Master Thesis in Geographical Information Science nr 46

Can the introduction of the topographic indices in LPJ-GUESS improve the spatial representation of environmental variables?

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2016
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Alejandra Narváez Vallejo (2015). Can the introduction of the topographic indices in LPJ-GUESS improve the spatial representation of environmental variables?
Master degree thesis, 30/ credits in Master in Geographical Information Sciences
Department of Physical Geography and Ecosystems Science, Lund University

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Master thesis, 30 credits, in Geographical Information Sciences

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Acknowledgements

This research has been successfully finished thanks to the support and motivation of many people. First of all I would like to thank Dr. Abdulghani Hasan for his supervision and support, for the allowance to use one on his developed hydrological tools and specially for giving me the push and the chance of going from an idea to a Master thesis. Deepest gratitude also to Dr Mats Lindeskog, for his enormous help and disposition to help me with all my questions relating to LPJ-GUESS and for helping me to do the proper changes. Thanks for his huge patience and comments. Special thanks also Dr. Jing Tang for her initial supervision, further comments, and for her support and the changes done within the model to introduce the climate data and other input in the model, and also for bringing me into the world of environmental modelling. Huge gratitude to Guido Lüchters for his great and generous marathon introduction on the statistical analysis, for showing me the way to go and not to go.

I thank very much Simon Stisen in behalf of HOBE Center for Hydrology in Denmark for the provision of the data needed and the proper clarifications. Thank you very much for your patience and the answering of all the needs.

Dear Family, mother, Gunther Schorcht, little son, I love you all immensely, thank you for your understanding, support and love. Thank you God for the strength, thank you God for the new chapter of my life.

ABSTRACT

Ecosystem modelling is an always evolving science trying to catch the complexity of the nature and its principles to model environmental responses in a realistic way. Over and over, models try to introduce more variables and interactions to achieve better representations of phenomena of interest like the responses of the ecosystem to a fast changing world (climate change, land use change). LPJ-GUESS is a flexible dynamic ecosystem model widely used to model the structure and dynamics of terrestrial ecosystems. It is based on plant physiology, biochemical cycles and feedbacks on independent gridcells, there is no consideration of lateral transfer of water between cells. On the other hand, soil moisture is essential for vegetation growth and its distribution is known to be driven by the topography of the landscape, which drives the lateral transfer of water. Based on this, it was considered important to assess the modelled spatial representation of environmental variables (soil moisture, LAI) from LPJ-GUESS and to evaluate a possible method to include the effect of topography over the hydrology in LPJ-GUESS model. For this, Alergaarde catchment (smooth relief) was chosen and by the use of correlation analysis and visual interpretation the following issues were studied, 1) Importance of topography on the spatial distribution of environmental variables based on topographic indices (Ln (Drainage area), tan (angle slope) and topographic wetness index, TWI); 2) LPJ-GUESS ability to catch the environmental variables spatial distribution and 3) Implementation of a coupled LPJ-GUESS - topographic indices model to account for the topography influence on hydrology and assessment of its performance on modelling the spatial patterns of environmental variables.

Results of the first two topics showed how LPJ-GUESS could not catch the spatial variations of satellite based LAI, and that even the gentle topography of the catchment was an important issue on explaining the heterogeneity of vegetation related variables. Nevertheless, there are many factors, like climate conditions, which affect the strength of this relationship, as reflected on low correlation coefficients (never over 0.25), the variable correlation coefficients along the year and the identification of areas more related to the topographic indexes than others. Additionally, TWI was selected, based on its higher correlations with respect to the other topographic indices, to be one used to represent the topography influence in the catchment. The integrated model, LPJ-Topographic index (LPJ-TI), use the TWI to make a cell wise characterization and create weights affecting the water inputs to the soil layer as a way to account for hydrological processes driven by topography. LPJ-TI showed localized and time dependent improvement of the spatial representation of the satellite based LAI. These results confirm the need to include the topographic influence on the hydrological module of LPJ-GUESS and present a possible low computational method to start working on.

Keywords: Physical Geography and Ecosystem Information Systems, GIS, LPJ-GUESS, topographic wetness index, slope, drainage area, smooth topography, leaf area index, spatial patterns, MODIS LAI.

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LIST OF ABBREVIATIONS

BNE	Boreal needleleaved evergreen tree
CFT	Crop functional type
CRU	Climatic Research Unit
DA	Drainage Area
DEM	Digital Elevation Model
DGVMs	Dynamic global vegetation models
Ei	Interception loss
E_s	Evaporation from the soil
E_t	Transpiration
fPAR	daily fraction of the photosynthetically active radiation
FPC	Foliar protective cover
GPP	Gross primary productivity
LAI	Leaf area index
Ln (DA)	Natural logarithm of the drainage area
LPJ-GUESS	Lund –Potsdam-Jena General ecosystem simulator
LPJ-TI	coupled LPJ-GUESS with TWI index
MODIS LAI	LAI computed from MODIS NDVI
NEE	Net CO_2 ecosystem exchange
NPP	Net Primary production
per	Percolation
PAR	Photosynthetically active radiation
PFT	Plant functional type
PHU	Phenological heat units
Pr	Precipitation
Pt	Throughfall
Rsub	Subsurface runoff.
Rsuf	surface runoff
Sm	Snowmelt
SOM	Soil organic matter
tan (b)	Tangent (slope angle)
TFM	Triangular Form- based multiple flow algorithm
TWI	Topographic wetness index
w_{max}	available water holding capacity
Δw	Daily changes in the soil water content as a fraction of the available water holding capacity

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1 INTRODUCTION

Hydrological cycle and vegetation structure are inevitably bound to each other. Vegetation is a very complex living component of the ecosystem, and as a living entity it changes and feeds itself mainly with water, CO_2 and energy (light). Vegetation productivity and distribution depends on water availability. In turn plants intercepts water on their leaves, catches water and nutrients with their roots, metabolize water and CO_2 by photosynthesis, transpires and respires releasing CO_2 again. Additionally plants changes surface albedo altering the amount of energy reaching the surface needed for evaporation (Mika et al., 2001). In this way vegetation changes alter energy and water distribution on the ecosystem.

As explained above CO_2, water, vegetation interactions and feedbacks are complex, and very important for assessing the ecosystem dynamics, impacts of climate change, land use change and many other related issues are continuously coming to light on a fast transforming world (Mahmood et al., 2010). Accordingly, the interest on models capable of dealing with such phenomena is growing. Consequently, since the late 1980s global terrestrial models integrating biochemistry and biogeography are gaining importance (Sitch et al., 2003) and have led to the development of what was been called the “Dynamic global vegetation models” (DGVMs).

DGVMs uses a variety of biochemical processes, biogeochemical cycles and feedbacks to reproduce vegetation dynamics, composition and distribution (Bondeau et al., 2007). LPJ-GUESS is a well- established DGVMs model which has been proven to be very accurate on the simulation of carbon cycles, runoff, biomass prediction, and vegetation distribution at the global, regional and local scale (Lindeskog et al., 2013; Bondeau et al., 2007; Sitch et al., 2003; Gerten et al., 2004; Tang et al., 2013). Initially LPJ-GUESS was developed to investigate potential natural vegetation, but on the last decade the strong need to incorporate the great influence of manmade ecosystems on water and carbon cycles have led to the incorporation of new strategies to assess areas influenced by human activities. Accordingly, some human activities where included on LPJ-GUESS on LPJ managed land (LPJml) for global scale simulations (Bondeau et al.,

2007) and LPJ-GUESS crop version for regional /local scales (Lindeskog et al., 2013). These models present a very realistic and functional image of the world´s terrestrial ecosystem by allowing the representation of natural vegetation, agricultural and grazing lands together with their special features. On the implementation of the models Bondeau et al., (2007) found realistic values on the simulation of CO_2 seasonal cycles in regions of Finland and USA, and on the yields prediction of temperate cereals in western Atlantic Europe, Central Asia, Australia and Caucasus. Similarly Lindeskog et al. (2013) reported a better representation, than the original LPJ-GUESS, on the vegetation greenness seasonality on areas of extensive croplands in Africa and promising results on potential optimal yields.

Though the positive results found, LPJ-GUESS requires no kind of topographic input and ignores horizontal fluxes between adjacent areas (neighbouring grid cells). This fact does not allow the modelling of water routing, affecting the seasonal performance of the rivers modelled by early runoffs (Gerten et al., 2004). Additionally, given the strong link between vegetation and water, the underestimation / overestimation of water input on the regions affects most of the model components, like soil respiration, vegetation distribution and productivity. This limitation was recently meant to be overcome by LPJ-Distributed Hydrology (LPJ-DH) model (Tang et al., 2013), which integrates initially LPJ-GUESS with a single flow algorithm (Tang et al., 2013) and later on with a multiple flow one (Tang et al., 2015). The outputs of LPJ-DH simulation on a small catchment (16 km^2) in Northern Sweden (Tang et al., 2013) showed an upgraded performance than the non-integrated LPJ-GUESS version: better representation of the drainage network and better agreement of runoff and biomass to the observed data. The LPJ-DH approach confirmed the necessity to integrate the topography influence on the water dynamics into the model; nevertheless, this approach increased greatly the computational effort of the model.

Topography is a critical factor on determining the overland flow of water on a catchment, which is a key process on defining the amount of water available at every specific site; therefore basic for the water balance and all the ecological processes linked to it. During all the modelling history there have been many approaches, known as hydrological models, trying to estimate the distribution of water in a catchment. Such models can compute among others information regarding, slopes, flow direction, drainage area and important indexes like the topographic wetness index (TWI). This information defines water routing and help on creating a hydrological characterization of every site on a catchment.

On a specific location, drainage area (DA) measures the extension of area which have the potential of moving water towards it, the angle slope (b) gives information on its possibility to retain water, while the TWI comprises both:

$$TWI = Ln\ (DA/\tan(b)) \qquad \text{Eq 1.}$$

TWI is considered good for quantifying the topographic control on hydrology (Sørensen et al., 2006). TWI gives an indication of soil moisture, it is an essential part of TOPMODEL (Beven and Kirkby, 1979), which was originally included on the hydrological module on RHESYSS (Regional Hydro- ecological Simulation system) (Tague and Band, 2004). TWI has been used to characterize net primary productivity, runoff (White and Running, 1994), vegetation patterns (Moore et al., 1993), distribution of plant species richness (Zinko et al., 2004) and has been found to correlate well with groundwater depth and soil pH (Zinko et al., 2004).

Under this frame it is considered possible and necessary to include the influence of the topography on LPJ-GUESS to get a better representation of the reality. Additionally, it was remarked that the topographic information can be resumed into topographic elements or indexes that are able to characterize hydrological properties of a site. Based on this information the present master project aims to a) evaluate the performance of LPJ-GUESS focusing on the simulation of the spatial patterns of environmental variables (soil moisture, Leaf Area Index); b) test whether the inclusion of TWI on behalf of the topography into LPJ-GUESS (LPJ-TI), can improve the spatial pattern representation on distributed environmental variables (Leaf Area Index, soil moisture). The proposed method makes a site specific characterization of the influence of the topography on the hydrology based on the TWI. This characterization is used as weights affecting the water input into the soil of every cell of the catchment. This method will therefore not simulate the physical movement of water, but is meant to make a site specific approximation of the influence of the topography on the hydrology under a low computational cost. As a consequence, positive results will show how a simple methodology could help on the approximation of complex dynamics, and will open the path for LPJ-TI's further tuning and later on the possibility of intensive usage and application on larger areas given its simplicity.

For this purpose, the Alergaarde catchment on Denmark was selected. Though this is a catchment with very little relief/smooth topography, it has been well studied and counts with time series of soil moisture observation data and long time series of satellite based LAI ideal for making analysis of the spatial patterns and heterogeneity. As a consequence of the catchment election, a derived aim of this work is to analysing the importance of topography on the definition of spatial heterogeneity of environmental variables on a smooth catchment. Generally, studies analysing topographic influence on soil moisture deal with undulating and rough landscapes (Western et al., 1999; Feng et al., 2013; Qui et al., 2001). Hence, this work is also contributing with the comprehension of the magnitude of the relationship between the water dynamics and the topography.

1.1 Objectives

<u>Main objective</u>

Evaluate the importance of introducing the influence of topography, represented by topographic indices, on LPJ-GUESS for the hydro-ecological modelling of a smooth relief catchment (Alergaarde catchment, Denmark)

<u>Specific Objectives</u>

a) Analyse the importance of topography on defining the spatial heterogeneity of environmental variables on a smooth catchment.
b) Evaluate LPJ-GUESS' ability to reproduce the environmental variables spatial distribution.
c) Implement the proposed LPJ-TI to account for the topography influence on hydrology in LPJ-GUESS and assess its performance on modelling the spatial patterns of environmental variables.

1.2 Work structure

Based on the exposed objectives the structure of the work is as follows. After the background information and site description, the methodology is presented. This part starts describing LPJ-TI and then the overall information on data collection and pre-processing. Finally on the methodology section, the specific methods to approach the objectives are explained within two main topics:

- Topic one "Topographic influence on the soil moisture and LAI spatial patterns on the Alergaarde catchment" related with the first specific objective.
- Topic two "Original LPJ-GUESS vs LPJ-TI" related to the second and third specific objectives.

The topics are developed one after the other through the results and discussion sections and finally the overall conclusions and recommendations are presented.

2 BACKGROUND

2.1 LPJ-GUESS: Model description

For a better comprehension of the model on the following sections, LPJ-GUESS as natural module will be first described together with the hydrological module. Following LPJ-GUESS features for managed land are explained, which is the module run on this work.

On this text LPJ-GUESS is the generic name of the model and it includes two vegetation modes (population and cohort). On the literature these two vegetation modes are usually given separate names, LPJ-DGVM for the population mode and LPJ-GUESS for the cohort mode. Please, keep this on mind when reviewing literature.

2.1.1 LPJ- GUESS

LPJ-GUESS (Lund – Postdam - Jena General ecosystem simulator) is a flexible dynamic ecosystem model widely used to model the structure and dynamics of terrestrial ecosystems at different spatial scales (Smith et al., 2001). Such dynamics covers the vegetation growth, competition, demographic growth and natural fire disturbances and the land/atmosphere carbon and water exchanges (Sitch et al., 2003). Many studies on the model has proven its success on simulating fluxes and seasonal cycles of CO_2, vegetation distribution (Sitch et al., 2003, Zaehle et al., 2005), biomass, runoff (Gerten et al., 2004, Sitch et al., 2003,) and the soil moisture (Sitch et al., 2003; Wagner et al., 2003). The results of these studies were found to be very accurate, on the range of the measured data or at least to properly follow the seasonal pattern of the phenomena.

The model is based on plant physiology, soil geochemistry and biogeographical processes grouped in modules and simulated at different spatial and temporal resolutions (Figure 1). The input data to the model consist of climate parameters at daily or monthly scale, atmospheric CO_2 concentrations at annual scale, a soil code used to derive texture-related parameters governing the hydrology and thermal diffusivity of the soil and the plant functional type (PFT) parameters. The soil code and the PFT are static input data during the model run. The processes modify the state variables of the ecosystem (Net Primary production (NPP), Soil water availability, vegetation structure, etc.) (Smith et al., 2001). As a result, new state variables are obtained, allowing the assessment of vegetation dynamics on time and space. Furthermore, outputs regarding the biogeochemical fluxes of CO_2 and H_2O between land and atmosphere completes an integrated view of the ecosystem and broadens the assessment frame of the biomes.

The model may be applied to simulate on particular areas or regions, or across a tessellated area, where each grid is modelled independently no allowing interactions with vicinity: no species dispersal, no runoff fluxes between areas (Smith et al., 2001).

2.1.1.1 Plant functional types and the average individual

The key entity of LPJ is the average individual of a plant functional type (PFT). The PFT are the simplified representation of the structure and functional variety of all the groups of higher plant species (Sitch et al., 2003). Each PFT has key attributes describing specific physiology, morphology, phenology, bioclimatic limits (defining its survival and regeneration), life history strategy and fire response attributes (Smith et al, 2001). The differences between the features of each PFT affect the way they regenerate, compete for resources, response to disturbances; consequently its success on specific climates.

2.1.1.2 Vegetation dynamics modules

Originally LPJ-GUESS were two related ecosystem models differing on the way vegetation was internally represented in the model: 1) LPJ (Lund, Postdam, Jena), a dynamic global vegetation model simulating growth of populations of PFT over a grid cell, named “Population mode” on the current model and 2) GUESS (general ecosystem simulator) which simulates explicitly growth and competition among individuals, currently found as “cohort mode” on the LPJ-GUESS model (Smith et al., 2001).

The population mode is a very simplified and fast mode. The modelled unit is a cell of large extension, where different vegetation stands can be represented with a single “average individual” for each PFT. On the other hand, the cohort mode consist of a patch- based representation with many averages individuals for each PFT representing different class ages. Here the population dynamics are stochastic and based on a “gap model” approach, FORSKA (Leemans and Prentice, 1989; Prentice et al., 1993 from Smith et al., 2001). The cohort model is the one used on this study, and the following descriptions are therefore based on this mode.

2.1.1.3 Simulated processes

The simulation on any grid cell is driven by the input climate, soil and CO_2 concentration data, from which variables such as soil temperature, potential evapotranspiration, cloudiness and precipitation on daily basis are derived.

Based on a coupled photosynthesis and water balance scheme of BIOME3 the gross primary productivity (GPP) is calculated (Sitch et al., 2003). Afterwards the maintenance and growth respiration subtraction is made resulting on the net primary production (NPP), from which a new subtraction of the reproduction cost (goes to litter) is performed to obtain the total carbon available for being allocated on the tissue compartment (Figure 1).

Annually there is a tissue turnover, going to the soil as litter (leaves and roots) or transforming from sapwood to heartwood. Following and simultaneously, decomposition processes are taking place on the new and old litter materials, liberating CO_2 to the atmosphere, which in the model is known as heterotrophic respiration and given on a monthly time frame. Decomposition rates of the resulting above and below ground litter depends on moisture and air or soil temperature respectively.

Population densities are defined annually depending on the mortality, establishment and disturbances. The mortality is the reduction on the population density occurring as a response to depress growing efficiency, heat stress, negative NPP, exceedance of bioclimatic limits, light competition and a background mortality associate to the PFT longevity. The biomass associated to the death organisms distributes to the above and below ground litter pools according to the specific PFT. Mortality events are separate on tree ages on the cohort mode, where the life history characteristics are taken into account and the seedling state (young plants: between germination and the appearance of the first leaves) is the most vulnerable one.

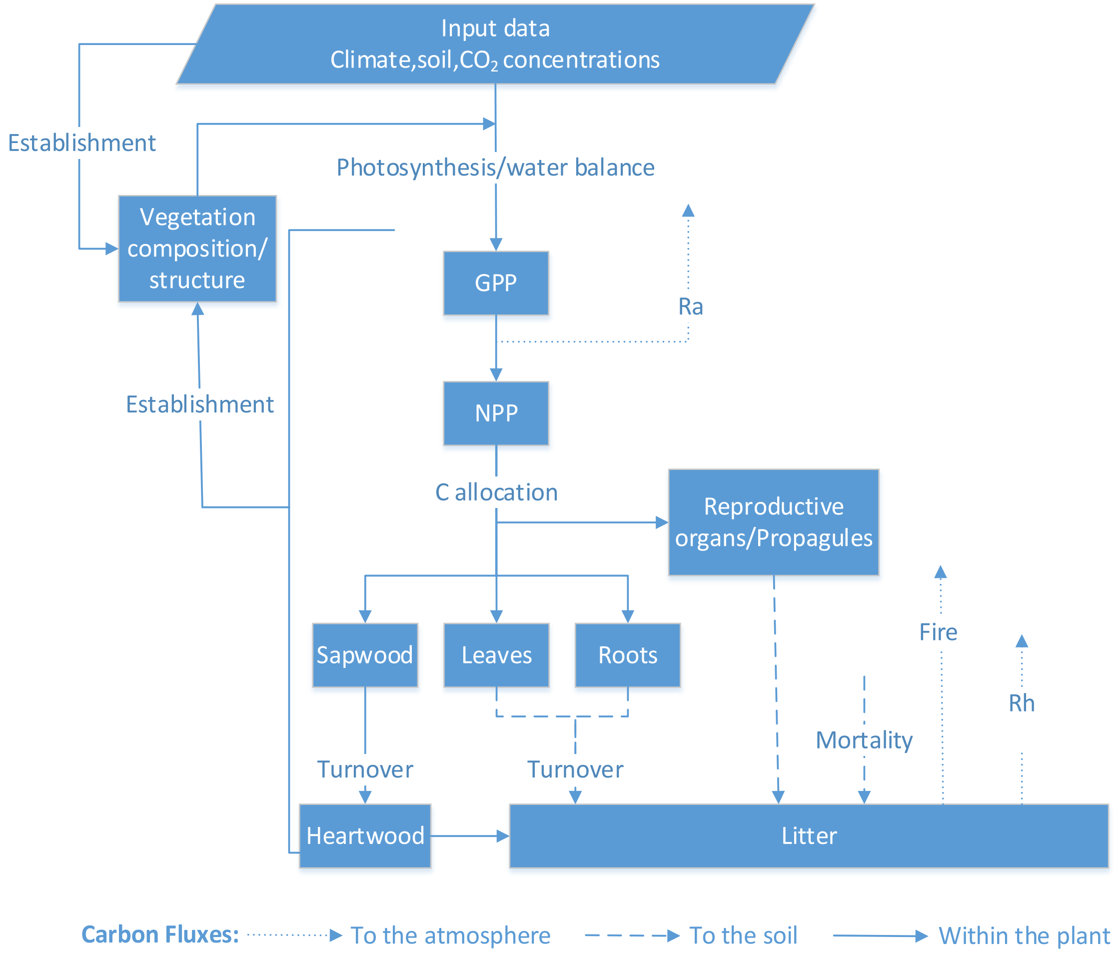


Figure 1: Carbon pools and fluxes simulated by LPJ_GUESS. Gross primary production (GPP), autotrophic respiration (R_a) and net primary production (NPP) are computed daily in accordance to the leaf phenology (daily). $R_{h,}$ heterotrophic respiration (decomposition) is also simulated daily. Individual allocation and growth, population dynamics and disturbances are implemented yearly. The carbon pools are represented on the square boxes.

Fire is the most important disturbance at a global scale (Sitch et al., 2003).Fires result on mortality and full combustion of biomass and litter, generating a CO_2 flux to the atmosphere. Cohort mode only takes an average fire disturbance interval and works as a stochastic process destroying all biomass on the patch affected (Smith et al, 2001).

2.1.1.4 LPJ-GUESS hydrological cycle

The hydrological cycle is immerged on all the components of LPJ-GUESS. This section is dedicated to cover the components of the water balance and the water fluxes occurring in the model in accordance to the description of Gerten et al. (2004).

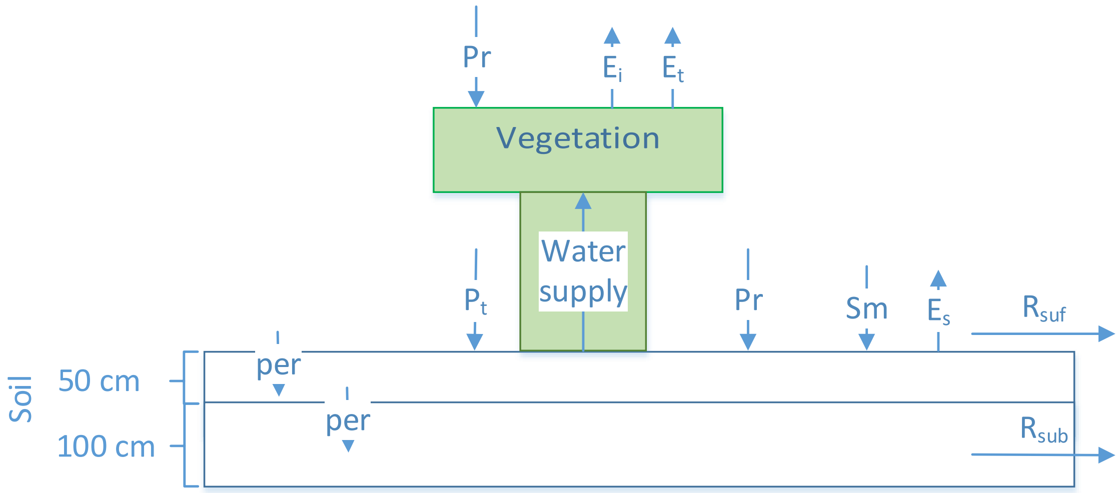


Figure 2: LPJ-GUESS water balance components. Pr, Precipitation; Pt, throughfall; Sm, snowmelt; E_i, interception loss; E_t, transpiration; E_s, Evaporation from the soil; per, percolation; R_{suf}, surface runoff; R_{sub}, subsurface runoff. The soil hydrology are daily processes. Based on Gerten et al. (2004)

The hydrology scheme bases on two main points: 1) Availability of water for plant growth based on storage and flow within a two-layered soil profile of define thickness; 0.5 m and 1 m for the upper (ul) and lower layer (ll) respectively, and 2) All water above the water holding capacity will produce runoff or go to deep percolation.

Water enters the system as precipitation (Pr) or snow, one fraction of it reaches the soil directly or through the vegetation and a second fraction is retained on the vegetation and leaves by evaporation (interception loss E_i) (Figure 2). E_i is a function of PFT, leaf area index (LAI) and precipitation amount. The water reaching the soil enters the upper soil layer through precipitation, or melting of snow. This water can be used by plants and lost via transpiration, lost directly via evaporation from bare soil, produce runoff or percolate to the lower layer or beyond the reach of plant roots. Plant transpiration is coupled to photosynthesis potentially limited by PFT-specific root distribution and soil water content on each layer.

Based on the mentioned processes the water content on both soil layers are update daily as follows:

$$\Delta w_1=(P_t + Sm - E_t - E_s - per_1 - R_{surf})/w_{max1} \qquad \text{Eq. 2}$$

$$\Delta w_2= (per_1 - E_t - per_2 - R_{sub})/w_{max2} \qquad \text{Eq. 3}$$

Where, Δw_1 and Δw_2 are the daily changes in the soil water content as a fraction of the available water holding capacity w_{max} of the upper and the lower soil layer respectively; P_t is through fall (precipitation minus interception lost), Sm is the snow melt, E_t is transpiration, E_s soil evaporation, per percolation, R_{surf} surface runoff and R_{sub} subsurface runoff (Gerten et al., 2004)

The percolation coming from the upper layer to the lower layer is the only water input of the lower layer. Additionally, transpiration effect is taken into account given the intrusion of roots into this last layer.

LPJ-GUESS ignores horizontal fluxes between the grids which means that runoff cannot flow to neighbouring cells, but it is simply removed from the model. This simplification has a great influence on most of the model components, such as on soil respiration and vegetation distribution and productivity given their strong dependency on water availability.

2.1.2 LPJ-GUESS features for managed land

The new features of LPJ-GUESS for managed land, exposed on Bondeau et al. (2007) and Lindeskog et al. (2013), present a much more realistic and functional image of the world´s terrestrial ecosystem by allowing the representation of all, natural vegetation, agriculture and grazing land together.

The managed land features are dynamic vegetation models for the representation of global agriculture ecosystems based on the concept of plant functional types. Its implementation is based on concepts developed in the crop growth modelling of SWAT (Arnold et al., 1994), EPIC (Williams et al., 1989) and SWIM (Krysanova et al., 2000, 2005). Thus, this model does not simply treats agriculture as the replacement of forest to grass land, as other models do, but includes special features mainly related to human intervention and land management.

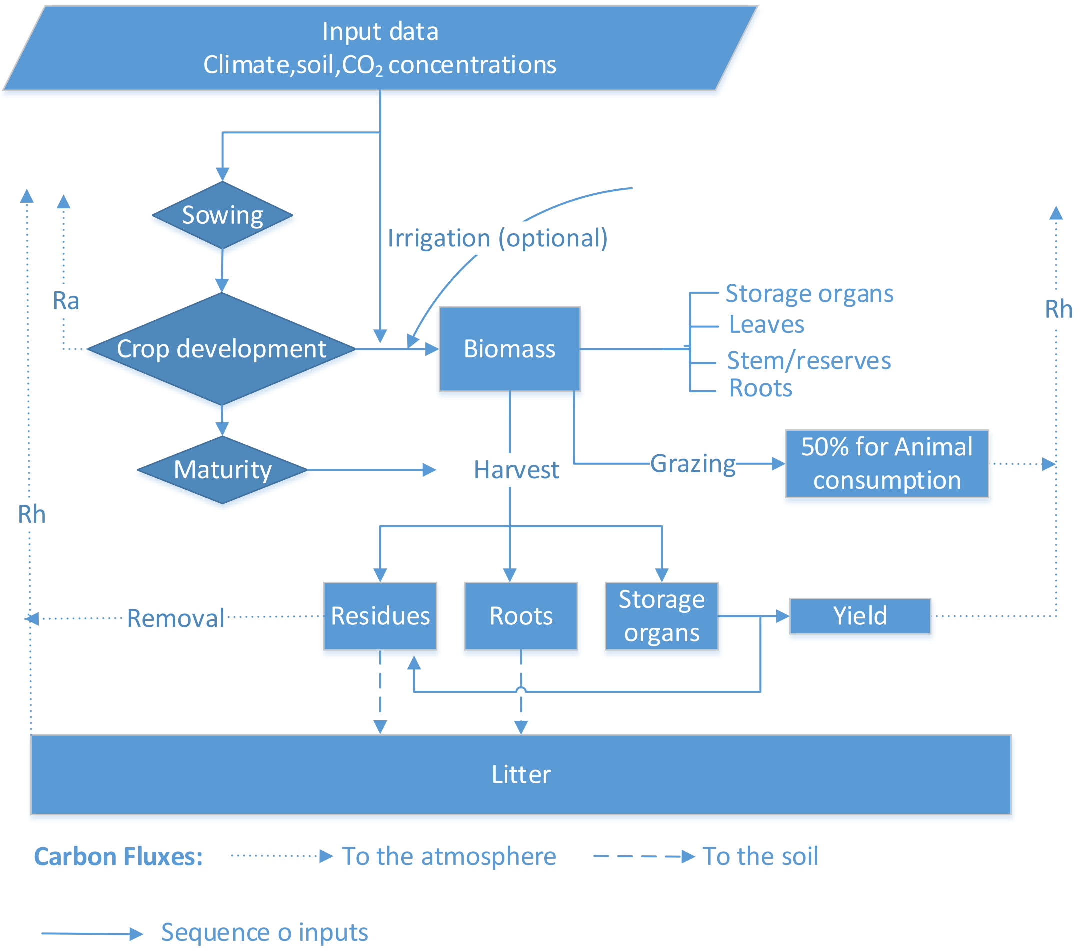


Figure 3: LPJml carbon pools and fluxes scheme. R_a autotrophic respiration; R_h, heterotrophic respiration. The carbon pools are represented on the square boxes. Main crop development stages in rhombus.

This broad view of the ecosystem is meant to allow a biophysical and biochemical assessment of the replacement of natural vegetation by agroecosystems under the climate change scenario and the way in which each related ecosystem services can be affected. Bondeau et al. (2007) and Lindeskog et al. (2013) reported better representation of the fPAR (daily fraction of the photosynthetically active radiation (PAR): portion of PAR absorbed by plants) seasonality on areas of extensive croplands than the one from LPJ-GUESS natural. Additionally they found promising results on potential optimal yield, and the fact that including the crops simulation on the model generates a significant change on the carbon fluxes and balance as compared to a purely natural simulation.

2.1.2.1 LPJ-GUESS managed land description

Here the managed land components of LPJ-GUESS will be described based on Bondeau et al. (2007), the modifications from Lindeskog et al. (2013) can be located when these last authors are cited.

2.1.2.2 Simulated processes and rules

LPJ-GUESS managed land simulates the fluxes of carbon and water due to land use, the specific phenology and seasonal CO_2 fluxes of agricultural-dominated areas, and the production of crops and grazing land. The definition of eleven crop functional types, CFT, (Temperate cereals, Rapeseed, Maize, Pulses, Sugar beet, Rice, Soybean, Sunflower, Tropical cereals, Groundnuts and Cassava) helps to account for the most important global agricultural groups of crops and their phenology. Pastures and rangelands are represented by C3- and C4-managed grasses.

These CFTs are compatible with the PFTs, but include functional formulations related to agro-ecosystems such as temperature limit for crop sowing, vernalisation requirements (cold dormancy requirement to acquire the ability to flower), phenological heat units (PHU) range and harvest parameters. Moreover, it is important to notice that as opposed to the natural PFT, these CFTs are simulated without inter-CFT competition, except for the C3 and C4 grass on pasture grass and cover crop grass (intercropping: second crop season) (Lindeskog et al., 2013)

The managed land consists of irrigated or rain-fed (only precipitation or snow melt as water input) segments of each CFT. This segments division is used for a better representation of the agricultural landscapes in which single crops types grow on fields.

In other to account for the land management effects on productivity, soil organic carbon and carbon extracted from the ecosystem LPJ-GUESS sets some general assumptions divided in three different groups: one group regarding the land management and the human activities, the second one related to the ecosystem dynamics and the last one referring to the land use change dynamics:

Land management and the human activities assumptions:

- Crops are annual or are harvest annually.
- Farmer rational decisions:
    - The farmer will select the cultivar that is best adapted to the local pedo-climatic environment.
    - Farmer’s decision on sowing in accordance to climate
    - Farmer’s decision to harvest as soon as maturity is reached.
- When irrigation occurs it is efficient.

Ecosystem dynamics assumptions at grid cell level:

- CFTs carbon allocation is calculated daily for a better capture of the influence of land management and climate, which are of major importance on the yield.
- Each grid cell has a unique macroclimate and soil texture.
- All fluxes and pools are updated independently for each segment.

Land Use change dynamics assumptions:

- Land use change can only occur annually:
    - Expanding agricultural land removes natural vegetation (Forest).
    - Abandoned agricultural land becomes part of the natural segment and succession starts (Lindeskog et al., 2013).
- Deforestation is represented as: 70% of tree stems are harvested. Of this 67% is used as firewood and 33% used as paper and timber with a 25-yr turnover period. The residual part of the forest is burned within the year (Lindeskog et al., 2013).

Based on the previous assumptions, LPJ-GUESS can simulate the growth and development of each segment independently and evaluate the effects of land use change on the ecosystem. Such effects take into account the dynamics of the new vegetation cover, the emergence of the natural vegetation and special litter allocation.

2.1.2.3 Crop cycle (Figure 3)

Sowing date

The sowing date simulation on Lindeskog et al. (2013) is based on Waha et al. (2012). Here the sowing date under rain fed conditions is model deterministically as a function of climate and assumes the farmer experience for choosing the best moment. The climate parameters for the model are the historical (weighted moving average climatology of the last 10 years) and present (year under concern) temperature and precipitation data, as well as their intra-annual variability.

Crop development and harvest

On a daily basis crops are producing a carbon fraction which can be allocated to the main carbon pools: leaves, roots, harvestable storage organs and a pool representing stems and mobile reserves. This process occurs daily as a function of the heat requirements, water availability and the eventual heat stress.

Heat requirements or PHU are the base of the phenology towards maturity, where temperatures above a base temperature are accumulating daily and so defining when the plant goes from one stage to the other on its life cycle up to maturity (heat unit theory).With respect to the leaf phenology, a feedback between daily leaf area index and leaf mass via NPP is applied, in order to prevent discrepancies between the LAI development and the carbon available for leaf growth. As a result the leaf development occurs before flowering and the onset of senescence is more consistent with physiological constraints (Lindeskog et al., 2013).

The amount of heat units for the full development of the crop is calculated dynamically, using a 10 yr. running mean of accumulated heat units up to maturity; according to the sowing and harvest limit dates from Bondeau et al. (2007).

When maturity has been reached harvest occurs. At harvest, the biomass of the storage organs defined by the harvest index (hi) is removed, 90% of this fraction constitutes the yield in carbon units (dry matter carbon content is assumed to be 50%) and is assumed to oxidize within the year. The carbon of the roots is added to the belowground litter pool and the residues can fall into different manage strategies.

Land management effects

Three management strategies are included: irrigation, intercropping, treatment of residues and grazing. The last one applies only for pastures and rangelands.

- *Irrigation:* Irrigation segments are assigned from land use data and simulated separately. On these segments daily irrigation is determined based on the water balance. If the atmospheric demand for transpiration is greater than water supply, irrigation occurs; nevertheless water stress happens if atmospheric demand exceeds a maximum evapotranspiration rate (5 mm day^{-1}) (Lindeskog et al., 2013). Irrigation water does not depend on local water supply and is subtracted from runoff on an annual basis (Bondeau et al., 2007).
- *Intercropping*: Intercropping is used to describe what happens between two main crop cycles: e.g. wheat is harvested in July and peas will be sown next spring. Farmers may cultivate a crop on the meantime, or leave grass for covering the soil. In the model, extensive grass growth occurs between two cycles and it is called “intercropping”. Before the start of the next crop cycle the grass carbon is added to the litter.
- *Crop residues*: can either be left on field , ‘residues in’ in which case they are sent to being part of the litter pool, or removed on a specified fraction, ‘residues out’ in which case this fraction carbon content is entirely oxidized to the atmosphere within the same year.
- Grazing: Simulates the human or livestock disturbance of a managed grass (grass with human or livestock disturbances) when the LAI has reached a threshold value. At this moment intensive grazing occurs removing 50% of the aboveground biomass which carbon goes to the atmosphere within the year (Lindeskog et al., 2013).

Although assumptions are big and the possibilities of the management strategies are limited in the model, it is a good approximation to the inclusion of these activities and an important step on the improvement of the agricultural ecosystems modelling.

2.1.3 Simulation protocol

The simulation may consist of two or three steps depending on the objectives: The spin up phase, the historical phase, and the prediction phase.

Spin up phase: typically the simulation starts from bare soil, for which the first need is to create an equilibrium between the carbon pools and the vegetation cover. This is done by running a simulation for around 1000 years (using first few years of historical data) in order to accumulate vegetation, soil, litter carbon pools and approach equilibrium with the climate at the beginning of the period which would like to be simulated using historical data (Sitch et al.,2003).

Historical phase: The equilibrium state achieved on the spin up process is used as the starting for a simulation based on observed climate and CO_2 data. The results of this analysis can be used to validate the model when comparing with observed data, to explore the results for important issues that may be happening on the ecosystem according to the model (if model validated) or look for potential features to be improved.

Predictions (Scenarios): Follows the historical phase but bases on climate scenario data, rather than observed data. The main use of this simulation has been to explore the potential effects of the CO_2 increasing concentrations and global warming on the ecosystem, responding to the current concerns on the consequences of climate change.

2.2 Soil moisture and topographic elements.

Topography is considered a first control on the spatial variation of hydrological conditions at the watershed scale. It is closely linked with the water routing, water movement and potential incident radiation (Sørensen et al., 2006; Qiu et al., 2001; Western et al., 1999; Feng et al., 2013). Moreover, in many landscapes pedogenesis of the soil catena occurs in response to the way water moves through the landscape; thus, the spatial distribution of topographic attributes inherently captures the spatial variability of soil properties at the meso-scale as well (Moore et al., 1993b) .

Topographic indices aim to represent the key hydrological processes driven by topography in a simplified but realistic way. Some of the most often studied topographic attributes related to the distribution of water in the environmental compartments are slope, aspect and drainage area, and compound attributes such as the topographic wetness index a combination of both slope and specific drainage area.

- Slope is the degree of vertical change of a physical feature or landform with respect to the horizontal. It can be express as angle or percentage, where lower values accounts for flatter areas and larger values represents steeper ones. Slope influences the hydraulic gradient driving any surface flows and also subsurface flows when the water table has a similar slope to the ground surface. Therefore, it is of great importance on defining the water retention, runoff generation, runoff speed and erosion potential within others. Usually steeper slopes are likely to be drier than flat areas owing to lower infiltration rates, rapid subsurface drainage, and higher surface runoff (Qiu et al., 2001; Feng et al., 2013). Commonly the tangent of the slope angle, tan (b) (equivalent to the height difference over the horizontal distance), is used as a topographic index when related to water controlling processes.
- Drainage area (DA): Refers to the extent of area which has the potential to drain surface water (contribute with lateral flow) towards a specific location at a lower elevation. This attribute is strongly correlated with the location in slope. Theory applied to homogeneous sloping plane says that soil moisture increases from top to bottom; studies from Hawley et al. (1983) found the relative elevation very important in determining soil moisture variations even on watersheds with extremely low slopes.). Commonly the Ln (DA), is used as a topographic index when related to water controlling processes.
- Aspect is the orientation of the slope and defines the potential of receiving solar irradiance and thus influences the evaporation and consequently the soil moisture and vegetation patterns.
- The topographic wetness index (TWI): developed by Beven and Kirkby (1979) is defined as Ln (A/ tan (b)), where A is the specific drainage area (local upslope area draining through a certain point per unit contour length) and b is the slope angle. This compound index has been largely and successfully used to quantify the control of local topography on hydrological processes (Qin et al., 2007). This index has been used to indicate soil moisture, zones of saturation and variable

source areas of runoff (Moore et al., 1993; Western et al., 1999), to characterize net primary productivity, runoff (White and Running, 1994), vegetation patterns (Moore et al., 1993), distribution of plant species richness (Zinko et al., 2004) and has been found to correlate well with groundwater depth and soil pH (Zinko et al., 2004). TWI's often positive predictions have encouraged its use on popular hydrologic models (e.g., TOPMODEL, Beven and Kirby, 1979; VSLF, Schneiderman et al., 2007;SWAT-VSA, Easton et al., 2008). TOPMODEL, for example, redistributes saturation zone water based on the TWI, and was successfully used as part of the Regional Hydro-Ecological Simulation System (RHESSys) (Tague and Band, 2004).

As seen on its definition the TWI allows to incorporate two important determining elements for the hydrology processes, the slope and the drainage area. Nevertheless, the definition of this last element, the drainage area, has been often criticized now that it assumes that the entire catchment upslope of a point contributes to water to that point by subsurface lateral flow, which is a very slow process (Barling et al., 1994).

According to these descriptions the topographic indexes have a rational physical explanation to justify its use on predictions and many researchers have analysed them and showed clear relationships with different important water compartments such as the soil. Feng et al., (2013) and Western et al. (1999) found significant negative correlation with slope and relative elevation/ location on the hillslope; Moore et al. (1988), Western et al. (1999) and Famiglietti et al. (1998) showed positive correlations and patterns with the slope aspect; Qiu et al. (2001), Western et al. (1999), Feng et al. (2013) and Nyberg (1996) found positive significant correlations with the logarithm of the specific drainage area and the TWI, which were actually higher than the correlation to other topographic indexes such as slope or aspect. The similarity in correlation coefficients between the logarithm of the specific drainage area and the TWI versus moisture content, and the lower correlation between slope and moisture content, led Nyberg (1996) to conclude that upslope contributing area was a more important factor than slope in controlling the spatial distribution of soil moisture, so that macro-topography is a major contributor to the spatial variability in soil water content.

Regardless of the positive results, it is important to notice that the significance of the correlations of soil moisture and the different topography attributes is influenced by environmental factors such as seasons (Qiu et al., 2001), soil characteristics, antecedent soil moisture (Qiu et al., 2001), land cover (Feng et al., 2013), heterogeneity and density of vegetation (Hawley et al.,1983), and that these influences hinder the use of the topographic indexes alone to represent all the processes that are important in determining the spatial pattern of the soil moisture (Western et al., 1999) .

To summarize, the topographic indexes have a great potential to explain in a physical an simple way the soil moisture spatial variability and possibly also in landscape with low slopes; not all indexes are appropriate over time or space; and some like the TWI seem to be able to better explain the soil moisture variability in many regions. Thus, the use of these indices in the prediction of soil moisture is valuable, but requires careful interpretation of the results.

2.3 Triangular Form- based Multiple Flow Algorithm

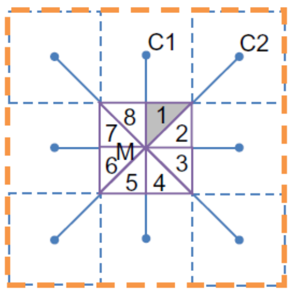


Figure 4: Representation of the cell division into 8 faces on a 3x3 window. Each facet is formed from three points; one is the centre cell (M), and the other ones are on the middle of two adjacent cells .From Pilesjö and Hasan, 2014.

There are two main approaches to compute the topographic elements and indexes: Single flow direction, convergence allowed, and multiple flow direction where divergence and convergence are allowed. Falling on this last group is the Triangular Form-based multiple flow algorithm (TFM) developed by Pilesjö and Hasan (2014). The TFM is a raster based distributed hydrological model, which has proven to be quantitatively and qualitatively superior on the calculation of flow estimations and spatial patterns of flow distribution in comparison to other hydrological models, under a low computational cost (Pilesjö and Hasan, 2014).

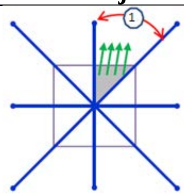
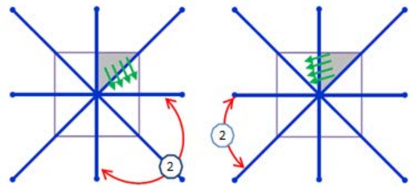
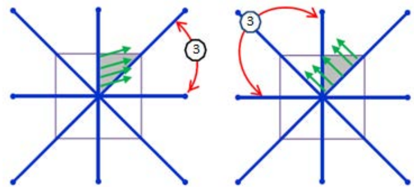
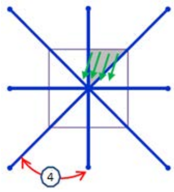
The Triangular Form- based multiple flow algorithm (TFM) (Pilesjö and Hasan, 2014) has proven to estimate better the specific catchment area over mathematical surfaces compared to other single and multiple flow algorithms. Furthermore, superior results from the TFM compared with the single flow D8 algorithm (O'Callaghan and Mark, 1984) has been achieved on a mountainous area with a lower flat peatland area in northern Sweden (Tang et al, 2015). Tang et al (2015) study demonstrated how TFM algorithm modelled a more continuous and smoother spatial patterns than the D8 algorithm, and better correspondence with the measured monthly runoff. Additionally more realistic DA values at the flat and low lying region were observed. All this characteristics, together with its relatively low computational cost contributed to the choice of TFM for this study, especially taking into account the smooth topography of the study area (Numeral 4. Study area).

The TFM (Pilesjö and Hasan, 2014) is based on a segmentation of the grid cells into 8 triangles (facets) **(**Figure 4**)** which allows the water to move and repartition within the cell and then be redirected to neighbouring cells (ncells).

The model starts by dividing the centre cell (zcell) into eight local triangular facets between its cell centre and the eight surrounding cell centres of the ncells. Each triangular facet has a constant slope and aspect derived from the x, y and z distances of the zcell centre to the two ncells centres involved on the creation of facet (Figure 4). This construction is the key stone on the definition on how the water moves and splits within the cell and out of it.

Within the cell: Flow has the possibilities shown on Table 1.

Table 1: TFM description of the within cell flow routing cases according to the aspect.

Description	**Water routing within cell according to the aspect (taken from Pilesjö and Hasan, 2014)**
Case1. Aspect 0 to 45°: All the water stays on the facet before going to a ncell (s).	
Case 2. Aspect 90 to 180° or 225 to 270°: All the water on the facet will *move* to one adjacent facet and added to it.	
Case 3. Aspect 45 to 90° or 225 to 270°: The water on the facet *splits* based on a vector split (Pilesjö, 2008). Part of the water moves to a neighbouring facet and part of the water stays on the facet before being routed to a ncell(s).	
Case 4. Aspect 180 to 225: All the water on the facet *splits* between two adjacent facets based on a vector split.	

In the case of two facets sloping towards each other, no water is routed between the two facets. The water *stays* on the each facet before being moved to neighbouring cells.

The redistribution of water within a cell continues until all water has reached the outflow facet(s) of the zcell, then the transport to neighbouring cells occurs. The movement of water between facet and cell(s) occurs either a) completely to one ncell if there is only one ncell with a lower elevation than the centre cell or b) will divide between b ncells when both are lower than the centre cell (i.e. On Figure 4, the water from facet 1 will divide between C1 and C2). In the latter case the amount of water going to each ncell will dependent on the slope. The flow distribution to ncells is estimated for all cells except for the border cells as flow accumulation values.

2.4 Study Area: The Alergaarde River catchment

The Alergaarde catchment is part of the river Skjern catchment, on central Jutland Denmark, covers 1055 km^2 with a 96 km long river system (Karlsson et al., 2014) (Figure 5). It limits to the east with the Jutland Ridge and to the west the Skjern River continues flowing until it reaches the North Sea through the Ringkøbing Fjord (Karlsson et al., 2014). The area consists mainly of cultivated areas and sandy plains sloping smoothly from east to west (Figure 5 and Figure 6). The average discharge at the Alergaarde discharge station is 16 m^3 s^{-1}, corresponding to 480 mm/yr. (1990-1995) (Fu et al., 2011).

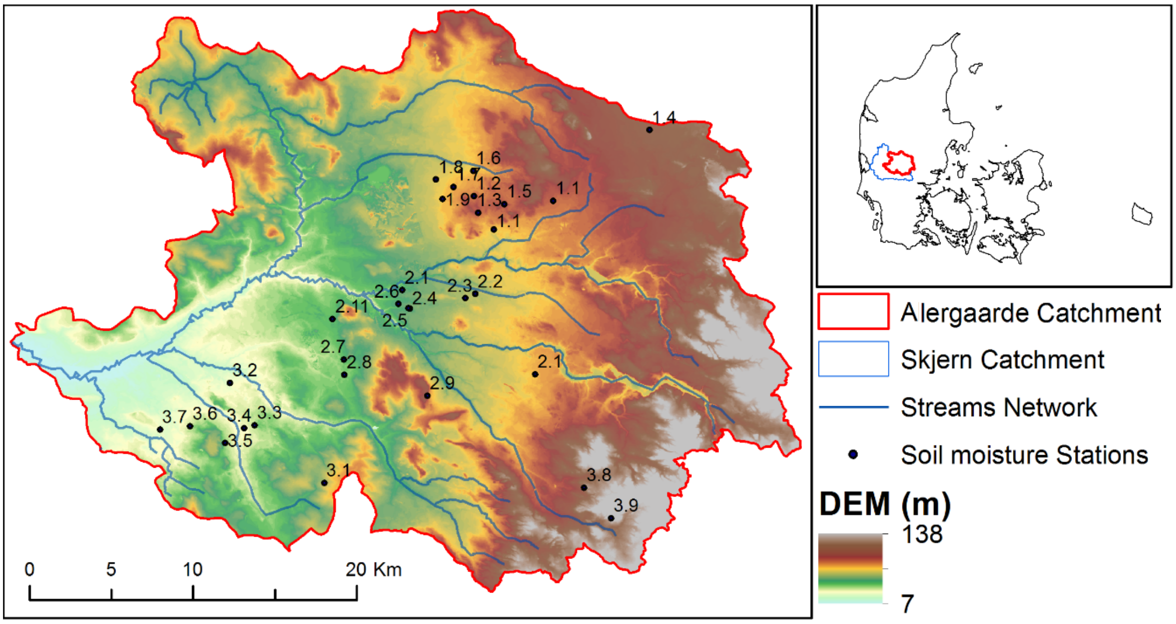


Figure 5: Model domain of the Alergaarde catchment in western Denmark and soil moisture stations. Alergaarde station is located on most western part of the stream network.

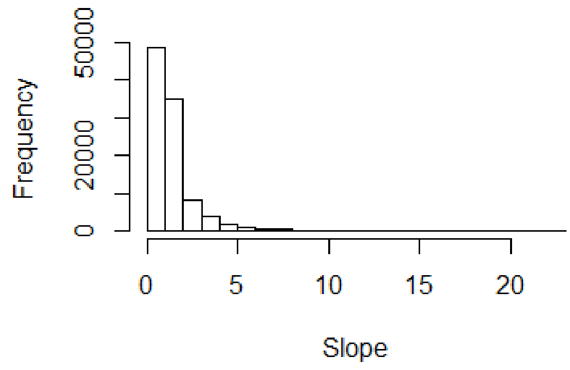


Figure 6: Slope histogram of the catchment based on 25 x25 m resolution DEM. Distribution skewed to the left showing a landscape with little relief.

2.4.1 Geology and Topography

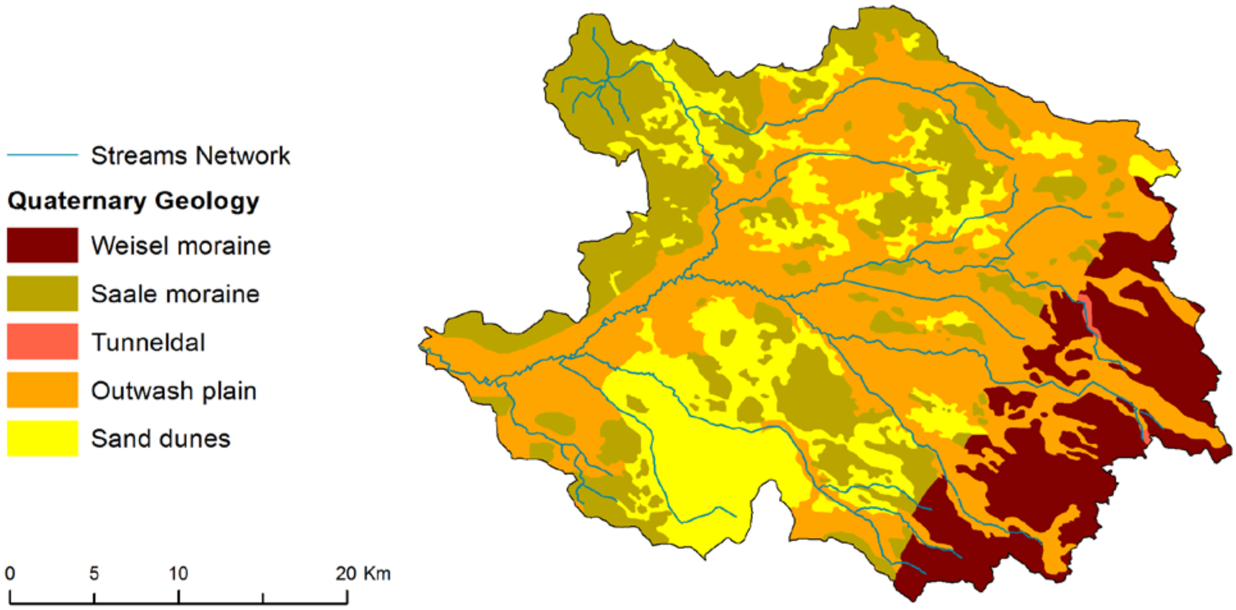


Figure 7: Landscape elements of the Alergaarde.

The catchment area is dominated by glacial material from the Quaternary age. The present topography reflects the physical environment from the last glaciation with a maximum glaciation border trending north–south through central Jutland (Houmark-Nielsen and Kjaer, 2003 from Stisen et al., 2011) (Figure 7). It is characterized by low elevations sloping gently from 138 m on the east to 7 m on the west and its terrain is dominated by three landscapes:

- Weisel moraine: Sedimentary remnants from the last glaciation on the area, Weisel ice age. It is the result of a younger ice sheet front at the main ice advance at the Jutland Ridge, and consists of moraine deposits of sand and clay on the eastern part (Karlsson et al., 2014).

- Hill islands: Sedimentary remnants from the Saale ice age. They are located around the main River Skjern and many of its tributaries. Consist mainly of the older sand moraine, and melted water deposit constituting a sandy and clayey sandy soil with a high and relatively high permeability. They are mainly smooth due to longer exposure to wind and erosive natural agent (Alwan et al., 2001; Stisen et al., 2011).

- Heath plain or outwash plain: Distributed almost all over the catchment, consists of spread flats around the hill islands formed during the last ice age, by the melting water discharging of ice masse. The soil type is defined as coarse sandy soil, generally with high permeability (Alwan et al., 2001; Stisen et al., 2011).

Alternating layers of marine, lacustrine, and fluvial deposits of Miocene age underlie the Quaternary deposits and thick clay layers from Paleocene underlie the Miocene deposits and these act as an impermeable flow boundary (van Roosmalen et al., 2007 from Fu et al. 2011; Jensen and Illangasekare, 2011). The hydraulic conductivity of the sand formations is generally high, on the order of 10^{-4} to 10^{-3} m s^{-1}, while the Quaternary and Miocene clay units have low conductivities on the order of 5×10^{-9} to 1×10^{-6} and 1×10^{-8} to 1×10^{-7} m s^{-1}, respectively (Harrar et al., 2003; Sonnenborg et al., 2003 both from Stisen et al., 2011; Ringgaard, 2012).

2.4.2 Soil

Coarse sand soil is the prevalent soil type in the watershed, according to Svendsen and Hasen (1997) (from Alwan et al., 2001) 95 % of the watershed consist of sandy soil, and the rest is clayey soil type. As a consequence the catchment is highly permeable.

The predominant naturally occurring soil type is Spodsol, 80 to 85% of the River Skjern Watershed (Alwan et al., 2001). This soil type have: 1) a sandy acidic topsoil where the water drains quickly leaching nutrients, organic matter, aluminium and iron oxides, and 2) a hardpan organic-rich layer subsoil , which is almost water tight causing ponding of water at its surface. Under well managed fertilization, pH control and irrigation high-yield cultivation is possible (Bircher et al., 2012). The rest of the watershed is loamy (downwashed) erosion soil, causing high groundwater level (Svendsen and Hasan, 1997 from Alwan et al., 2001).

2.4.3 Climate

The relative small size and flat topography promotes only very small gradients in meteorological parameters across the catchment. The catchment climate is mainly maritime, dominated by westerly winds from the Atlantic Ocean and frequent passages of extratropical cyclones leading to mild winters, cold summers and variable weather conditions with frequent rain and showers (Jensen and Illangasekare, 2011; Stisen et al., 2011).

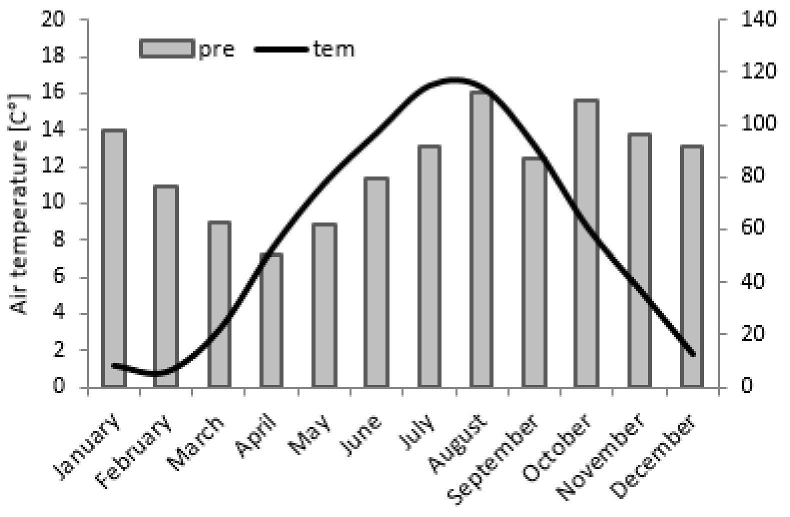


Figure 8: Alergaarde catchment averaged areal monthly climate statistics for the period 2001-2011.

The average annual temperature is 8.3°C, with a maximum in July and August (around

16 °C) and a minimum in January and February (around 1°C) (Figure 8). The mean annual precipitation is 1041 mm (1961-1990) with maximum precipitation in autumn and minimum in spring (Karlsson et al., 2014). During the winter season, the dominant precipitation system is extratropical storms from directions between southwest and northwest. The frontal precipitation mechanism is enhanced by orographic effects caused by the moderate increase in surface elevation from west to east (Frich et al., 1997; Fu et al., 2011). In summer, convective rain events significantly influence the precipitation pattern, and the most intense rainfall events are observed from June to August (Fu et al., 2011; Stisen et al., 2011). Generally, high-intensity precipitation events apply more uniformly over the catchment, whereas low-intensity events present a higher spatial variability (Fu et al., 2011)

2.4.4 Land use/cover distribution

The land use distribution of the catchment is mainly rural: 71% Agricultural area (57% arable land and 14.3 % heterogeneous agricultural areas and pastures), 16.1 % forest, 7.6 % Heathland/ sparse vegetation, 2.9 % urban and 2.1 % wetlands/water bodies (Figure 9). The main grain crops are winter and summer barley (*Hordeum vulgare* L.), wheat (*Triticum aestivum* L.) and mais (*Zea Mays L*). Most agricultural areas perform rotation shifts, while some are covered with multiannual grasses. The area covered by forest is dominated by conifer trees (Jensen and Illangasekare, 2011; Stisen et al., 2011) and one often studied area is the Gludsted plantation of Norway spruce.

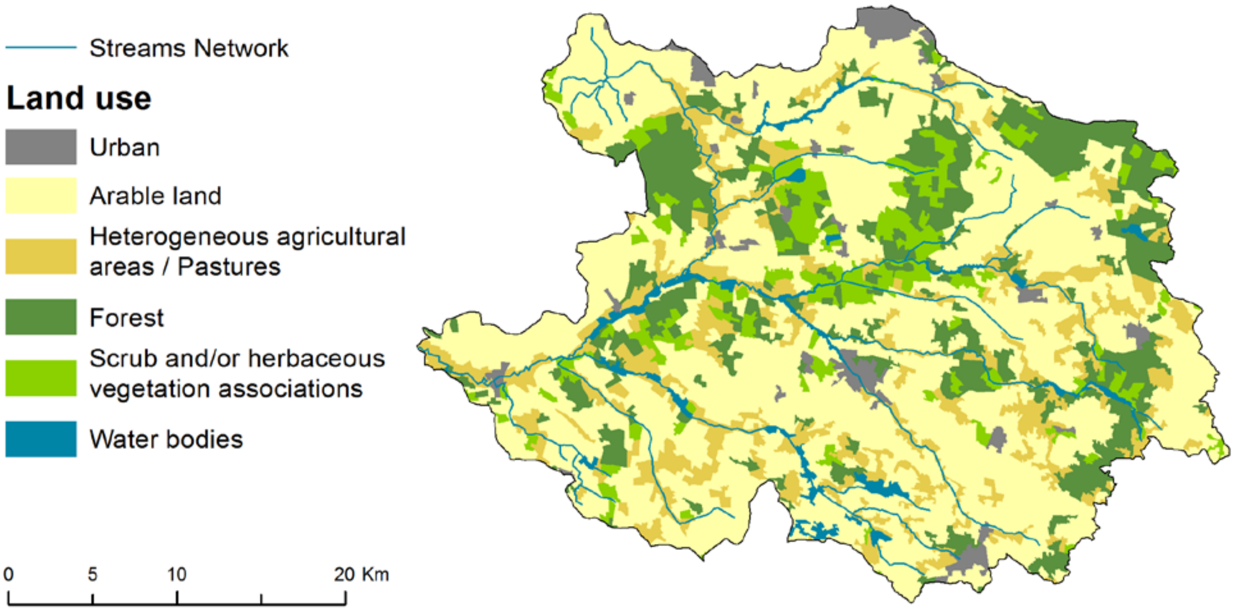


Figure 9: Corine Land Cover 2006 seamless vector data of the Alergaarde watershed.

Studies on the region (Ringaard et al., 2011; Ringaard, 2012; Vasquez, 2013) have proved a large influence of the land use types on the Net CO_2 ecosystem exchange (NEE) and on the hydrological processes.

2.4.5 Hydrological processes for the Skjern catchment

Given the high permeability of the soil in the river basin hortonian overland flow are rare, except in cases when the rainfall event happens over frozen soils, which is seldom. As a consequence, about 90% of the precipitation infiltrates into the soil and only a small fraction results in surface runoff. The rest is evaporated to the atmosphere by interception loss. The infiltrated water is either returned to the atmosphere by evapotranspiration or recharged to groundwater. Some of the recharge is captured by the drainage system composed of tile drains, ditches, and small creeks and is transferred relatively rapidly to the streams. The remaining part of the recharge enters the aquifers and discharges to the streams downstream of the infiltration area as base flow, which constitutes the dominate part of the streams discharge (Van Roosmalen et al., 2007 from Fu et al., 2011).

The main river is the Skjern River, with an average annual runoff at the Alergaarde station of 480 mm/yr., corresponding to approximately 45% of the mean annual precipitation (1041mm/yr.) (Fu et al., 2011).

2.4.6 Water extraction

The water in the catchment had many withdrawals and diversions related to anthropogenic activities, mainly for agricultural purposes and industrial and domestic uses.

Groundwater extraction varies over the season and from year to year due to variable demands and climatic conditions. Due to high soil hydraulic conductivity, there is a need for frequent irrigation to maintain crop growth during most growing seasons (Schelde et al., 2011 from Ringgaard et al., 2011). Farmers are permitted to irrigate up to 100 mm yr−1 on irrigated land, the area that would need irrigation comprises 39% of the total catchment area, according to simulations based on irrigation wells and climate data for the period 1990-2003, (2014, Simon Stisen personal communication). Based on these simulations the average irrigation amounts 35 mm yr^{-1} for the Alergaarde catchment area, corresponding to approximately 90 mm yr^{-1} for the irrigated areas. In dry summers the total basin irrigation can be considerably increased.

On the other hand, the extraction for domestic and industrial purposes amounts to approximately 10 mm yr−1 for the Skjern catchment , where part of this water returns to the stream system as point sources after being captured by the wastewater plants (Jensen and Illangasekare, 2011; Stisen et al. , 2011).

3 METHODOLOGY

3.1 LPJ-Topography index model (LPJ-TI)

LPJ-GUESS lacks of communication between the gridcells, all cells are independent. This feature of the model neglects the importance of water transfer between the cells, which is very important on defining environmental conditions for vegetation growth particularly on smaller scales such as the catchment level. As topography is a key driver of water movement, its introduction within LPJ-GUESS is considered meaningful for the improvement of the spatial patterns and spatial variability of the modelled ecosystems at small scales.

A simple algorithm was used to include the influence of the catchment topography on the hydrology. The soil water input coming from through fall precipitation, snowmelt is multiplied by a topographic index weight. This is done for every cell in the catchment to account for the influence of the topography on the hydrological processes. The output of this operation is a slightly altered water amount, which will continue redistributing on the different compartments defined by the processes on the hydrology module of LPJ-GUESS. The new equation for the water content is:

$$\Delta w_1=((P_t +Sm) * TI)-E_t-E_s-per_1- R_{surf})/w_{max1} \quad \text{Eq. 4}$$

$$\Delta w_2= per_1-E_t–per_2- R_{sub}/w_{max2} \quad \text{Eq. 5}$$

Where, Δw_1 and Δw_2 are the daily changes in the soil water content as a fraction of the available water holding capacity w_{max} of the upper and lower layer; P_t is through fall (precipitation minus interception lost), Sm is the snow melt, E_t is transpiration, E_s is soil evaporation, per is percolation, R_{surf} surface runoff, R_{sub} subsurface runoff and TI accounts for the topographic index weight. Changes in the code for the introduction of the topographic index are on appendix A.

Irrigation is an optional water input that can be activated on LPJ-GUESS; however this should not be activated when running LPJ-TI. Irrigation cancels the influence of the index by adding water daily to maintain a ratio of 0.7 between plant canopy water supply and atmospheric demand for transpiration (Bondeau et al., 2007). With the irrigation option activated every time water is needed to reach optimum plant development, water is added to the fields, so that if the topography causes one place to have less water, this deficiency will be solved, causing topography influence to be masked out from the LAI or soil moisture variables.

In order to construct the weights (TI), which are to be introduced on Eq. 4, the selected topographic index has to be rescaled. This scaling is proposed to be a linear scaling of the topographic index, where:

- the 0 value on the new scale is set to the index value where no water is expected to be retained on the cell, for example slope = 90;
- the 1 value on the new scale is the index value where no water is expected to be moved out of the cell due to the topography influence; for example slope = 0.
- Values greater than 1 are possible to obtain on areas with great potential to receive and retain water, such as areas with slope 0 and a large DA (details on section 3.3.2.3).

The rescaling of the topographic indices, depends on the specific characteristics of the index.

3.1.1 Constrains and assumptions

In reality the influence of topography is a complex issue, because it depends on soil type, intensity of the precipitation event, land cover, previous water content conditions, length of slope and the interaction of all of them together in time and space.

The proposed approach assumes that a fixed percentage of the soil water input increases or decreases accounting for the topography. Later on, this new weighted water input continues on partitioning between the different water cycle components, and affects the environmental conditions for the vegetation growth. This model is what Morton (1993) calls mediating models, which reflects physical intuition, while containing arbitrary elements for convenience. For sure this simple method does not physically cover the complexity of the system briefly described above; nevertheless, it is considered as an exploratory approach worth of testing with the following constrains and assumptions:

- This approach should be used on catchments with relatively homogeneous soils, because at this stage no change is given to the weight in regard to the soil characteristics; nevertheless, it is thought that the lack of differential weighting on catchments with low soil typed heterogeneity can be allowed, now that soil genesis is to a great extent driven by hydrology and topology (Moore et al., 1993b). On this matter Alergaarde catchment fits well the prerequisite with 95% of the area being course sand soil.
- The influence of the vegetation is on the air and not on the ground. Which means that this model keeps untouched the interception process accounted by vegetation, but ignores the effect that vegetation has on the horizontal movement of water. This effect can be adjusted by adapting the weights according to the vegetation cover: greater scale range on bare soil, and smaller on grasslands.
- As the weighting is applied to all collected water before its interaction with the soil, the influence of the topography feature is considered identical no matter the initial conditions such as water content, or the different kinds of precipitation events.
- The weighting artificially alters the input of water into the soil system module and does not relocate the water as runoff (for the moment) or holds the water from other cells. For this reason a water balance cannot be done from the individual components at cell level nor at catchment level, which is a consequence of implementing the influence of topography without allowing lateral transfer. Nevertheless, an improvement on the soil water content affecting the vegetation dynamics at cell level, and on the vegetation and soil moisture spatial patterns over the catchment could be expected. Runoff cannot be properly assess, because of the condition just mentioned but is also not of interest in this study.

3.2 Data Collection

The DEM (25 x 25 m resolution), land use (500 x 500 m resolution), soil type (500 x 500 m resolution), soil moisture point data and LAI data of the non- forest areas (500 x 500 m resolution) were provided by the HOBE Center for Hydrology- Hydrological Observatory, Denmark. The land use raster is HOBE's best estimates of land use classes and crop cycles from around 2007. The soil type map is originally from the Faculty of Agricultural Sciences (DJF), Århus University. The soil moisture measurements consisted of daily data for the years 2009-2012 taken on 30 points distributed over the catchment (Figure 5) with Decagon ECH2O data loggers with ECH2O 5TE capacitance sensors (more technical details on Bircher et al., 2012) at 25 cm depth. The LAI data of non-forest areas consist of a time series for the years 2000-2010 at 16 days interval (Stisen et al., 2011b), these data were determined from the NDVIs from MODIS data using the relation described by Boegh et al. (2009) to convert to LAI, the relation was established for a different region in Denmark using the same MODIS product.

The annual atmospheric CO_2 concentration data for the period 1913-2011 were obtained from the work of Tang (2014). Monthly nitrogen deposition rates for the period 1901 - 2009 at a 0.5° x 0.5° grid resolution are from the work of Smith et al. (2014).

The climate dataset was constructed with a combination of different sources given the need to get a large time series:

- From HOBE Centre:
    - Daily precipitation and temperature climate data between 01-01-2001 and 31-12-2011 were obtain at an original resolution of 10 km grid cell and 2 km grid cell respectively (HOBE data set). Precipitation data were already corrected for undercatch caused by turbulence using standard methods (Allerup et al., 1997; Stisen et al., 2011)
    - Historic catchment average daily time series for precipitation and temperature between 1901 and 2000 (Provided by HOBE Center). Data based on the PhD work of Ida Karlsson (This dataset will be referred as HESS). Documentation on the data on Karlsson et al., 2014.

- CRU TS3.20 from the DataGuru application: Monthly precipitation, temperature and cloud cover at 1000 m x 1000 m resolution, for the period January 1901 to December 2011.

Illustrative vector data of the landscape elements, stream network, and catchment boundary were also obtained from HOBE Centre.

3.3 Data processing.

3.3.1 LPJ-GUESS input data

3.3.1.1 Soil and land use cover

The cells centroids of the soil and land cover raster layer were used as reference for setting the study points positions on the study regions; which means that these centroids were used to extract the information from the climate and topography related data.

The soil type information obtained was from the 30-80 cm layer. This information was used to set both the 0-50 cm layer and the 50 to 150 cm layer in the model. HOBE centre soil types classes were very detailed, thus after looking at the properties of the soil classes two big groups were created “medium coarse” and “fine medium” in order to fit with the predefined classes of LPJ-GUESS.

3.3.1.2 CO_2 and Nitrogen inputs

In order to have a complete time series between 1901 and 2011, the nitrogen and atmospheric CO_2 concentration time series data are needed to fill in gaps. For nitrogen input data, the annual value of 2009 was repeated for the years 2010 and 2011 whilst, the annual CO_2 concentration of the year 1913, was repeated for the period 1901-1912.

3.3.1.3 Climate data

The HOBE daily and CRU TS3.20 monthly climate data were downscaled to 500 m grid cell sized using the bilinear resampling algorithm. Thereafter, the “extract value to points" tool in ArcGIS 10.2 was used to get climate data for each cell and time period.

3.3.1.4 Scheme for constructing climate data timeseries

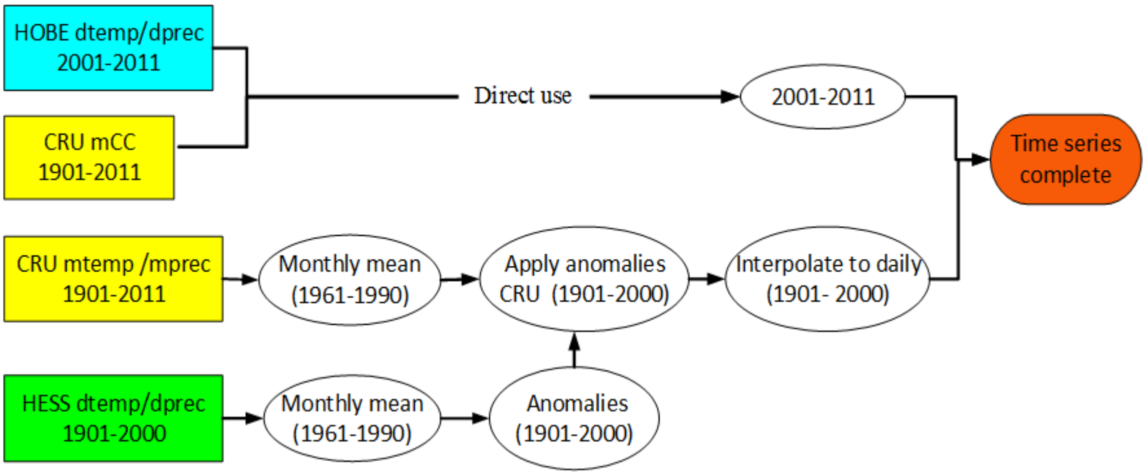


Figure 10: Scheme of how the climate time series were constructed. mtemp, mprec and mCC stand for monthly temperature, precipitation and cloud cover; dprec, dtemp stand for daily temperature and precipitation. mCC is transformed within the program to daily radiation.

The construction of a code within LPJ-GUESS, which could read the 500 x 500 resolution climate data and that was able to construct a long daily time series based on the three data sources was done by Jing Tang. The description of the construction of the time series (1901-2011) is represented on Figure 10.

The annual precipitation and temperature time series (Figure 11) for the whole 110 years on the catchment goes from one CRU corrected data to the HOBE data without any obvious break between them (both periods are on a similar range of values). HOBE mean annual temperature is on the same range of the former decade (1991-2000), with no significant difference between the means (Mann-Whitney-Wilcoxon Test, p= 0.1321). The HOBE precipitation is within the range of the 1991-2000 decade; nevertheless, the period comprehended by HOBEs data (2001-2011) does not fluctuate as much as the decade before.

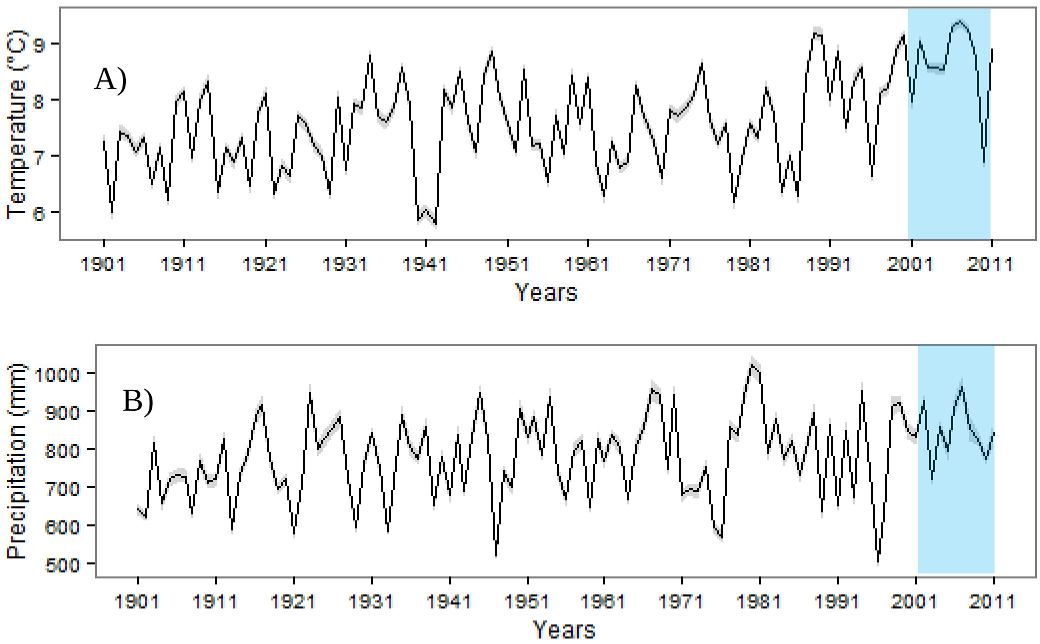


Figure 11: A) LPJ-GUESS catchment mean annual temperature based on mtem output file. B) LPJ-GUESS catchment mean annual precipitation based on mprec output file. Grey shadows correspond to the standard variation (Variation comprehends both spatial and monthly). Blue Shadows correspond to the HOBE time series.

3.3.2 Topography indices

3.3.2.1 DEM pre-processing

The cells with no data in the original 25 x 25 m DEM were filled before the following calculations. The filling was done by moving a 3 x 3 mean filter all over the 25 x 25 m DEM. The resulting filter DEM was then used to fill the NoData areas of the original DEM.

3.3.2.2 Topographic indices calculations

The Triangular Form-based multiple flow algorithm (TFM, see section 2.3) (Pilesjö and Hasan, 2014) was used to calculate the slope angle (b), drainage area (DA) and TWI (Eq 1. TWI = Ln (DA/ tan (b)) as used within the TFM program) from the 25 x 25 m DEM, based on them the tan (b) and Ln (DA) were also derived. Figure 12 shows how the stream network derived with the TFM well matches the stream network provided by the HOBE center supporting the use of the TFM algorithm for the catchment.

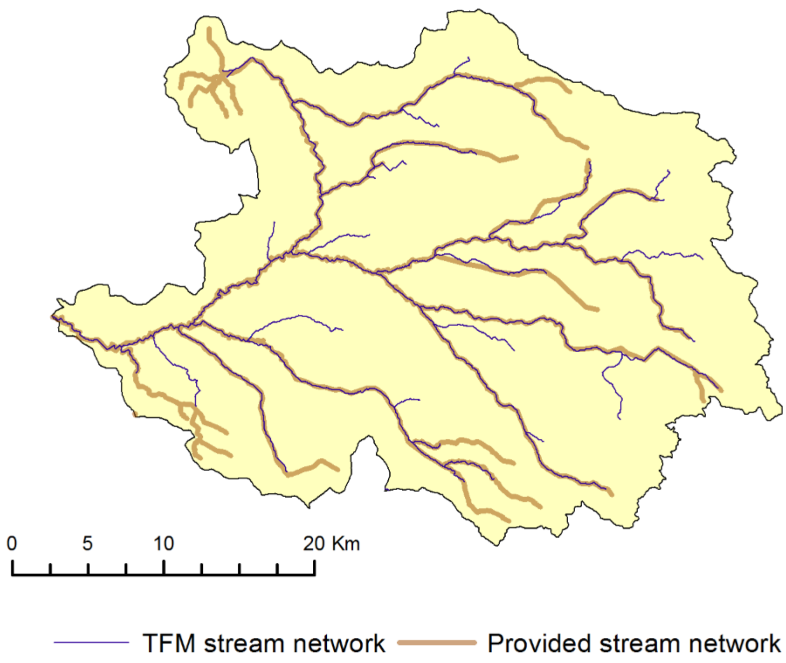


Figure 12: Comparison of the stream network derived with the TFM with the stream network provided by the HOBE center.

As some analysis and also the LPJ-GUESS runs were done at 500 x 500 m resolution. The topography indices and the topographic weights (explained in section 1 and 3.2.3 of the methodology) were snapped to the gridcells of the land use layer and aggregated by the mean to the 500 x 500 m resolution. It is clear that the mean is an inadequate statistic to characterize a place especially in the presence of extreme values. Notwithstanding, it is consider that the little relief of the catchment allows this approximation (Figure 6: Slope histogram of the catchment based on 25 x25 m resolution DEM. Distribution skewed to the left showing a landscape with little relief.). This methodology was used, in order to get the most of the finer 25 x 25 m resolution DEM, now that it is known that TWI is sensitive to the grid cell resolution (Mukherjee et al.; Wu et al., 2008). Mukherjee et al. (2013) observed overestimation TWI at smaller resolutions especially in rugged terrains and Beven (1997) stated that if the resolution becomes too low and hillslope lengths are comparatively small, no meaningful TWI can be derived.

On Table 2 the effect of the aggregation over the statistics of the layers for the three topographic indices can be seen. Generally, the maximum values were highly affected on all the indices, situation which is related with the fact that those values occur at a low frequency and tend to disappear when aggregating over the large 500 m pixel size.

Table 2: Effect on the statistics of the different topographic index layers when aggregating the DEM by the mean from 25 x 25 m to 500 x 500 m.

	25 x25 m			500 x 500 m		
STATISTICS	**tan (b)**	**Ln (DA)**	**TWI**	**tan (b)**	**Ln (DA)**	**TWI**
Maximum	0,455	20,773	31,728	0,200	10,053	18,706
Mean	0,021	7,949	13,088	0,021	7,928	13,059
Minimum	0,000	6,438	7,578	0,000	6,438	8,362
Stddev	0,024	1,791	2,868	0,015	0,371	1,340

3.3.2.3 Topographic indices weights (TI on Eq. 4)

TWI (Eq.1) was selected the topographic index to include into LPJ-TI, the scaling procedure to create the weightings is explained specifically for it.

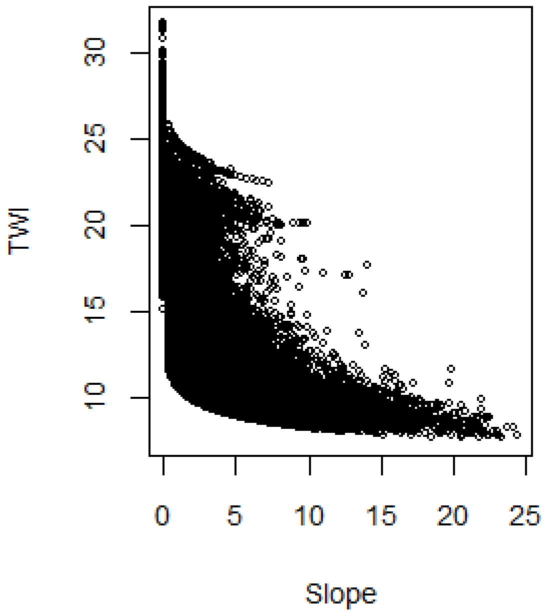


Figure 13: Scatterplot of the TWI values vs the Slope in the catchment Alergaarde based on the 25x25 m resolution layer.

The construction of the TWI weight is based on two settings:

1) the 0 value on the weighting scale should correspond to TWI of 0 (approaching 0), which is characterized by a maximum slope of 90°.

2) the value 1 on the scale has to correspond with the TWI value where the slope is 0 and the DA equals the area of one cell; above this value only greater DA for a 0 slope can happen, thus an increase potential of the site to receive water exists. Important to notice is that the TWI weight value set to 1 is also possible to achieve with higher slopes, together with greater DAs (Figure 13).

The initial scaling was done using Eq. 6.

$$\frac{\mathrm{TWI}}{\mathrm{TWI}_1} = TI_{\mathrm{twi}} \qquad \text{Eq. 6}$$

Where TI_{twi} is the TI for the TWI and TWI_1 is calculated with slope equal 0 (slope equal 0.001 used given tan (0) is 0 and DA/0 is undefined) and the DA equal 625 m^2. This transformation had a scale ranging between 0.600 and 1.075 for the catchment, which was considered to be too big considering: a) the smooth topography with slopes ranging between 0 (0.001) and 11.3 on the 500 x 500 m resolution layer and b) the high permeability of the soils, which does not favour the surface runoff . For this reason the weights were rescaled to lower ranges following Eq. 7:

$$\left(\left(\frac{\mathrm{TWI}}{\mathrm{TWI}_1}\right) * a\right) + (1 - a) = TI_{\mathrm{twi}} \qquad \text{Eq. 7}$$

Where *a* is shrink factor used to shrink the range of TI_{twi}, can have values between 0 and 1. Three arbitrary *a* where used 0.2, 0.3 and 0.5 obtaining scales 0.920-1.015, 0.880 – 1.023, 0.800-1.038 respectively (so that maximum 20% of the water is affected by the means of topography); the different scales are meant to give different importance of the topography on the hydrology of the catchment. The smallest scale 0.920-1.015 is still thought to be big, but for this exploratory study it is chosen in order to accentuate the topography influence so that the changes can be more easily detected.

The scaling weights at 25 x 25 m resolution were snap to the soil data raster and upscaled to 500 x 500 m resolution using the average topographic weights of every cell, in order to match with the LPJ-GUESS resolution.

3.3.3 Environmental variables

In order to be able to compare with the monthly outputs of the LPJ-GUESS monthly values for the two environmental variables of interest were calculated.

Monthly average for each one of the 31 soil moisture stations was computed for the years 2009-2012. As the measurements have some gaps it was decided that at least 8 days were needed to calculate the monthly values, otherwise the month was excluded.

The maximum monthly LAI values of the satellite based LAI (MODIS LAI) were calculated for the years 2000 - 2010. Given that LAI values equal or below 0.5 cannot be correctly computed by the model of Boegh et al. (2009), the months January, February, March, November and December, with lower LAIs, were not used. Additionally all LAI values equal or below 0.5 on the other months were processed as no data, which means that they were taken out of the mean.

3.4 Analysis methods

3.4.1 Topographic influence on the Soil moisture and LAI spatial patterns on the Alergaarde catchment

This investigation topic is a quantitative and qualitative evaluation of the influence of the topography on the spatial distribution of the soil moisture and MODIS LAI in the catchment. The evaluation is based on two analysis.

First, the month/year (every month of every year) correlation of each of the environmental variables with the topographic indices (tan (b), Ln (DA) and TWI) is used to elucidate the monthly variations of the relationships. This approach increases the ability to understand the factors which may be responsible for temporal changes of the correlations; a similar approach was used by Famiglietti et al. (1998) but on daily basis. The correlation between the month/year maximum MODIS LAI and the topographic indices was done using the corresponding topographic indices extracted from the 500 x 500 m grid size layers. On the other hand, the correlation between the month/year soil moisture and the topographic indices was done using the data from soil moisture stations with similar characteristics (arable land with sandy top and subsoil), 14 in total, and the corresponding topographic index extracted from the 25 x 25 m grid size layers. Additionally, as the soil moisture dataset had many periods with lack of data in diverse stations, a minimum number of 8 active stations was set to run the correlation of the corresponding month/year, this to guaranty a minimum statistical significance and make the analysis more homogeneous.

Second, a visual comparison examination of the MODIS LAI spatial patterns compared with the topographic indexes was included as a qualitative analysis.

3.4.2 Original LPJ-GUESS vs LPJ-TI

This topic implements and discusses how the introduction of topography influence in LPJ-GUESS affects the modelled spatial patterns of LAI. To do this, first the performance of LPJ-GUESS is evaluated with the observed data. Second, the integration of LPJ-GUESS with a topography index is discussed focusing on the representation of the spatial patterns of environmental variables.

Following, the general settings of the model are described. Afterwards, the respective analysis methods for both parts of this section are presented.

LPJ-GUESS was run for the period 1901-2011 using the historical Nitrogen, CO_2 concentrations, climate data, soil information and land use information, gridded at a 500 m resolution. No land use time series were available, but given small changes on the land use during the last 10 to 20 years on the catchment (Simon Stiesen personal communication), the data was considered as a fair representation of the last decades. From the land use classes temperate cereals CFT was chosen for the model, because it is well distributed all over the area, covering 41 % of it (1701 grid cells). On each of the modelled grid cells 100 % temperate cereals was set. The spin up period was 500 years repeating the first 30 years of the historical data. Cropland contained only one patch since the stochastic processes of natural vegetation establishment and mortality or different disturbances are not needed (Lindeskog et al., 2013).

3.4.2.1 Specific methodology

The respective analysis methods for developing both parts of this topic are explained below:

- Performance of LPJ-GUESS on the Alergaarde catchment:

For the evaluation of the performance of LPJ-GUESS on the Alergaarde catchment, the simulated monthly soil moisture and the monthly maximum LAI values were compared with the observed monthly soil moisture and the monthly maximum MODIS LAI data respectively. The model was run as explained above using the cft “irrigated temperate cereals” (TeWWirr), since irrigation is a common and a necessary practice in the area.

The validation of the soil moisture is based on the correlation of the time series between the observed and simulated data, but not on the comparison of the absolute values. This consideration is taken as it is not reasonable to consider point measurements as being representative of a 500 x 500 m cell and because the TWI values corresponding to the soil station location covered only a small range of the possible TWI values for the catchment (Table 4). For the same reason and the low density of points (11 stations on cereal areas) no spatial analysis was done. Ideally, in order to show a meaningful correlation between field-sampled soil moisture measurements and topographic indices, the field-sampled and DEM-derived topographic indices need to represent conditions occurring over a comparable spatial support (Tenenbaum et al., 2006).

The evaluation of the LPJ-GUESS against the MODIS LAI is a model- model comparison with no real observational truth. Nevertheless, as MODIS LAI is based on remote sensing data, it has a great capacity of providing detailed spatial coverage, pattern information and temporal information as also mentioned by Stisen et al. (2011b). For this reason, the evaluation of LPJ-GUESS vs MODIS LAI is mainly based on the temporal and spatial analysis and not on the absolute values.

For the temporal analysis, both monthly maximum MODIS LAI and monthly maximum LPJ-GUESS LAI were normalized as z-scores; every value minus the mean and divided by the standard deviation. Additionally, LAI values equals or below 0.5 from the MODIS LAI were excluded from the calculation of the mean, in accordance the corresponding values on the LPJ-GUESS LAI were also taken out for the calculation of the LPJ-GUESS mean; this means that if a 0.5 value on a coordinate/month/ year was removed from the MODIS LAI, the corresponding coordinate/month/ year value was taken out from LPJ-GUESS dataset as well. As a consequence, months January, February, March and December were excluded from the normalization because they were mainly filled with 0.5 values on the MODIS LAI dataset. Finally, given the fact that the climate time series are constructed from different dataset, it was decided to exclude the first years of HOBE climate data set and use only the period 2005- 2011 for the analysis.

Correlation analysis and visual examination of the spatial patterns was done to analyse whether LPJ-GUESS LAI follows a similar spatial distribution as MODIS LAI. For this first analysis, every month/year of MODIS LAI was correlated with its corresponding month/year of the simulated LPJ-GUESS LAI. Same as before only the years 2005-2010 and the months April to November were used. The visual examination was done comparing the layers of monthly MODIS LAI and simulated LPJ-GUESS LAI. Year 2010 was taken as example.

- LPJ-GUESS vs LPJ-TI

The evaluation of the integration of LPJ-GUESS with a topography index was based on the comparison of the spatial patterns from MODIS LAI, LPJ-GUESS and LPJ-TI. Nevertheless, a brief analysis of the correlations of the soil moisture time series between the observed and simulated data was also done. For this purpose LPJ-GUESS and LPJ-TI were both run with the same settings as described before, but without irrigation. This, in order to prevent irrigation´s additional water input from masking the topographic influence out. As a consequence, the cft “Temperate cereals” (TeWW) was the CFT used.

As a first measure, the results of the LPJ-GUESS run with no irrigation were briefly compared with the irrigated one, to account for the differences and describe the new base LPJ-GUESS run.

LPJ-TI was run three times, each using a different shrink factor *a*, representing a different strength of the topography, *a* values 0.2, 0.3, 0.5. The evaluation of the models was done by comparing the results of correlation between the month/year MODIS LAI with the corresponding month/year of each one of the three LPJ-TI runs and the LPJ-GUESS run. This allows to move further not only into the spatial, but into the temporal analysis. Same as on the first part of this topic, only the years 2005 - 2010 and the months April to November were used. Visual examination of the spatial patterns of monthly LAI layers of the two models (LPJ-GUESS, LPJ-TI) and MODIS-LAI was done. Year 2010 was taken as example.

The topographic index to be used on LPJ-TI was the TWI (see section 3.3.2.3, Eq. 4 and Eq. 7), because of a) integrating two important water related properties of topography, b) its large and successful application on quantifying and predicting hydrological related processes, and c) most of all, because of the results of the first research topic "Topographic influence on the Soil moisture and LAI spatial patterns on the Alergaarde catchment".

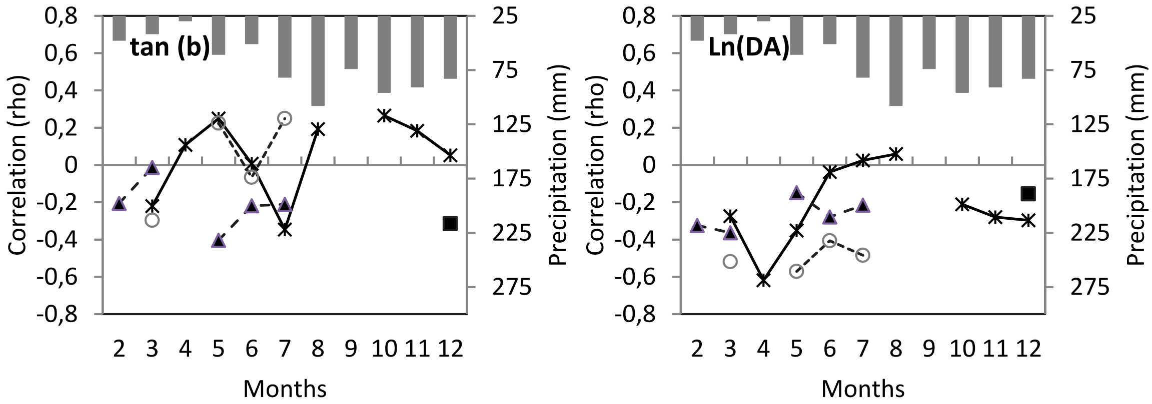
3.4.3 Statistics

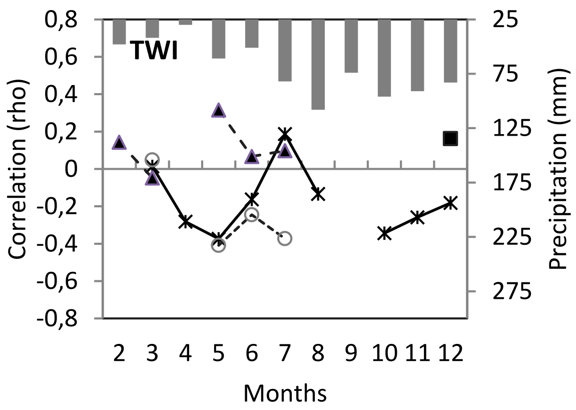
All the correlation analyses were done using the Spearman rank correlation (Spearman, 1904). The Spearman rank correlation (Spearman, 1904) was preferred, because it depicts monotonic relationships and not only linear ones, it is less sensible to influential observations on the tails of the distribution and better when low amount of pairs (as in the soil moisture analysis) are to be tested. Moreover, for the analysis of the time series, it is hard to guarantee the independence of the values which is needed for the Pearson correlation (Legendre and Legendre, 2012). Spearman correlation is similar to product moment Pearson correlation except that the ranks are correlated rather than the quantitative raw value; two descriptors are said to be in perfect correlation when the ranks of all objects are the same on both descriptors (Legendre and Legendre, 2012; Boslaugh and Watters, 2008).

4 RESULTS

4.1 Topographic influence on the Soil moisture and LAI spatial patterns.

4.1.1 Topographic indices vs soil moisture





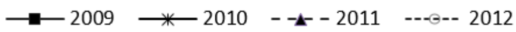


Figure 14: Monthly Spearman correlations between the topographic indexes and the soil moisture. Period 2009 - 2012. Monthly average precipitation for the whole catchment also shown (2009-2011).

Generally low correlations between the soil moisture and the topographic indices were found, ranging between -0.4 and 0.4; correlations above this range were only present for the Ln (DA) index, where the maximum value was -0.62.

The sign and magnitude of the correlation changed from month to month. Moreover, even within a month big differences in the magnitude and direction (positive or negative) of the correlation were seen for the different years (ex: May, June, July on Figure 14). The described situation did not allowed to establish a behaviour with respect to the average catchment monthly precipitation. As an overall, equal or almost equal number of positive and negative correlations were observed for the tan (b) and the TWI indices; oppositely for Ln (DA) the negative sign was the mode.

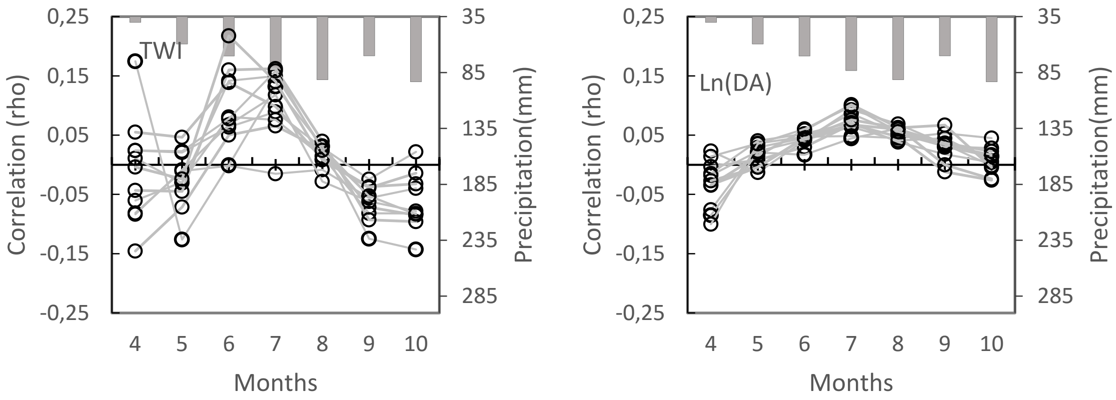
For the tan (b) and TWI the correlations sign oscillated greatly and no particular trend could be identified. On the contrary, for Ln (DA) (where positively correlations were expected) the correlations were mostly on the negative side and in two occasions relatively high (close to 0.6), singularities which were considered odd. Nevertheless, taking into account that the amount of observations is small (ex: on Ln (DA) April achieving rho =0.6 only 10 observations were used) and that the spatial resolution on the topography (25 x 25 m) data can be consider too coarse for the soil point measurements it is hard to decide on the significance of the results for any of the indices.

4.1.2 Topographic indexes vs MODIS LAI

The correlation analysis of the satellite based LAI data and the topographic indexes, showed generally low correlations (below 0.25), but consistent for every month. All TWI, Ln (DA) and tan (b) describe a particular and clear behaviour on the magnitude of the correlations during the year (Figure 15).

The greater correlations were seen on June and July for the TWI and tan (b) and in July for Ln (DA); where July is among the highest on precipitation. April, May, September and October were, on the opposite, the months with the lowest correlations for all indexes; April, May and September are also months with low precipitation. August though having high precipitation has low correlation values; this month is nevertheless part of the harvest season on the catchment, as a consequence the relationships between the topographic indexes and the vegetation is affected. Low correlations and high precipitation occurs again in October, which is on the secondary crop season; more information is needed to understand this behaviour.

A very similar behaviour on the magnitude of the correlation along the year was appreciated between TWI and tan (b), though opposite in sign; TWI correlations tending to positive values and tan (b) tending to negative values, as physically expected (direct relationship: high LAI related to high TWI values representing wetter conditions and inverse relationship: low LAI related with high tan (b) due to a greater potential of the site to lose water, dryer conditions). Mostly all the correlations with Ln (DA) were positive, but were the lowest from the three indices.



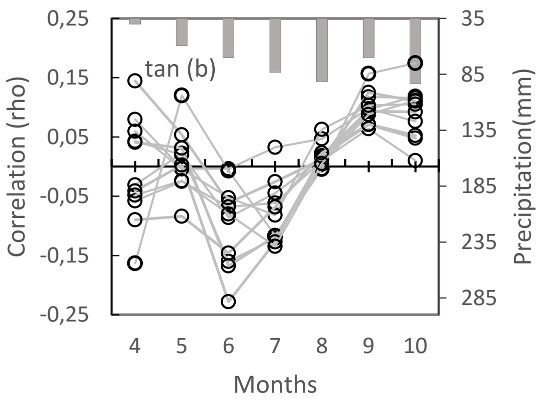


Figure 15: Monthly Spearman correlation of the MODIS LAI and the topographic indices for the years 2000 - 2010. The lines connect the correlations of every year. Also shown monthly average precipitation for the period 2001-2010 on the whole catchment.

Monthly MODIS LAI maps of 2010 evidences similar spatial patterns with the TWI maps (Figure 16). Very clear is for example the regions A and B on Figure 16, where both LAI and TWI have high values; for the region A this can be better seen in May, June and September on the MODIS LAI maps. Region B, on the other hand, is clearer in August and September. Tan (b) has similar spatial patterns as TWI but inverse.

The similarities of the spatial patterns of the LAI with the Ln (DA) are not easily seen; nevertheless, region A is still very distinguishable.

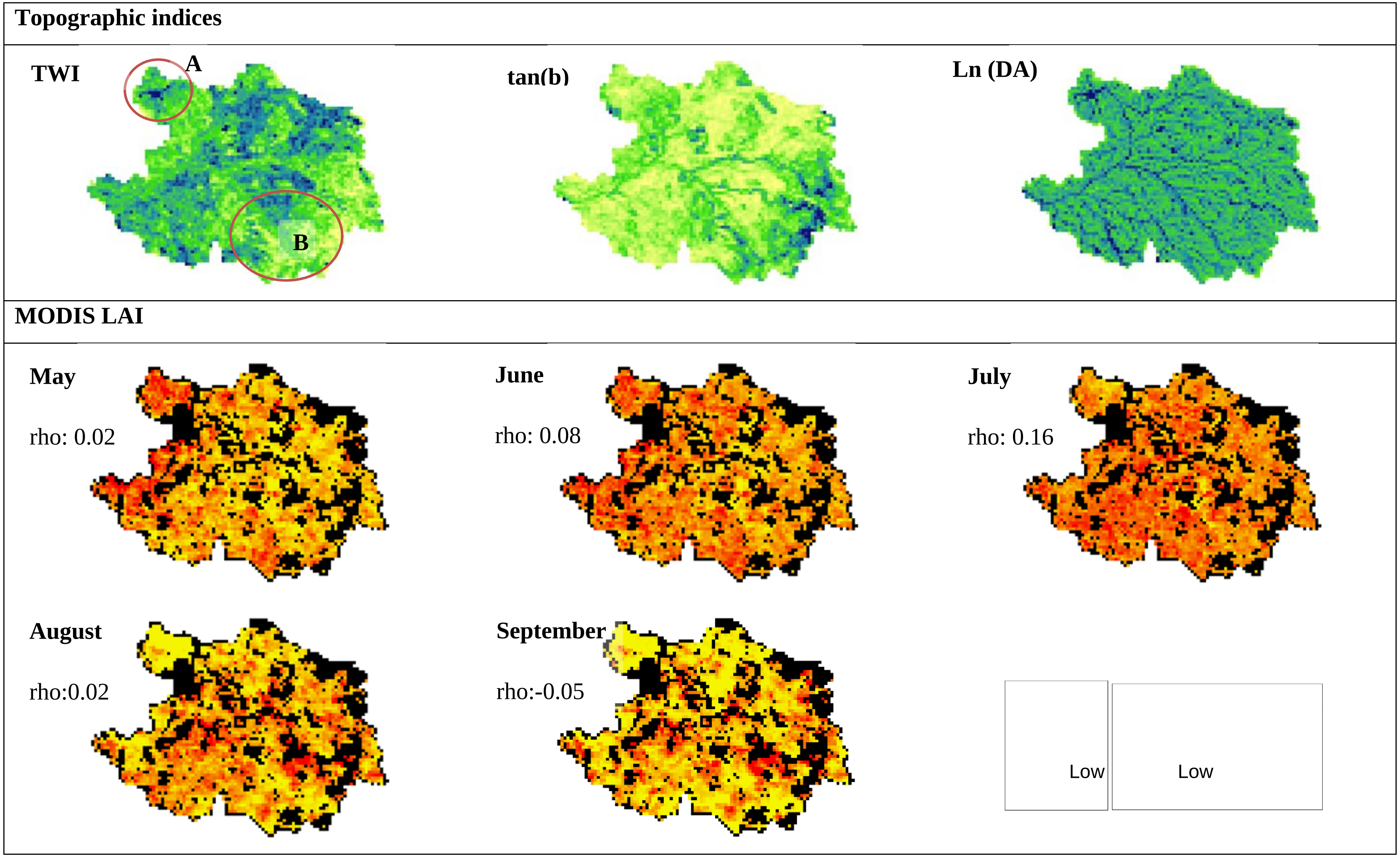


Figure 16: Alergaarde catchment topographic indices maps and MODIS LAI maps for May June, July, August and September of the year 2010. rho value with TWI on graph.

4.2 Original LPJ-GUESS vs LPJ-TI

4.2.1 Performance of LPJ-GUESS on the Alergaarde catchment:

The correlation analysis showed a good to very good agreement between the observed and simulated soil moisture time series (Table 3). The mean correlation coefficient value was 0.78, where over 73% of the stations correlate with coefficients above 0.75.

Station 3.2 had the lowest coefficient value of all. This result although notably different from all others was not associated to a model low performance on that specific site, since the uncertainty of the representability of the point for the cell (500 x500 m) is huge.

Table 3: Spearman correlation between the observed and the estimated LPJ-GUESS soil moistures time series.

Station	Correlation Spearman
1.6	0.869
1.7	0.775
1.8	0.847
2.3	0.814
2.5	0.784
2.7	0.804
2.8	0.864
3.1	0.738
3.2	0.567
3.7	0.776
3.9	0.729

MODIS LAI and LPJ- GUESS simulation for cereals showed a main growing phase between April and May; although, for some years LPJ-GUESS was slightly delayed. The highest peak was usually in June according to MODIS LAI, while July was the mode for LPJ-GUESS (Figure 17A, Figure 18). The harvest (usually evidenced in August) and the second peak on the LAI are not very conspicuous on the MODIS LAI (Figure 18A); nevertheless, there is evidence of the occurrence of a secondary crop season on the catchment with a corresponding peak appearing around October (Herbst et al., 2011, Figure 17B). On the other hand, LPJ-GUESS simulation sharply decreased in August as a consequence of harvest. Additionally, a well-developed and clearly defined secondary peak was seen, representing the secondary crop season as grass.

A) B)

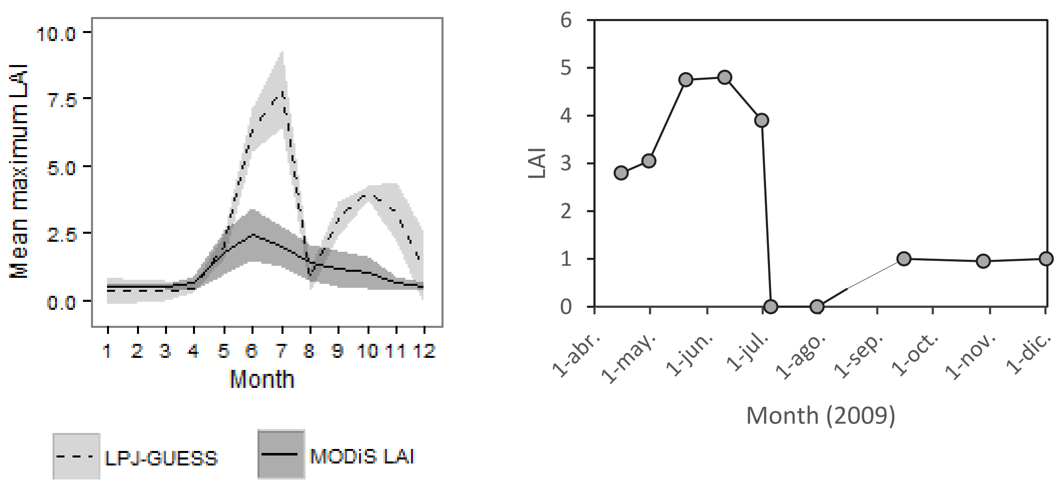


Figure 17: Along the year mean LAI maximum values for A) LPJ-GUESS LAI and MODIS LAI. Shadows are the standard deviations. B) Figure 2 recreated from of Herbst et al., (2011); LAI observed data on a barley field on Skjern catchment. Harvest on 21 July, second crop radish was sown the following day.

The highest peak of LPJ-GUESS was on average 7.5, which is above the mean value for the year 2009 at the representative agriculture district Voulund on the catchment (Herbst et al., 2011) (Figure 17) and the results of the agro-hydrological model Daisy on a closer catchment (Boegh et al., 2009).Oppositely, the peak of the MODIS LAI data was around 2.5, which is below the average 4.5 of the observed data (Herbst et al., 2011) and estimates from (Boegh et al., 2009)

When comparing the normalized LAI of both MODIS and LPJ-GUESS it can be seen that LPJ-GUESS LAI varies greater within the year than MODIS LAI (Figure 18), and that between the models the interannual height of peak does not always behave similar. This means, that it is expected that the highest peaks are found in the same years for both models: if an increase/ decrease of the peak's height occurs on one model the same should happen on the other. This is not always the case especially when looking at year 2007, and the relative difference between year 2005 and 2010 in both models (Figure

18). Nevertheless, MODIS LAI has a great variation and LPJ-GUESS a small one, which makes hard to conclude on the very specific differences of the yearly profiles.

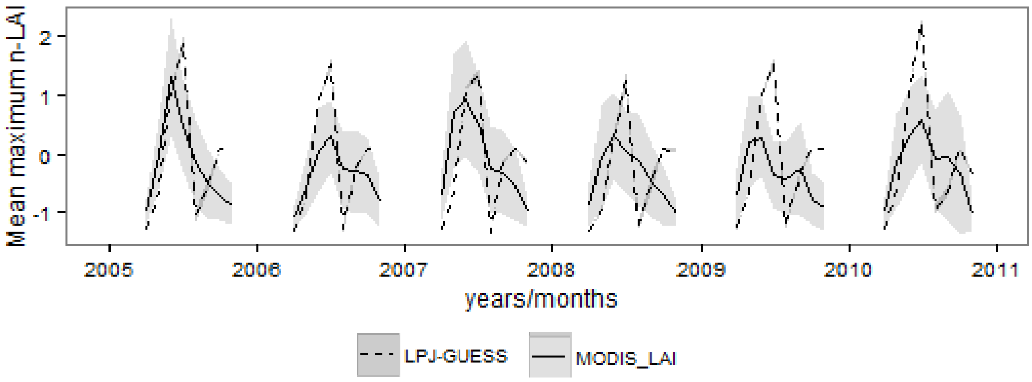


Figure 18: Comparison between the time series of the simulated LPJ-GUESS and the MODIS LAI mean normalized LAI. On the left the whole time series including only the months April to November (including November); the shadows represent the standard deviation.

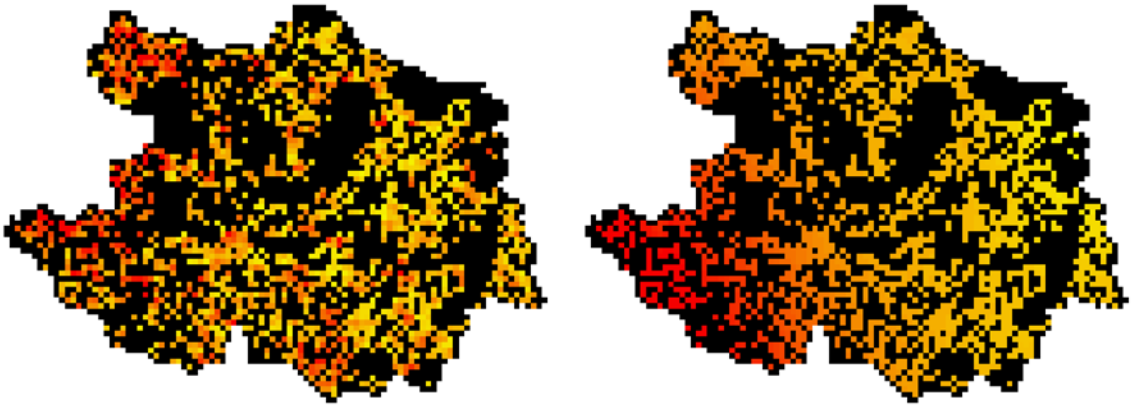
Figure 19: Monthly Spearman correlations between MODIS LAI and LPJ-GUESS LAI for the years 2005 - 2010. The lines connect the correlations of the every year.

The monthly spatial correlation analysis of the cereals LAI exhibits generally low correlations (below 0.4) (Figure 19). Along the years the higher values are on April, May and June; afterwards the correlations coefficients have more often negative values or are rarely above 0.1. September tends to stay on the positive correlation with maximum values not above 0.2. Moreover, it is important to notice that every year/month correlation changes differently; there is not a characteristic curve that all years follow.

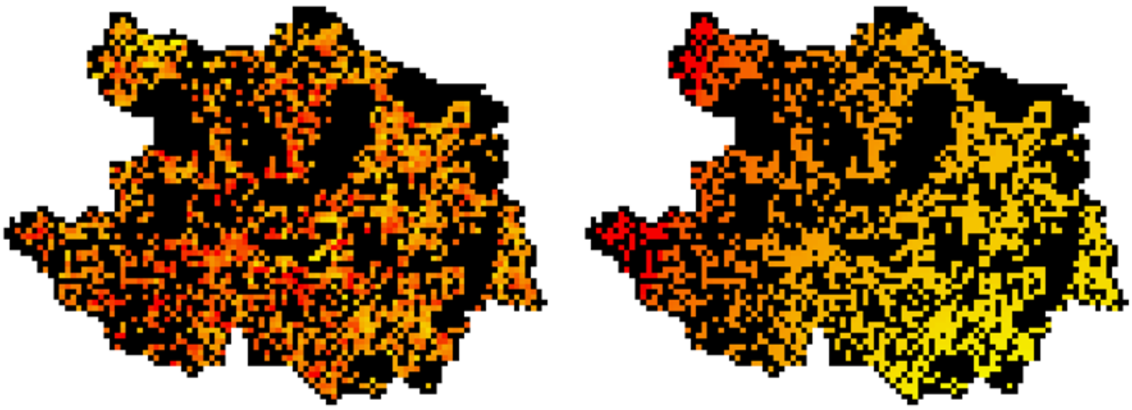
The visual evaluation of the different months of the year 2010 for both MODIS LAI and LPJ-GUESS (Figure 20) allows to see how the simulated LPJ-GUESS changes smoothly in a west - east gradient across the catchment. Meanwhile, the MODIS LAI is showing a much more variable pattern. On May some spatial similarities can be identified, higher LAI on the Western and lower on the East. For the other two months, July and September, not obvious similarity was found, which corresponds with their very small correlations coefficients (Figure 19).

MODIS LAI **LPJ-GUESS**

May



July



September

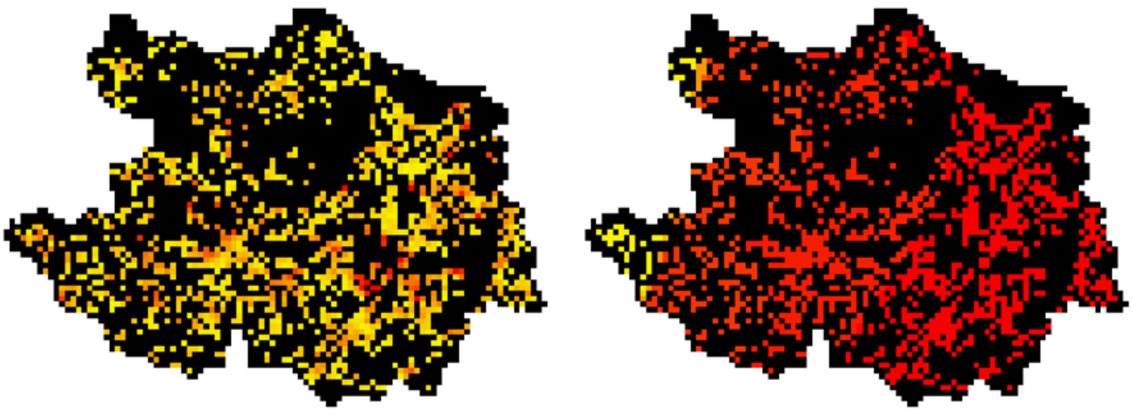
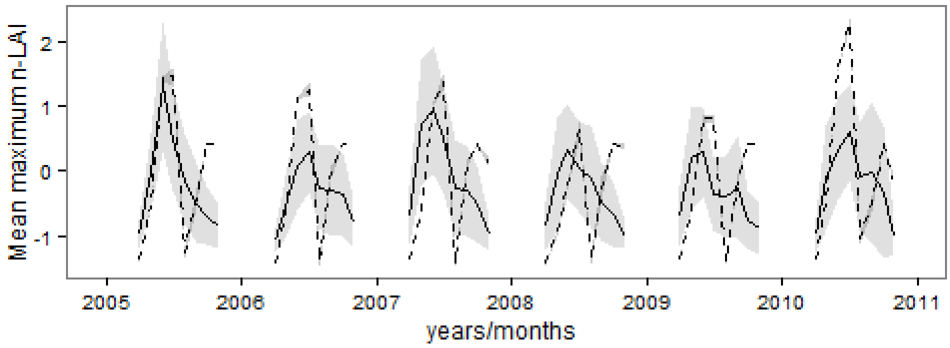


Figure 20: MODIS LAI vs LPJ-GUESS LAI for the months May, July and September of the year 2010. Yellow low LAI values, red high LAI values.

4.2.2 Irrigation vs no-irrigation

The exclusion of the irrigation option on LPJ-GUESS had no effect on the temporal correlations of the soil moisture time series (see section 4.2.1); showing good to very good agreement between the observed and simulated soil moisture time series (Table 4 ,Table 3).



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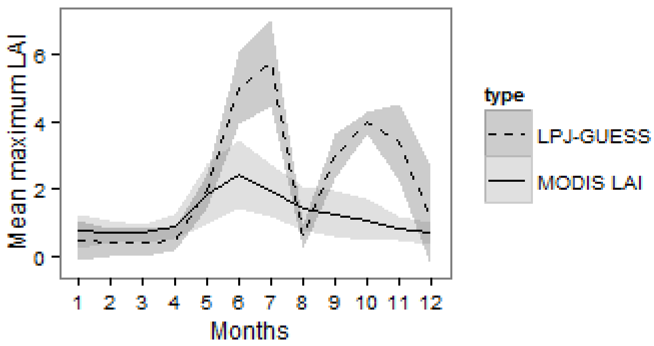

Figure 21: A) Comparison of the mean normalized LAI between the LPJ-GUESS simulated not irrigated cereals and the MODIS LAI time series. B) Monthly mean LAI maximum values for LPJ-GUESS and MODIS LAI. Shadows are the standard deviations.

Figure 21 showed mainly the same seasonality as the irrigated run (Figure 18A), but there is less difference between the height of the first and second peak, showing how the irrigation positively favoured the first crop season. The new no irrigated run showed a lower maximum LAI peak averaging 5, which is closer to the reported data on the region (Herbst et al., 2011). This shows how irrigation strongly influences the development of the plants in LPJ-GUESS, leading to a big overestimation of the LAI on the Alergaarde catchment. The strong influence of the irrigation was also seen by Lindeskog et al. (2013), where irrigation substantially increased simulated yields in Africa.

As the first crop (cereals) seasonality remains fitting the MODIS LAI and the LAI values are closer to the observed data on the region; the removal of the irrigation for the introduction of the topography index test was considered to be adequate.

4.2.3 LPJ-GUESS (no irrigation) vs LPJ-TI

The implementation of LPJ-TI affected minimally some of the temporal correlations of the soil moisture time series (Table 4); the agreement between the observed and simulated soil moisture time series is therefore good to very good.

Table 4: Spearman correlation between the observed and the estimated (LPJ-GUESS no irrigation and the three LPJ-TI) soil moistures time series. The values of the TWI at 500 x 500 m cell size

		LPJ-GUESS	LPJ_TI		
Station	**TWI**	**No irrigation**	**0,2**	**0,3**	**0,5**
16	14,635	0,869	0,860	0,860	0,860
17	14,306	0,776	0,768	0,769	0,768
18	14,998	0,847	0,847	0,843	0,843
23	13,947	0,814	0,814	0,814	0,801
25	14,339	0,784	0,784	0,784	0,784
27	11,719	0,804	0,804	0,804	0,811
28	15,140	0,864	0,864	0,864	0,864
31	12,914	0,738	0,738	0,738	0,738
32	14,020	0,567	0,568	0,568	0,568
37	14,105	0,776	0,776	0,776	0,776
39	10,680	0,729	0,729	0,729	0,724

The LAI correlations between the MODIS LAI and the non-irrigated LPJ-GUESS LAI had generally even lower correlation values than the ones observed on the irrigated run (Figure 19, Figure 22A). Nevertheless, the non-irrigated monthly correlation signs are generally the same are the ones from the irrigated run. In a similar way, the correlations for April, May and June are relatively higher than those of other months.

The implementation LPJ-TI affected the correlations magnitude and sign on all weighting scales, but not in all the months (Figure 22). The correlations from June and July became more positive from the smallest weighting scale (0.2) on, especially on July (rainy month). The difference between the bigger weighting scales and the 0.2 scale was minor. May 2010 reduced continuously the magnitude of the correlation with increasing scale size; while April, August, September and October correlations remained practically unchanged.

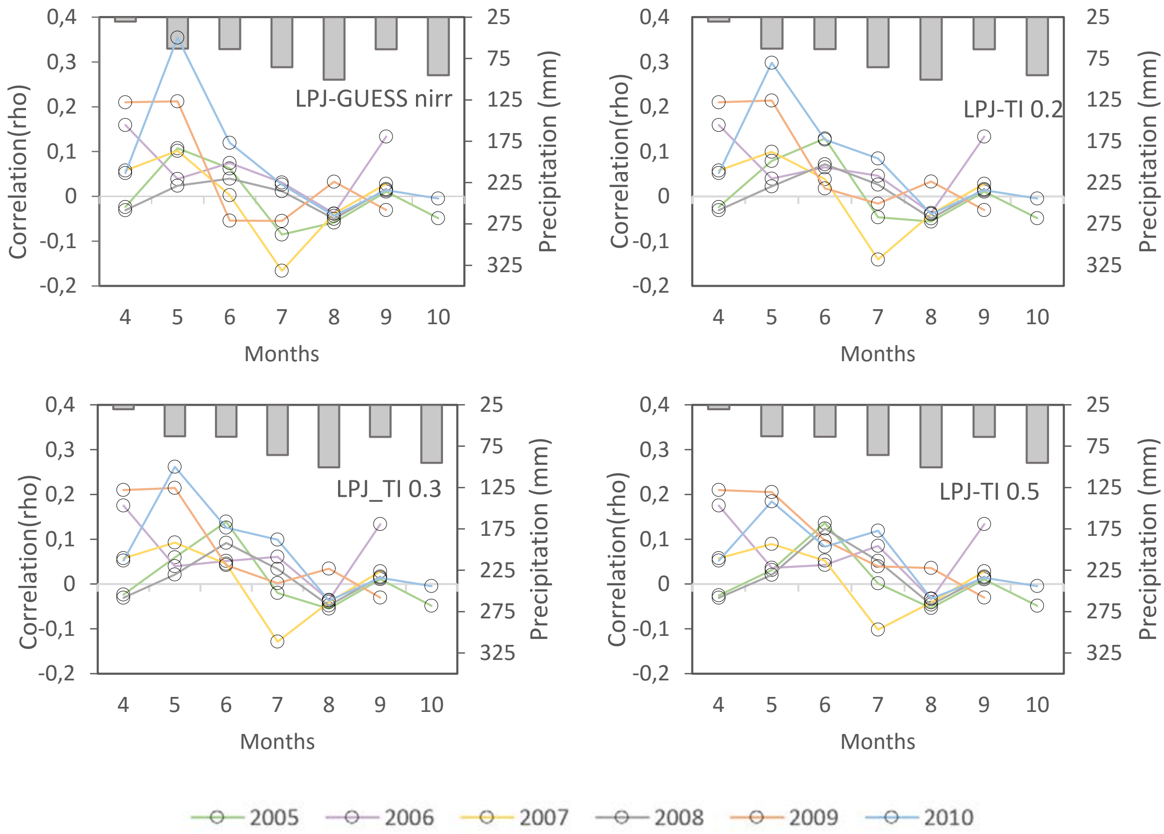

Figure 22: Monthly Spearman correlations of the MODIS LAI and the LAI obtained by the LPJ-GUESS runs using three different *a* values, for scaling, 0.2, 0.3 and 0.5. Years included 2005 to 2010. The lines connect the correlations of every year. On secondary axis the monthly average precipitation for the whole catchment (2005-2010). nirr stands for no irrigation.

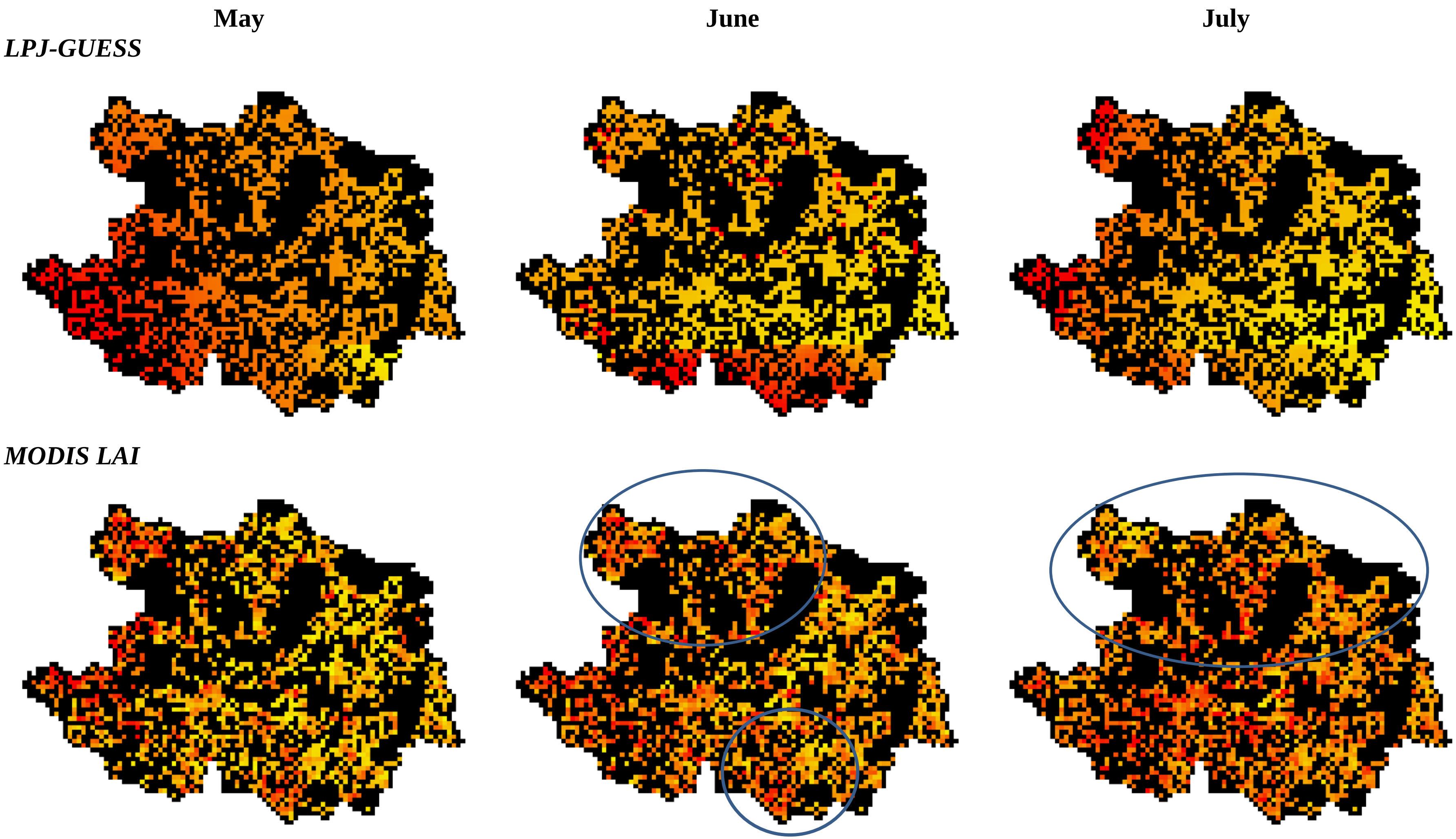

Figure 23: Alergaarde catchment temperate cereals LAI maps for the comparison of MODIS LAI and LPJ-GUESS non-irrigated run. Year 2010. Yellow low values, red high values.

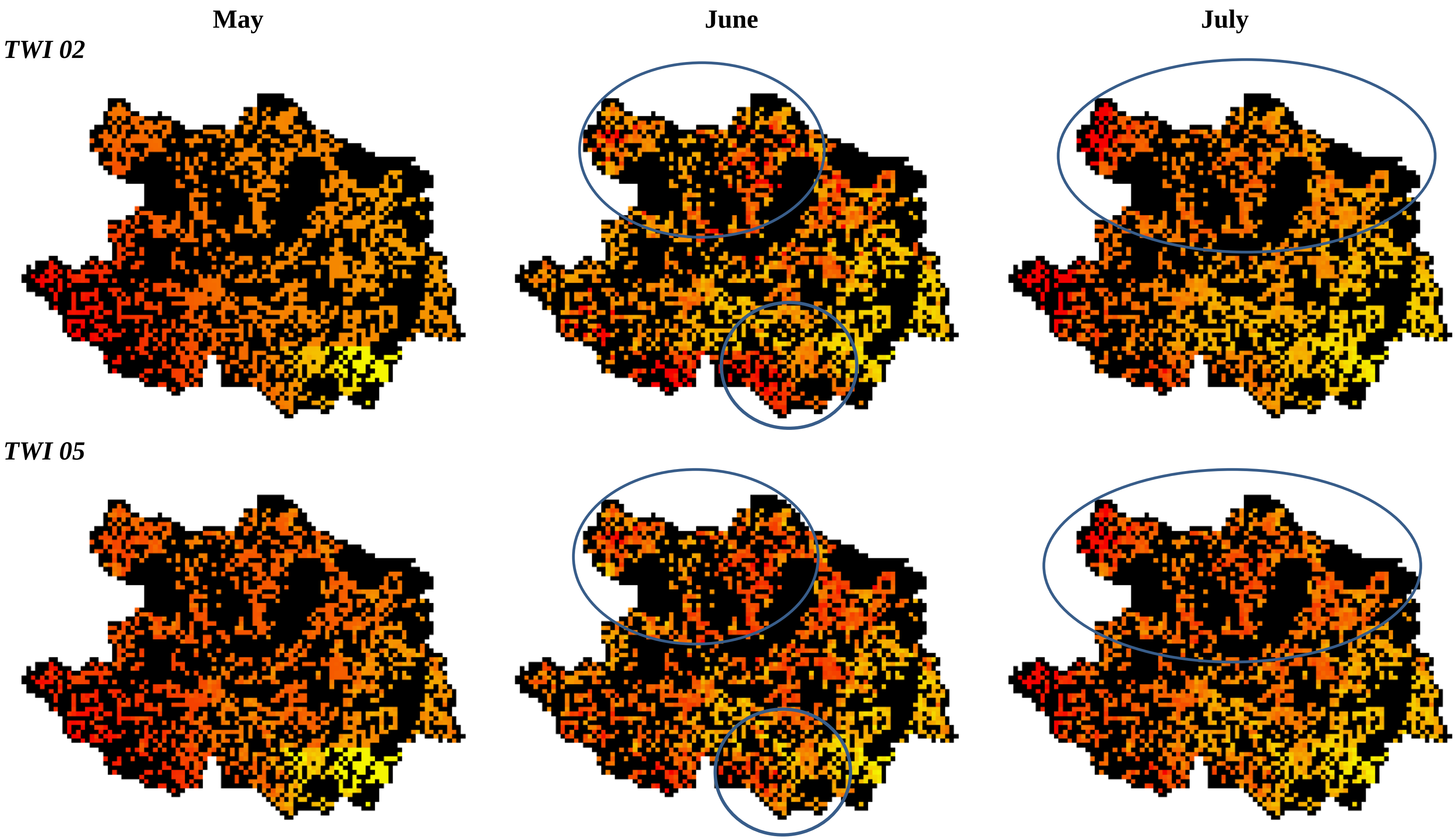

Figure 24: Alergaarde catchment temperate cereals LAI maps for the comparison of LPJ-TI 02 weighting scale and LPJ-GUESS 05 weighting scale with Figure 23 containing LPJ-GUESS runs and the MODIS LAI. Year 2010. Circle areas are areas where the MODIS LAI from Figure 23: Alergaarde catchment temperate cereals LAI maps for the comparison of MODIS LAI and LPJ-GUESS non-irrigated run. Year 2010. Yellow low values, red high values.Figure 23 is more alike with the LPJ-TI predictions. Yellow low values, red high values.

The observation of the spatial patterns for the year 2010 (Figure 24, Figure 25) shows how the introduction of TWI weigths changes a very uniform and smooth spatial LAI representation to a more diverse picture; especially for June and July. Within the blue circled regions in June and July a good spatial agreement between MODIS LAI and LPJ-TI LAI can be identified. This improvement is nevertheless not seen on the whole region, which is thought to be linked with the spatial distribution of the precipitation and the fact that LPJ-TI construction only allows the TWI weights to act in case of precipitation occurrence. In July, for example, precipitation is higher on the northern part (Figure 25), which corresponds with the region where more changes on the simulated LPJ-TI LAI compared with LPJ-GUESS were identified.

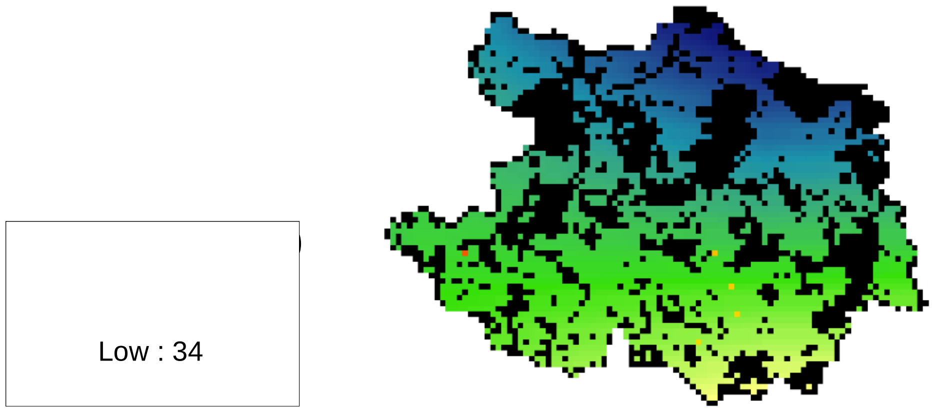

Figure 25: Precipitation distribution in July of 2010.

5 DISCUSSION

5.1 Topographic influence on the Soil moisture and LAI spatial patterns

5.1.1 Topographic indices vs soil moisture

According to the characteristics of the indices, and the often results from other studies, it was expected to found negative correlation between tan (b) and soil moisture, and positive correlations when evaluating soil moisture vs Ln (DA) and soil moisture vs TWI. Nevertheless, the results presented here did not showed these tendencies, and generally behave ambiguous through time (Figure 14). Additionally, no particular association between the correlations magnitude or sign was established with respect to the precipitation. These results may be explained by many reasons:

- Low representation of the data given the small size of observations.
- Even if all the soils used for this analysis are arable land, and have a sandy topsoil and subsoil, they have small differences on their textures and differ on the crops being cultivated. These differences affect the evapotranspiration, runoff and infiltration resulting extremely hard to distinguish the influence of topography on the regions.
- The points are variably and largely spaced, over (1 km), which brings even more variability to the analysis; for example attributed to different climate conditions (even if the catchment has only small gradients in its meteorological parameters). Usually in this kind of analysis the observation are done on transects, or grids low spaced.
- The 25 x 25 m resolution of the DEM could be too coarse for the soil moisture point measurements, hindering a meaningful comparison.

All these reasons make it difficult to make a statement on how strong the topography and the soil moisture are related on the catchment. The no-clear correlation result between the soil moisture and topographic elements have been found many times (Charpentier and Groffman (1992); Niemann and Edgell (1993); Crave and Gascuel-

Odoux, 1997; Ladson and Moore, 1992), but it is often explained partly or greatly by the low sampling frequency in time and/or space, as it is the case on the present study.

5.1.2 Topographic indices vs MODIS LAI

The LAI is a key emergent structural attribute of vascular plants closely linked to primary production and surface energy balance (Spadavecchia et al., 2008). It is well known that plant growth is influenced by factors such as soil water content, solar radiation, and soil organic community. Topography affects soil water content, and soil organic content distribution (Swanson et al., 1988, Rodriguez-Iturbe et al., 1999); moreover, the topography aspect also influences the absorption and reflectance/emission of radiation by the surface, affecting the photosynthesis of plants (He et al., 2007). Banerjee et al., (2011) found a significant control of topography on grassland productivity and heterogeneity. Consequently, associations between topography and LAI were expected to be found on the present work.

The correlations magnitude of the MODIS LAI and the topographic indexes were low, but showed a consistent behaviour along the year (Figure 15). The low correlation coefficients could be related, with the little relief, coarse soil texture, the land use type and the activities related to it. Alergaarde catchment minimal relief and sandy soil cause lateral redistribution to be less active and slower. Furthermore, as it an agricultural land there is an extra human force bringing variability to the area on both the temporal and spatial scale. Irrigation (common in the catchment) alters the natural soil moisture spatial patterns; tillage, causes translocation of soil; harvest, results on temporal removal of the vegetation. Another factor affecting the magnitude of the correlations is the coarse resolution (500 x 500 m) used. Most probably a higher resolution will help on getting better results, as it is known that the spatial resolution on this type of studies is of considerable importance (Famiglietti et al., 1998; Wu et al., 2008, Tenenbaum et al., 2006).

The variation of the correlations magnitude along the year (Figure 15) has been seen on other studies analysing soil moisture and topography (Western et al., 1999; Famiglietti et al., 1998; Qiu et al., 2001, Tenenbaum et al., 2006). As in those studies, these variations are thought to be partly associated with the precipitation regime: higher correlations found on wetter climate conditions. Famiglietti et al. (1998) stated that on wetness conditions the lateral and vertical hydraulic conductivities are high, which results in an active moisture redistribution downslope and to greater depths. Similarly, Qiu et al. (2001) found an increase on the correlation of soil moisture with slope gradient after a greater amount of antecedent precipitation (except for extremely heavy storms) and Tenenbaum et al., 2006 described a greater topographic organization of the soil moisture pattern with the increase of soil moisture on an urbanized catchment. On Alergaarde catchment June and July, the best correlated months, are characterized by intense precipitation. August is also part of the rainy season; nevertheless lower correlations were found, condition related with the harvest period.

The analysis of both the correlations coefficients (Figure 15) and the LAI maps for June and July (the months with the higher correlation values) (Figure 16) showed that even if the correlation coefficients range on low values, these are indicating a positive association between the topography and the LAI heterogeneity. Banerjee et al. (2011) analysing grassland LAI relationship with topography on a 381 m transect with observed data every 3 m, noticed that the coarse trend in the distribution of LAI was similar to the smooth trend of the wetness index, the significant correlation value between TWI and LAI was of 0.37. This result again shows that the LAI heterogeneity has a much higher variation than the topography index reflecting on a low correlation value, but nevertheless an association clearly exists and can qualitatively be analysed by visual methods. On the other hand, it is important to remember that the soils from Alergaarde catchment are mainly sandy and studies have shown that the surface runoff is rare; nevertheless, sandy soils have high hydrologic conductivity which favours the subsurface runoff; a much slower processes than surface runoff. As a consequence, the strength of the topography influence is reduced (not absent), and the principal hydrological element responding to it can be attributed to the subsurface runoff.

The visual interpretation showed that on the same month some regions were clearly related with the topographic index, while other regions did not (Figure 16). This can be partly explained by the small gradients in climate, specific local conditions and management strategies.

Aside from the temporal sensitivity of the relationship between topography and the environmental factors, this relationship can also be affected by DEM cell size, flow direction algorithm and slope algorithm (Güntner et al., 2004; Sørensen et al., 2006; Buchanan et al, 2014, Hasan et al., 2012). Accordingly, it is very important to have clear these limitations, and work with algorithms that give a better representation of the water flow in the catchment. For the Alergaarde catchment, the use of TFM algorithm offers a good representation of the flow direction and was consider a good starting point for this study.

TWI index is often found to be one of the best indices on demonstrating the association of topography with LAI (Banerjee et al., 2011; He et al. 2007). Similarly, Green and Erskine (2004) stated TWI as the strongest topography index for predicting up to half of the spatial variability in wheat yield. The current study also found association between the TWI and the spatial variability of MODIS LAI, exposing again the importance of topography on the dynamics of the ecosystem and also how TWI has a potential for predicting the spatial hydrological responses in the catchment.

Finally, it is important to notice that despite the coarse resolution (500 x 500 m) used, positive results of topography influence on the environmental variable LAI were detected. Such fact is an indication that a) topography is still a relevant factor for the environmental modelling in smooth catchments and, b) downscaling the TI using the cell mean resulted to be a good approach for summarizing the topographic characteristics.

5.2 Original LPJ-GUESS vs LPJ-TI

5.2.1 LPJ-GUESS performance

The results of the analysis for evaluating the performance of LPJ-GUESS on simulating the hydro-ecological conditions of the Alergaarde catchment showed how LPJ-GUESS could catch well to very well the temporal profile of the soil moisture (Table 3). In agreement with this, Sitch et al. (2003) found good agreement of the seasonal cycle between the modelled and observed monthly soil moisture for a number of sites in Europe and Asia, using a former model version.

The comparison of LPJ-GUESS with the studies of Boegh et al. (2009) and Herbst et al. (2011) shows that LPJ-GUESS is highly overestimating the LAI values for the irrigated cereals (Figure 17). One reason for this overestimation is thought to be the irrigation option, as the results from the comparison of the irrigated with the no irrigated run showed (Results. Section 2.2).

After the cereals harvest MODIS LAI and LPJ-GUESS LAI differ considerably (Figure 18). The highly conspicuous development of the second crop (grass) in LPJ-GUESS simulation disagrees with the MODIS LAI data, this implies that a better calibration of the model is needed to obtain better results on the development of the second crop. This is nevertheless, beyond the reach of the present study.

The cereals spatial analysis of the patterns showed, that LPJ-GUESS is failing on representing the spatial variation of the environmental variables such as LAI (Figure 20). LPJ-GUESS has proven its effectiveness on simulating fluxes and seasonal cycles of CO_2, vegetation distribution, biomass, and runoff, within others. Nevertheless, it is important to point out that traditionally the model has been used with grids of 0.5° (latitude, longitude), where the climate and soil are the main drivers on the definition of the environmental variables. When the resolution increases, the size of the study units becomes smaller and factors like topography influencing water redistribution on catchments become more relevant. For Alergaarde catchment LPJ-GUESS simulated smooth changes of LAI across the catchment, reflecting only: a smooth climate gradient, very homogeneous soil types and irrigation. This last one is particularly important, now that it plays an important role on smoothing the changes by adding water if the precipitation cannot cope with the optimum water requirement of the crop. On the other hand, MODIS LAI heterogeneous mosaic pattern showed that there is more affecting the response of the LAI than what was represented by LPJ-GUESS. According to the scale used and the results from the first topic, topography is consider one of those relevant factors.

April, May and June correspond with months with higher spatial correlations (Figure 19) and also with good representations on the seasonal LAI curve. This indicates the importance of having a good temporal behaviour in order to be able to analyse the spatial patterns at time steps. Intuitively one cannot pretend to look for similarities on the space if at a certain time the crops are at a different state on both “models”. Consequently, a no-significant or negative spatial correlations on bad represented periods should not be rashly stated as a wrong capture of the spatial patterns by the model, because it is biased by a temporal mismatch.

5.2.2 LPJ-GUESS vs LPJ-TI

The analysis of the correlation of the time series of observed and simulated soil moisture showed how LPJ-TI had no to little impact on the temporal behaviour of the soil moisture Table 4. Situation which indicates that at each location (pixel) the climate and soil properties are the main factors affecting the temporal behaviour of the soil moisture. How is the performance of the simulated soil moisture values with respect to the observed ones is a question to be solved when representative data to the pixel size are on hand.

The results on the previous sections have shown that the topography plays an important role on the hydrological processes of the Alergaarde catchment, and that LPJ-GUESS cannot catch the spatial variability of environmental variables, such as LAI. As a consequence, an exploratory test for evaluating the power on simulating spatial patterns of the Topographic weighted LPJ-GUESS, LPJ-TI, was conducted. The analysed variable was the MODIS LAI, which has a strong association with the water availability in the soil, soil organic matter and solar radiation, three factors affected by the topography. Moreover, MODIS LAI fits very well with the study purpose, as it is a spatial distributed data to evaluate a spatial distributed model.

The correlation and visual analysis showed how the inclusion of the topography as TWI weights immediately had an effect on the spatial appearance on selective months on the catchment (Figure 22). The most conspicuous changes and increases on the correlation (though staying in a low correlation range) occurred in June and July, months characterized by high MODIS LAI values. These two months have some characteristics which favours this behaviour 1) they are quite well represented by the LPJ-GUESS model (at least on the first vegetation peak); 2) they are humid months so that the scaled TWI can affect the period; taken into account that the current construction of model only allows the influence of TWI when precipitation or snowmelt occurs; 3) in accordance with the TWI vs LAI analysis (Topic 1), June and July are the months identified to be the most affected by the topography driven by the climatic conditions (i.e. precipitation intensity, frequency).

The lack of sensitivity to TWI for the other months is accounted to different reasons. In April, it can be associated to the early stage of the crops and the low precipitation for that month, now that on the current modified model the topographic weight can only affect the model if precipitation occurs, as mentioned before. This effect is also the cause for a differential spatial effect of the weights on the same month (precipitation spatial distribution). In August the lack of response is more related to the crop calendar, now that it is immediately after harvest, thus there is no (few) vegetation to answer to the changes. Finally, September and October are not temporally well represented by the model which already introduces an error and therefore two models which are not suitable to compare.

The particular construction characteristic of the model makes it dependent on the precipitation occurrence and gives the model a “static dynamic” characteristic. It is Static because a single constant value is associated to a cell, and dynamic because the difference in the precipitation occurrence generates a conditional influence of the index on time and space. This is reflected on areas more influenced by the index on the same month or by less response to the index between different months. It can be argue that this approach is somehow realistic now that studies like those from Qui et al. (2001), Famiglietti et al. (1998) Tenenbaum et al., (2006) and Western et al. (1999) showed higher correlation on wetter periods; nevertheless, their explanation does not simply associates this with the precipitation occurrence, but with the increase on the hydraulic conductivity of the soil due to wetness, which is not limited to the precise occurrence of the precipitation event. According to this, the current approximation is considered to be too rough, thus the elaboration of modifications on its construction that reflects its weather dependence and linked processes is suggested.

The former results showed that, even in smooth landscapes topography is an important factor modelling the spatial variability of the hydrological processes and that its modelling, by the use of topographic indexes like the TWI, is feasible. It is clear nevertheless, that topography is not the only nor the main factor acting on the spatial variability of the hydrological processes, as seen by the low correlation values found. In agreement with this last statement, the study from Wolf (2011), where LPJ-GUESS was couple with TOPMODEL, concluded that the soil properties were found to be more important for vegetation responses than explicitly modelling the lateral water exchange between the grid cells, even in steep topography. Nevertheless, her study did not explore the spatial effects deeply and did not evaluate the magnitude of the influence of topography on the spatial patterns. Moreover, on Wolf (2011) approach the daily remaining soil water (rain and melt water minus evapotranspiration) at each cell was redistributed based on the difference between the local TWI and the catchment average TWI, this approach results on spatial predictions that are only a function of the topographic index and therefore loses part of the information of the local conditions. This last issue is not evident when analysing the runoff, in that it represents an integrated catchment response, but will be evident when comparing observed patterns, with the simulated ones.

Recently, Tang et al (2013) successfully presented LPJ-DH model to integrate topography in LPJ-GUESS. LPJ-DH uses cells connectivity information, based on topographic attributes (DA, flow direction) to move water through the catchment. It has, as described, well physical bases and has achieved very positive results (Tang et al, 2013); nevertheless, it is very computationally demanding. LPJ-TI, on the other hand, does not physically model the water dynamics, but recognizes the role of topography in the catchment by characterizing every specific location using a simple algorithm, thus it is very computational efficient. The present study has shown that LPJ-TI, though its simplicity, has potential to simulate spatial patterns of environmental variables, such as LAI. For the moment, the evaluation on LPJ-TI's potential to simulate observe values is still to be answered, but it is thought to be solve by site specific calibration. The simplicity of the proposed method also allows to move to different scales with minimum increase on the computational effort above a normal LPJ-GUESS run; moreover as the topographic index are run separately and they can be easily upscale to characterize a place (i.e. TWI at 25 m grid upscale to 500 m grid using the mean), this allows to make the most of the finer resolution of the DEM data to get a better quality of the topographic indices.

Though LPJ-TI has proven to be a simple way to include topography influence in the model, it can at the moment only be used for specific purposes, like spatial representation, overall carbon balance, vegetation properties, etc. Other questions, relate to water balance and runoff are at the moment not possible to answer, especially because runoff allocation was not been implemented in the model. Nevertheless, one can decide according to the purpose of the research which assumptions or limitations are worth to admit.

6 CONCLUSIONS AND RECOMMENDATIONS

Ecosystem modelling is a science trying to simplify a complex system, with complex interactions and multiple actors and agents. Modelling is always evolving, there is always something missing, something to be improved; there is always a new question, a new goal and maybe also an alternative solution.

LPJ-GUESS dynamic ecosystem model is a continuing evolving model, which have originally ignored horizontal fluxes of water between adjacent areas, which are defined by topographic features and become more relevant when moving to smaller scales such as catchment level. This thesis has evaluated this condition by a) analysing the importance of topography on defining the spatial heterogeneity of environmental variables on a smooth catchment, b) evaluating LPJ-GUESS ability to catch the environmental variables spatial distribution and c) implementing LPJ-TI and assessing its performance on modelling the spatial patterns of environmental variables. The study was based on the land use type cereals of the Alergaarde catchment.

The results of environmental variables correlations with topographic indices and visual examinations of spatial patterns indicated that, at Alergaarde catchment level (~1000 km^2), even little relief is an important issue for explaining the spatial heterogeneity of environmental variables such as LAI and thereby of soil moisture; although the relationship with the last environmental variable could not be caught with the data on hand. The influence of topography on the environmental variables was not constant along the year, which was mainly associated with precipitation seasonality/distribution and land management. On the other hand, TWI was chosen to be the most appropriate index to characterize hydrological responses, given the higher correlation with representative months and because it integrates two important water related properties of topography; slope and drainage area.

Factors like soil type, climate conditions, land use and land management define LPJ-GUESS modelled spatial distribution of environmental variables; nevertheless, the modelled spatial variability was proven not to be representative enough on the study area. This observation together with the shown influence of topography on defining the spatial organization of environmental variables reinforces the idea of integrating topography into LPJ-GUESS.

The model LPJ-TI, implementing topography in LPJ-GUESS by the use of topographic indices (TWI) weights, improved LPJ-GUESS capacity to catch the spatial patterns of the environmental variable LAI at a very low extra computational cost. Notwithstanding, much more studies and improvements are needed, such as:

- Topography is acting on the hydrology of a catchment independently of a rain event, it is therefore important to change the current structure of the LPJ-TI to make the TI a constant effect. One example could be affecting the water content “wcont” instead of the water input “rain-melt” (current implementation).
- It is clear that a static TWI weight cannot represent the influence of topography on hydrology processes related environmental parameters, now that different factors along the year affect how strong such an influence is. Following this idea it would be interesting to analyse how this relationship in the catchment is, and create a dynamic topographic index scale which changes in accordance to such a relationship. For example, introducing temporal variability by making the “a” parameter in Eq. 7, which accounts for the strength of the influence of TWI, a function of the antecedent *fraction of available water holding capacity*. If different land uses are included then the weight should also make a land cover distinction.
- Topography can influence the hydrology processes of a catchment by other features than slope and drainage area. The aspect of slope, for example, is related with isolation potential and evapotranspiration and has proved to be important on soil moisture spatial variations (Western et al., 1999). Accordingly, the combination of topographic indexes is worth to study and evaluate whether the spatial patterns will be better represented.
- The current project evaluated the correlation between TWI with MODIS LAI and applied it in the LPJ-TI model. Nevertheless, the kind (i.e.: linear, exponential, etc.) of correlation was not analysed. It is important, for further studies to analyse the shape of this relationship and if needed transform it to warranty a linear relationship, now that this is the way it enters into the model.

The lack of lateral transfer does not allow the current modified model to fulfil the principles of the water balance equations, which is a great handicap of the model. Nevertheless, it is considered to have physical basis and is thought to have a good potential on representing realistic spatial variability and values (not part of this study), and therefore useful for many ecosystem analysis. It would be anyhow important to find a way to calculate the weights so that at least on catchment scale the water balance principles are met. Redistribution like in TOPMODEL could be a solution, but then the local “actual” conditions are lost.

Here it is considered that the proposed development of LPJ-TI could improve the estimations of the environmental variables (ex. evapotranspiration, vegetation responses) cell wise and the representation of the general spatial patterns. LPJ-TI model has its limitations, but one can consider appropriate to take advantage of the improvements to solve specific questions. As a mediating model, this model is an approximation to account for a phenomena and it could be as good as the model will be calibrated.

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8 APPENDIX

Appendix A

Code changes for the inclusion of weights

The topography related variable was introduced within the file_gridlist.txt file, which is the file defining the coordinates on which the model should run. The first column is longitude, the second latitude and the third the TWI weight.

Ex:

```
The new file_gridlist.txt looks like this:

9.17957652    55.82619121   0.895684

9.23547144    55.83058954   0.895346

9.17959722    55.83068378   0.904789 …
```

This file location is defined on the instruction file: global_cru.ins.

Changes in the code

Here the changes in the code for the introduction of the topographic index variable. All the changes are highlighted. The filename on which the changed was done appears at the beginning of the code section under "Filename". Following two parts are described: 1) How to introduce the variable into the program (Data input) and 2) The introduction of the weight into the hydrological model (operations)

+++ **Data input** ++++++++++

```
Filename: guess.h
```

```
/// The Gridcell class corresponds to a modelled locality or grid cell.
/** Member variables include an object of type Climate (holding climate,
insolation and
 * CO2 data), a object of type Soiltype (holding soil static parameters) and a
list
```

```
 *   array of Stand objects. Soil objects (holding soil state variables) are
associated
 *  with patches, not gridcells. A separate Gridcell object must be declared for
each modelled
 *  locality or grid cell.
 */
class  Gridcell  :  public  ListArray_idin2<Stand,Gridcell,landcovertype>,  public
Serializable {

public:
 .


.


.

double lon;
double lat;
double topo; // define the variable (aleja)
int soilcode;
```

___

Filename: InData.h

___

```
struct Coord
{
	// Type for storing grid cell longitude, latitude and description text
	int id;
	double lon;
	double lat;
	double topo;/// define the structure of Coord
};
```

___

Filename: cruinput.h

___

```
private:

	struct Coord {

		//  Type  for  storing  grid  cell  longitude,  latitude  and  description
text

		int id;
```

```
            double lon;
            double lat;
            double topo; /// define the structure of Coord        xtring
descrip;
        };
```

___

Filename: cruinput.cpp

___

```
 // USER-SPECIFIC SECTION (Modify as necessary or supply own code)
        //
        // Reads list of grid cells and (optional) description text from grid list
file
        // This file should consist of any number of one-line records in the
format:
        //   <longitude> <latitude> [<description>]
.

.

.

double dlon,dlat,dtopo; /// variable definition (aleja)
        bool eof=false;
        xtring descrip;

        // Read list of grid coordinates and store in global Coord object
'gridlist'

        // Retrieve name of grid list file as read from ins file
        xtring file_gridlist=param["file_gridlist"].str;

        FILE* in_grid=fopen(file_gridlist,"r");
        if (!in_grid) fail("initio: could not open %s for
input",(char*)file_gridlist);

        //file_cru=param["file_cru"].str;  // Jing disabled
        //file_cru_misc=param["file_cru_misc"].str; // Jing disabled


        ngridcell=0;
        while (!eof) {

            // Read next record in file
            eof=!readfor(in_grid,"f,f,f,a#",&dlon,&dlat,&dtopo,&descrip);    ///
define the elements and structure of the file_gridlist (aleja)
            if (!eof && !(dlon==0.0 && dlat==0.0)) { // ignore blank lines at
end (if any)
                Coord& c=gridlist.createobj(); // add new coordinate to grid
list

                c.lon=dlon;
```

```
                    c.lat=dlat;
                    c.topo = dtopo; // create object topo (aleja
                    c.descrip=descrip;
                    ngridcell++;
             }
      }
```

.

.

.

```
// Called by the framework at the start of the simulation for a particular grid cell
bool CRUInput::getgridcell(Gridcell& gridcell) {
```

.

.

.

```
      if (gridfound) {
             gridcell.lon=gridlist.getobj().lon;
                gridcell.lat=gridlist.getobj().lat;
                gridcell.topo = gridlist.getobj().topo; // Add topo to the gridcell class (aleja)
          }
```

+++++ **Operations** ++++++++++++

The variable rainmelt (rainfall after interception and snowmelt today (mm)) and irrigation will be multiplied by the topography based weight.

Soilwater.cpp

```
void hydrology_lpjf(Patch& patch, Climate& climate, double rain_melt, double perc_base,
             double perc_exp, double awc[NSOILLAYER], double fevap, double snowpack,
             bool percolate, double max_rain_melt, double awcont[NSOILLAYER],
             double wcont[NSOILLAYER], double& wcont_evap, double& runoff, double& dperc) {
```

```
.

.

.

	Gridcell& gridcell = patch.stand.gridcell; /// For the inclusion of the topo 			variable (aleja)

	patch.irrigation_d *= gridcell.topo; //// multiply irrigation by the topography  based weight (aleja).


	// Add irrigation water
	rain_melt += patch.irrigation_d;
	max_rain_melt += patch.irrigation_d;

.

.

.

}



void initial_infiltration(Patch& patch, Climate& climate) {
///void initial_infiltration(Patch& patch, Climate& climate, def_topo) { //aleja maybe change
	Soil& soil = patch.soil;
	snow(climate.prec - patch.intercep, climate.temp, soil.snowpack, soil.rain_melt);
	snow_ninput(climate.prec - patch.intercep, soil.snowpack, soil.rain_melt, climate.dndep, climate.dnfert, soil.snowpack_nmass, soil.ninput);
	soil.percolate = soil.rain_melt >= 0.1;

	Gridcell& gridcell = patch.stand.gridcell;/// For the inclusion of the topo 			variable (aleja)
	soil.rain_melt *= gridcell.topo; // multiply raimelt by the topography based weight (aleja).

	soil.max_rain_melt = soil.rain_melt;

	if (soil.percolate) {
		soil.wcont[0] += soil.rain_melt / soil.soiltype.awc[0];

		if (soil.wcont[0] > 1) {
			soil.rain_melt = (soil.wcont[0] - 1) * soil.soiltype.awc[0];
			soil.wcont[0] = 1;
		} else {
			soil.rain_melt = 0;
		}

		soil.wcont_evap = soil.wcont[0];
	}
```

```
}
```

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