and plantation forests in the hillslopes; right: the 2011 fire.

2. Description of the work carried out during the STSM

During my 6-month visit to Dr. Saskia Keesstra at Wageningen UR, I have achieved the purpose of the STSM using two methods:

Data-based analysis of the impacts of terraces on runoff and erosion. Observations on runoff, erosion, soil moisture and vegetation cover during 2 years for a terraced field in Macieira were analyzed to determine how terracing can affect runoff generation and erosion processes, by analyzing correlations between key parameters during runoff and erosion events, and the hydrographs for major storms. Erosion values were then compared with typical impacts of forest fires on erosion in the region to compare soil degradation between terraced agriculture and plantation forestry. An article was submitted to Land Degradation & Development.

Model-based analysis of the long-term (10 years) impacts of terraces and forest fires on erosion and sediment yield. The Soil and Water Assessment Tool (SWAT) eco-hydrological model was applied to the Macieira catchment in collaboration with MSc student Paula Naranjo Quintanilla. The model was calibrated at the hillslope and catchment scales using measured data between 2010 and 2013. SWAT was applied to determine erosion rates in normal and terraced agriculture fields, and burnt and unburnt forests, during this period, and well as catchment sediment yield. Different scenarios were also built to explore the impact of fire severity, post-fire management practices, and type of forest on erosion and sediment yield. The results were used for an MSc thesis at WUR and will be used to write a research article.

During this period, I have also collaborated in other activities related with COST Action ES1306:

Model-based analysis of the impacts of fire on runoff connectivity during storms. Before this STSM, MSc student Christel van Eck worked in collaboration with Dr. Keesstra and myself to apply the LISEM soil erosion model to study the impact of vegetation cover destruction on runoff generation for the Colmeal burnt catchment (central Portugal) between 2010 and 2012. During this STSM, we have analyzed the results of this collaboration to prepare and submit an article to Land Degradation & Development, which is already accepted for publication.

Other activities. My stay at WUR offered the possibility for additional collaboration with ongoing teaching and research activities in WUR regarding connectivity, including:

- co-authoring an article on a new conceptual framework for water and sediment connectivity with Dr. Keesstra, to be submitted to Land Degradation & Development;
- collaborating with PhD student Rens Masselink, Dr. Arnaud Temme and Dr. Keesstra on connectivity between slopes and streams for an experimental study site in Spain;
- working with PhD student Mohammadreza Hosseini and Dr. Violette Geissen on an article on the impacts of fire history on sediment sources in a burnt area of central Portugal, to be submitted to Geoderma;
- helping Dr. Jantienne Baartman organize a connectivity modelling workshop at WUR, to be held in late June 2016 with support from COST Action ES1306;
- lecturing WUR MSc students on the impacts of forest fires for hydrological and sediment connectivity.

3. Description of the main results obtained

3.1. Data-based analysis of the impacts of terraces on runoff and erosion

Figure 2 shows the experimental field and installed instruments. It is an irrigated field, part of a network operating under the "águas de lima" system, common in central Portugal and characterized by irrigation in both the wet and dry seasons: the first to promote soil saturation and prevent frost damage to pasture, and the second to allow for the cultivation of maize under water limiting conditions. The main results for runoff, sediment yield, soil moisture and vegetation growth are found in Figure 3.

The results of this study indicated that the terrace network promotes saturation-excess runoff generation, due to a combination between wet season irrigation practices characteristic of the "águas de lima" system, and the terrace wall limiting water drainage, leading to the occurrence of a shallow water table. In dry years with limited irrigation, results suggested a strong decrease of the runoff generation ratio. Direct run-on from the irrigation network was also found to occur, especially during the largest storms. Figure 3 illustrates how the combination of irrigation and the terrace wall promote soil saturation during winter, even with low rainfall.

Results also indicated that the terrace network promoted sediment export in consequence of additional runoff generation, but this was counteracted by the pasture cover made possible by terracing. Therefore, drought spells during winter may also have an erosion-promoting effect due to the lack of water to irrigate pasture and preventing its growth. This is also illustrated in Figure 3; the drought in the second year limited pasture growth and enhanced sediment export.

The irrigation network was found to promote sediment mobilization within the field, but not necessarily sediment losses, due to the strong soil conservation effect of the terrace. Sediment export was rather limited and unlikely to negatively affect soil quality inside the field, but could be relevant for downstream contamination with phosphorus or pesticides attached to soil particles.

In summary, results found that terraces have a strong impact on connectivity in the Macieira catchment, in two ways:

- by strongly limiting subsurface flow, leading to soil saturation and increased runoff generation;
- by limiting sediment export from the terraced fields.

Published data indicates higher erosion in plantation forests than in this terraced field, especially after recurrent disturbances such as management operations and wildfires. In any case, the dataset of this study is somewhat limited, especially in time, opening the door for further studies aiming at a better understanding of the "águas de lima" system and its role in hydrological and sediment connectivity in northwestern Iberian landscapes. In particular, there is a need for further information on soil moisture for the entire soil profile, on irrigation practices and on the hydrological and erosion response behavior of these systems during stronger storms with infrequent return periods.

Figure 2. Left: view of the experimental field, from the highest point facing downslope; the upper picture was taken in October 2010, as pasture was just beginning to grow, while the lower picture was taken in March 2011. Right: aerial photograph of the experimental field with the direction of the photos.

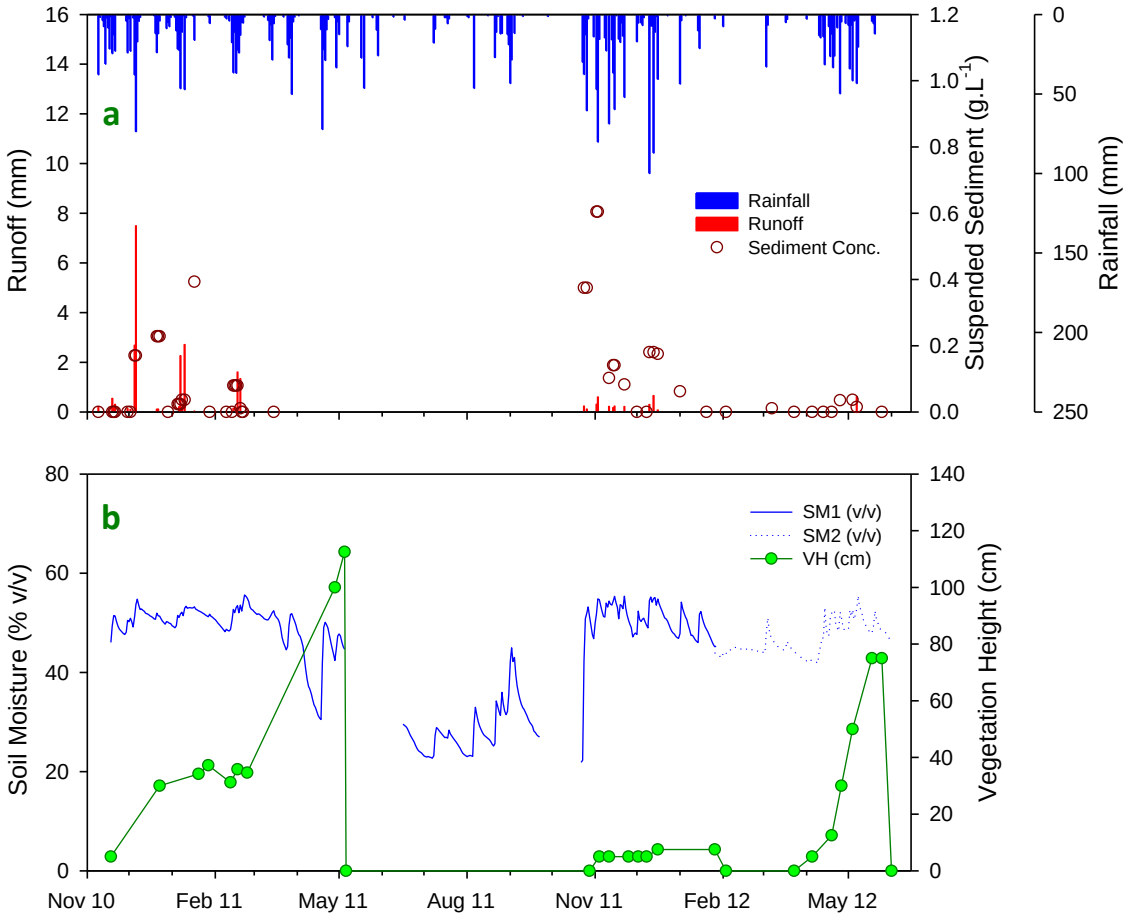

Figure 3. a) daily rainfall, runoff and sediment concentration from the field. b) soil moisture (SM1: measured inside the field, SM2: measured in a nearby pasture) and height of pasture vegetation (VH); the field was covered by maize between May and November 2011, but vegetation height was not recorded.

3.2. Model-based analysis of the long-term (10 years) impacts of terraces and forest fires on erosion and sediment yield

The SWAT (Soil and Water Assessment Tool) eco-hydrological model was applied to Macieira de Alcôba between 2004 and 2013, a period which included a forest fire in 2011 (Figure 4). The model was successfully adapted to simulate the effects of forest fires. SWAT was not originally developed to simulate environmental disturbances such as the impacts of forest fires; however, the effects of the 2011 forest fire were correctly simulated by adding multiple land-use change operations to the model, such as removing the vegetation just after the fire, introducing resprouting vegetation immediately after the fire, simulating terrain preparation for re-planting using deep ploughing, and introducing a crop to represent young re-planted forest.

In general terms, SWAT was able to the hydrological and sedimentological response of Macieira de Alcôba. Satisfactory results were found for streamflow in model calibration and validation at daily timescale, although it was not possible to simulate the seasonality of hydrophobic processes in the soil (Figure 5). Model performance for sediment yield was only satisfactory at the monthly scale due to a poor performance of the stream sediment transport module. At the field scale, the erosion results provided by SWAT match the field measurements for agricultural areas and burned forest plots.

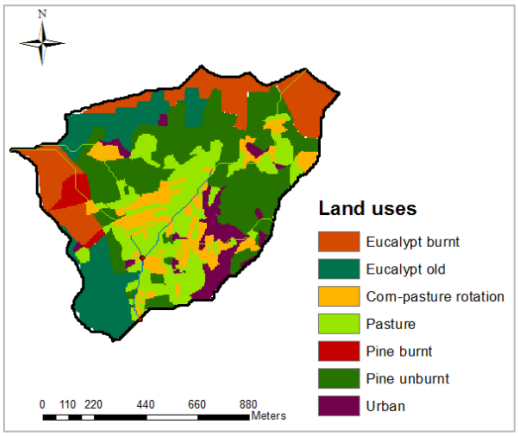

Figure 4. Land use classes used in the SWAT application to the Macieira de Alcôba catchment.

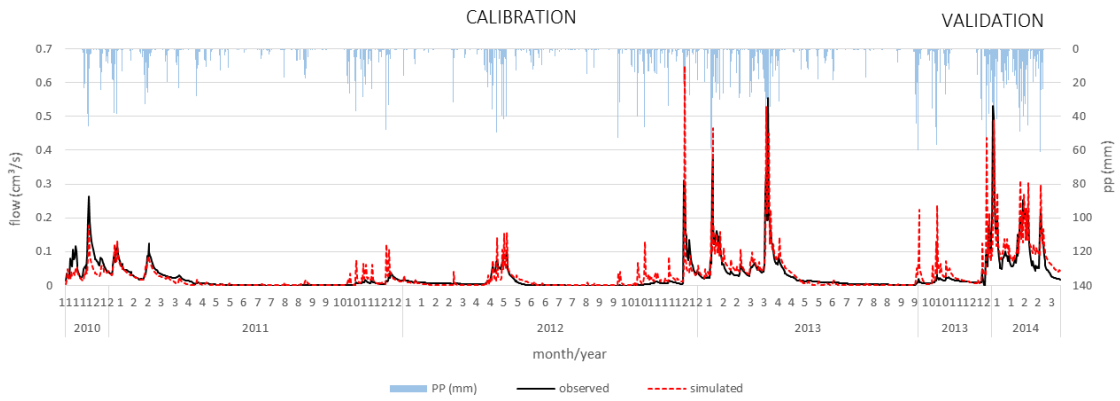

Figure 5. Observed (black) and simulated daily streamflow data (red) in the Macieira de Alcôba catchment, for the calibration and validation periods.

The results show that vegetation cover and terracing are key factors influencing erosion and sediment yield. 90% of erosion between 2004 and 2013 occurred in the burnt forest hillslope; the average rate was estimated at 2.3 ton.ha^{-1}.yr^{-1}, of which most (23 ton.ha^{-1}) occurred in the two and a half years after the fire (Figure 6). In contrast, erosion rates in the agricultural areas were 0.4 ton.ha^{-1}.yr^{-1}, of which most occurred in non-terraced fields (about 2/3 of the total, with 0.6 ton.ha^{-1}.yr^{-1} erosion rates); these tended to occur mostly in years with a combination of delayed pasture development and high autumn and winter rainfall in the low vegetation cover period (Figure 6). Even when considering the return period for forest fires in Macieira since the 1980's, which is about 20 years, long term erosion rates for forested slopes would still be twice of those for unterraced agricultural fields, and two orders of magnitude higher than those of terraced fields.

Six hypothetical land-use scenarios were also simulated in SWAT, and compared in terms of their hydrological and sedimentological response. These included:

- "no plough", where the burnt forest was not ploughed in preparation for re-planting;
- "afforestation", where the entire catchment was covered by forest (and hence without terraces), also considering a slightly larger fire in 2011;
- "old times", where hillslopes were covered by managed shrublands instead of forests, representing a pre-afforestation scenario;
- "pine plantation", where forests were maritime pine instead of eucalypts, representing the situation before the 1980s';
- "no fire"; and
- "severe fire", where the entire catchment was considered burned, simulating what happened to many neighboring catchments during the very severe 2012 forest fire in the Caramulo mountain range (Figure 7).

The lowest runoff and erosion rates are attributed to the scenario without fire, while the highest values were found for the severe fire scenario (Figure 8). For similar fires, eucalypts were associated with higher erosion and runoff values, while pine and natural vegetation (shrubs) were expected to show less soil loss. Moreover, simply avoiding post-fire ploughing led to a large

decrease of erosion. The scenario analysis confirmed that the forest fire was the main cause of erosion in Macieira between 2004 and 2013; however, rates could be highly affected by the forest type and post-fire management operation. In this case, model results indicate that the combination of eucalypt plantation and post-fire ploughing is the worst for soil conservation, and that better results could be obtained with, for example, afforestation with pines and no ploughing after fires. However, erosion from the burnt area was dominant over that from agricultural fields in all scenarios except "no fire".

Overall, model results indicate support the assessment that, by destroying the pre-existing terrace network, afforestation has promoted sediment connectivity in Macieira, especially after being disturbed by forest fires; and therefore, that it has not promoted soil conservation in this region. They also indicate that mitigation strategies could be achieved by modifying planted forest types and not using post-fire management practices which enhance sediment connectivity. Further research is needed to assess the significance of these long-term erosion rates for soil degradation in forested hillslopes, although empirical evidence suggests that soils in frequently burnt slopes are less capable of supporting forests due to accumulated erosion.

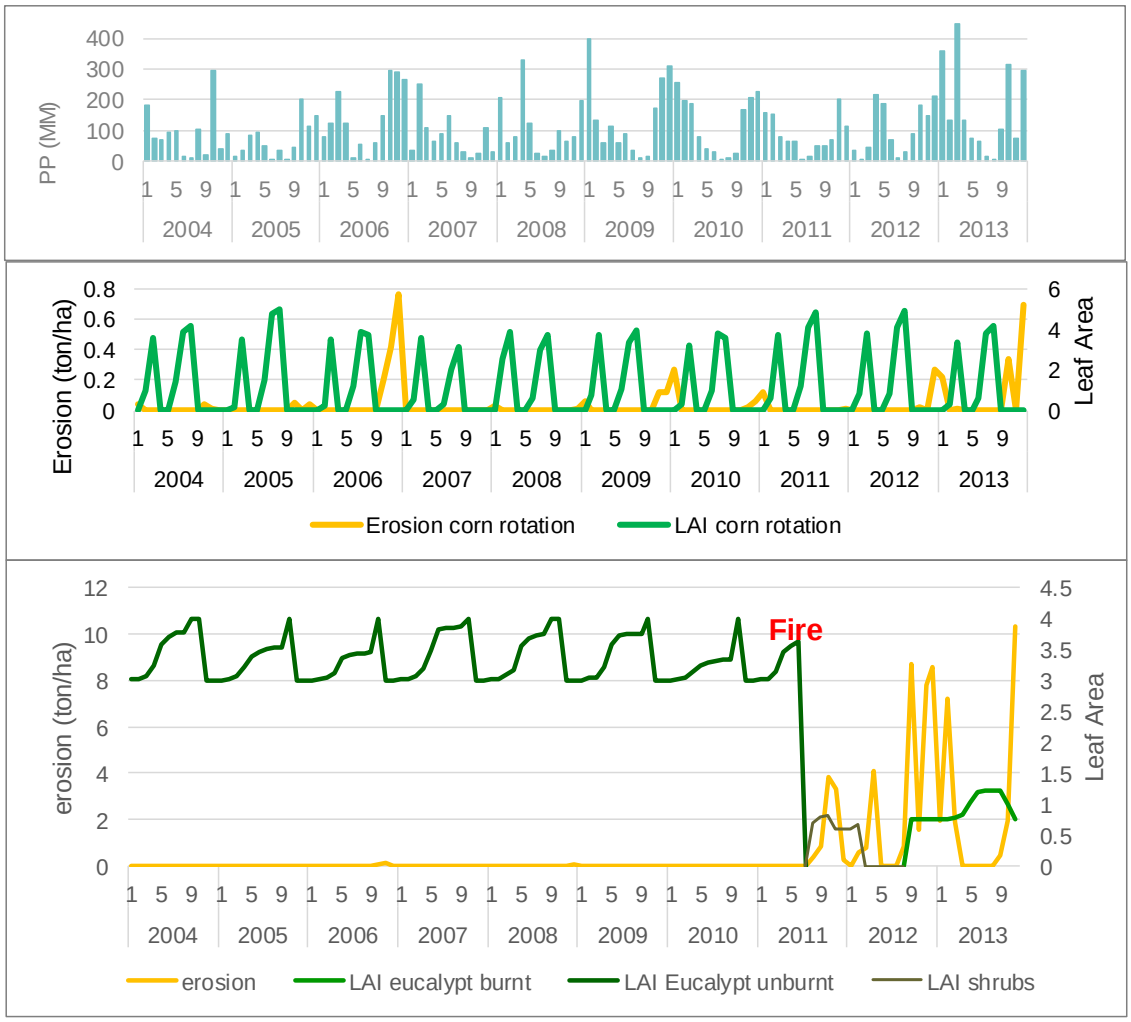

Figure 6. Top: measured rainfall; middle: simulated LAI and erosion for the pasture/corn rotation in agricultural fields; and bottom: simulated LAI and erosion for the burnt forest area.

Figure 7. Impacts of the 2012 forest fire in the Caramulo mountain range, close to the Macieira catchment.

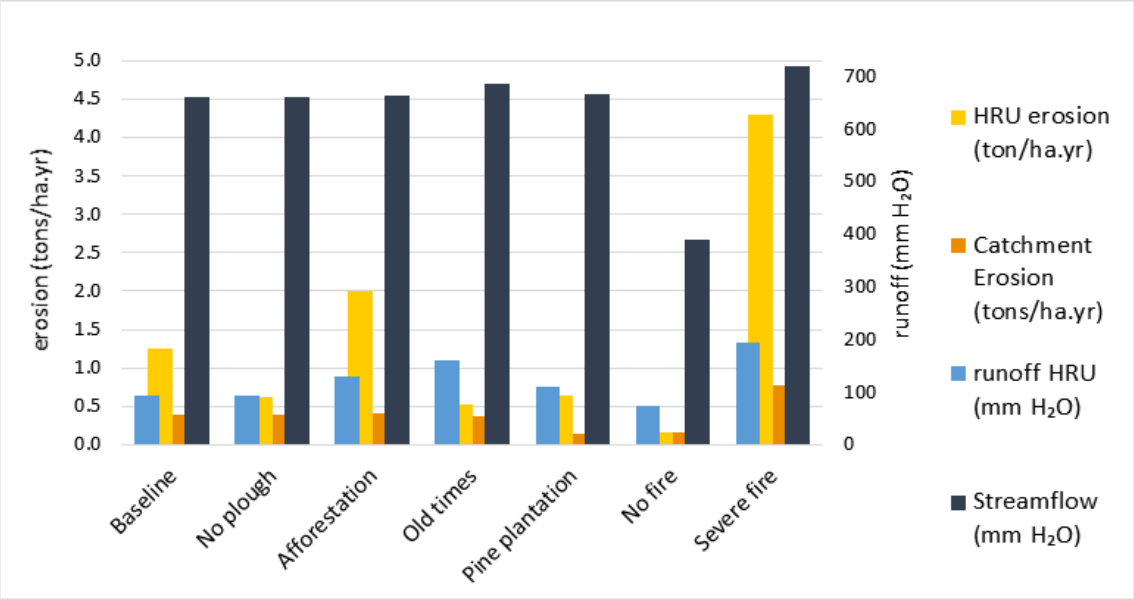

Figure 8. Average erosion and surface runoff rates at the field scale, compared with catchment streamflow and sediment yield, for the different simulated scenarios.

3.3. Model-based analysis of the impacts of fire on runoff connectivity during storms

The LISEM rainfall-runoff model was applied to the Colmeal burnt catchment (0.1 Km^2) in central Portugal to assess the impacts of vegetation loss and recovery on hydrological connectivity in a burnt catchment. Vegetation cover, in this case eucalypt plantatons, was assessed in two ways: direct measurement and satellite imagery (NDVI), for different moments two years after the fire (Figure 9). The model was applied to storms which occurred in these moments, using both measurement methods and also a simulation of pre-fire vegetation cover conditions.

LISEM showed an acceptable performance for simulating relative differences between peak and total flows, but not for actual values (Figure 10). This could be attributed essentially to problems with simulating soil moisture, underestimating flow peaks in repellent conditions, and underestimating total flow with saturated soils near the stream. In contrast, LISEM showed little sensitivity to the interception simulation, regardless of the method and of the presence of full vegetation recovery (Figure 10). This can be attributed to the generally low interception rates by eucalypts, which average c. 20% but are much lower in the stronger rainfall events. This indicates that fires over eucalypt plantations tend to have small impacts on runoff connectivity, mainly since connectivity is already high in unburnt conditions. However, further research should evaluate the impacts of vegetation cover loss on sediment connectivity.

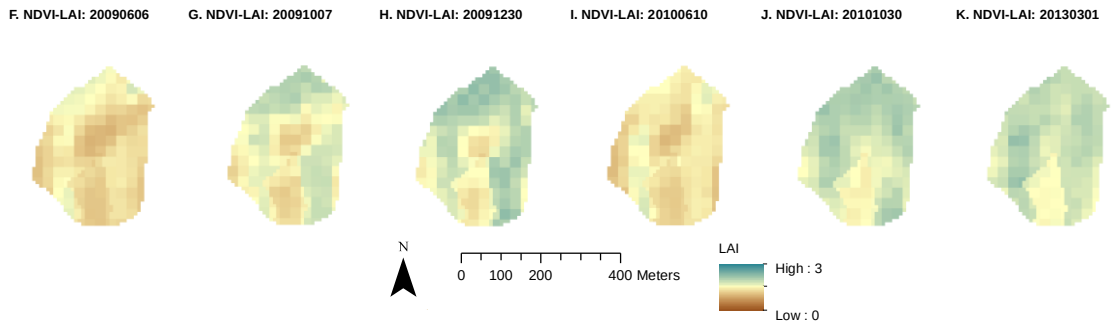

Figure 9. Evolution of vegetation cover in the Colmeal study area measured by satellite imagery; "K" represents a situation with full recovery of canopy cover.

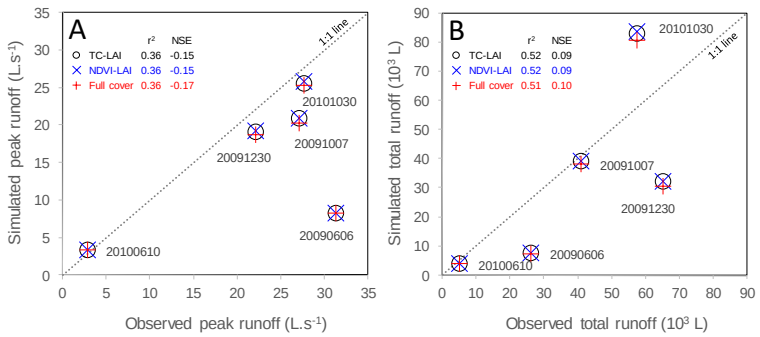

Figure 10. Overall model performance LISEM for total runoff (A) and peak runoff (B), evaluated with r^2 and NSE for TC-LAI relationship (black), NDVI-LAI relationship (blue), and full-cover scenario (red).

4. Future collaboration with the Host Institution

My successful visit to WUR has led me to explore several options for continuing collaboration. In particular, the connectivity of sediments in post-fire environments is still a very relevant research topic due to their potential for contamination of streams and drinking water supplies. Several activities are already being proposed:

- the join supervision of a new master student in 2016/2017 has been agreed, with the proposed topic of quantifying and mapping the impact of terraces on sediment connectivity in central Portugal;
- a funding request for a subsequent STSMs in WUR during the latter half of 2016 has been submitted to the Portuguese funding agency;
- an individual research grant was submitted to the Portuguese funding agency for 2017-2021, which includes a strong collaboration with WUR and several STSMs;
- I have integrated a Marie-Curie ITN proposal, which includes a PhD student jointly supervised by myself and WUR in 2017-2020.

5. Publications resulting from the STSM

From the main STSM results:

Nunes JP, Bernard-Jannin L, Rodríguez Blanco ML, Santos JM, Coelho COA, Keizer JJ. Submitted. Hydrological and erosion processes in terraced fields: observations from a humid Mediterranean region in northern Portugal. Submitted to Land Degradation & Development.

Nunes JP, Naranjo Quintanilla P, Serpa D, Rocha J, Carvalho Santos C, Keizer JJ, Keesstra S. In prep. Assessing the effects of forest fires and land use change on erosion and runoff in a small humid agroforestry catchment. For submission to Land Degradation & Development.

From other activities:

van Eck CM, **Nunes JP**, Vieira DCS, Keesstra S, Keizer JJ. In press. Physically-based modelling of the post-fire runoff response of a forest catchment in central Portugal: using field vs. remote sensing based estimates of vegetation recovery. Land Degradation & Development (DOI: 10.1002/ldr.2507).

Hosseini M, **Nunes JP**, Gonzalez Pelayo O, Keizer JJ, Ritsema C, Geissen V. In prep. Modelling the effect of fire frequency on runoff and erosion in north-central Portugal using the revised Morgan-Morgan-Finney model. For submission to Geoderma.

Keesstra S, Cerdà A, Parsons T, **Nunes JP**, Saco P. In prep. A new conceptual framework for water and sediment connectivity. For submission to Land Degradation & Development.

6. Other comments

A letter from Dr. Saskia Keesstra from WUR confirming the successful execution of the STSM is attached. I hereby authorize posting this report at the COST ES1306 Action website.

Aveiro, 16/04/2015

João Pedro Carvalho Nunes