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Modelling module for biological diversity and functions in land surface water balance

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Overview

The WP2 "Soil Functioning and Ecosystem Services" has produced a modelling module linking soil biodiversity and its functioning to hydrological properties of agricultural soil. The scope is of a proof-of-concept, including only earthworm burrows as a proxy for cropping systems. The biodiversity focus is on anecic earthworm burrows, which traverse vertically into the deep soil. At the LTO Lusignan this group of earthworms dominates the cropping systems of permanent grass (T5) and of three years of grass in a sequence with three years of annual crops (T2). In contrast, a cropping system without grass and with frequent tillage (T1) is dominated by the soil dwelling endogeic earthworms. The hydrological modelling starting point was the Joint UK Land Environment Simulator (JULES), but the soil hydrology module in JULES only considers water-flow through the soil matrix. Hence, we incorporated a representation of the water flow through macropores made by earthworms by adopting representation of macropore soil water flow in the open source soil-plant-atmosphere model, DAISY. The macropore parameters used for this module are: density, diameter, depth, conductivity of the macropore wall and soil water pressure. The approach has enabled the assessment of events of waterlogging and water deficiency in agricultural soils in real case scenarios, identifying the periods of risk in relation to earthworm burrowing. Two metrics were calculated from the simulated soil water contents: trafficability and vegetation soil water stress, corresponding to detrimental effects of water logging and insufficient plant accessible water.

The presence of burrows could somewhat mitigate the risks for soil water logging and hence increase trafficability of the land. However, a trade-off was observed in a corresponding increase of the risk for water deficiency, although this may be a model artefact as water uptake related to crop type was not included in the model. A sensitive aspect in our data is the number of hydrologically active earthworm burrows which vary by season. The results of this study should not be extrapolated to other soil types or land uses and management. For extrapolation purposes, further research would be required.

The output of the modelling is input to an economic assessment, e.g. by quantitatively assessing the occurrences of soil water deficiency and water logging as risk to farmers' income stability as a result of reduced yields or loss of entire crops.

1. Introduction

The WP2 “Soil Functioning and Ecosystem Services” has aimed to produce a modelling module for biological diversity and functioning for land surface water balance, with focus on earthworm burrowing activity. The present delivery report describes this newly developed modelling module, which is a numerical addition to the existing JULES model for modelling land surface water balance.

Soil biodiversity of relevance to hydrological modelling has been narrowed down to the large anecic worms and their burrowing function, although ecological complexity would predict a broader range of organisms involved in this process. Hence, this was concluded in WP2 Deliverable 2.2. «Identification of key biota in soil functioning and ecosystem services« and in reasoning based on ecohydrological studies (Bastardie *et al.*, 2002; van Schaik *et al.*, 2013).

The present deliverable report presents a “proof of concept” where we demonstrate the approach of combining information on functional soil biodiversity with hydrological modelling in a scenario study with data from the Lusignan LTO. We come up with a prediction of consequences of water-logging for trafficability of the land (accessibility for agricultural machinery) and soil water drought stress inhibiting crop growth. Agronomic consequences of water-logging and ponding are a well-covered subject with established practices for mitigation in terms of drainage measures, conservation tillage, and periodical cropping with deep rooting trees and legumes. Farmers need to avoid excess soil water conditions in the plant root zone, as these reduce crop productivity and have additional agronomic benefits as listed in Table 1. Such losses can be substantial if timing concurs with sensitive growth stages (San Celedonio *et al.*, 2014). As exemplified here, field conditions in spring and fall unfavourable for the use of farming equipment must be avoided to ensure a sufficiently long cropping season.

By identifying the occurrence of adverse periods during the year, the modelling has provided output for economic assessments performed within EcoFINDERS WP5, where the number of days of critical soil water logging and drought can be used to assess the economic risk to the farmer’s income stability.

Table 1. List of benefits of efficient drainage for farming (Madramootoo, 1997; Aalborg Nielsen, 2014).

- Promotion of beneficial soil bacterial activity and improved soil tilth.
- Less surface runoff and soil erosion
- Improved field machine trafficability reduces soil structural damage. Soil compaction is reduced and less energy is required for field machine operations. Drainage also allows for more timely field operations. Consequently, the growing season can be lengthened and crops can achieve full maturity.
- Crop yields are increased because of improved water management and uptake of plant nutrients.
- Higher value crops can be planted, and there is flexibility to introduce new and improved cropping systems.
- Land value and productivity are increased.
- Farm income is increased and income variability reduced.
- Drainage maintains favourable salt and air environments in the crop root zone.
- Earlier sowing – at higher temperature
- Fewer outbreaks of crop diseases
- Less amount of weeds
- Improved fertilizer use
- Ensuring good harvest conditions

2. Biological diversity relevant for hydrological modelling

2.1. Cropping sequences at LTO Lusignan

The farming systems hosting our investigation of earthworms and macropores are part of the long-term observatory “Observatoire de Recherche en Environnement – Agro-écosystèmes, Cycles Biogéochimiques et Biodiversité” (ORE-ACBB). The LTO was established in 2003 after a history of ley cropping systems since more than half a century. The mean annual temperature is 10.5 °C and precipitation is around 600 mm. The study location at 46°25’12.91", 0°7’29.35" is a completely flat grassland. The soil type at the site is a Cambisol with a loamy texture.

Comparison of three treatments at the ACBB Lusignan experiment were initiated during the field campaign in October 10-12, 2011. A conventional crop rotation of annuals in T1 and a rotation system with grass of T2 both with maize were just harvested, so only remains of maize and maize roots were left (Table 2).

Table 2. Overview of crops during the experiment.

Year	T1 Conventional rotation system	T2 Rotation system with grass	T5 Permanent grass
2005	Maize	Maize	Grass
2005	Wheat	Wheat	Grass
2007	Barley	Barley	Grass
2008	Maize	Grass	Grass
2009	Wheat	Grass	Grass
2010	Barley	Grass	Grass
2011	Maize	Maize	Grass

2.2. Earthworm ecological groups at Lusignan

At a March 2011 sampling occasion the following earthworm species were recorded in the experimental plots at LTO Lusignan:

Lumbricus castaneus (Savigny 1826)	Epigeic
Nicodrilus longus longus (Ude, 1886)	Endo-anecic
Nicodrilus caliginosus meridionialis (Bouché, 1972)	Anecic
Nicodrilus giardi (Savigny, 1926)	Anecic
Lumbricus centralis (Bouché, 1972)	Anecic
Lumbricus friendi (Cognetti, 1904)	Anecic
Lumbricus terrestris (Linné, 1758)	Anecic
Nicodrilus caliginosus caliginosus typicus (Savigny, 1826)	Endogeic
Allolobophora chlorotica chlorotica typica (Savigny, 1826)	Endogeic
Allolobophora rosea rosea (Savigny, 1826)	Endogeic
Octolasium cyaneum (Savigny, 1826)	Endogeic
Ethnodrilus zajonci (Bouché, 1972)	Endogeic

These 12 species represent two ecological groups, viz. the endogeics and the anecics. The group of epigeics was almost absent, also during later sampling occasions. The biomass of anecics was about 70% for the T2 rotation with grass and T5 permanent grassland, while for T1 arable land it was 20%, as normally observed for annual cropping systems being unfavourable for anecic worms (Fig. 1).

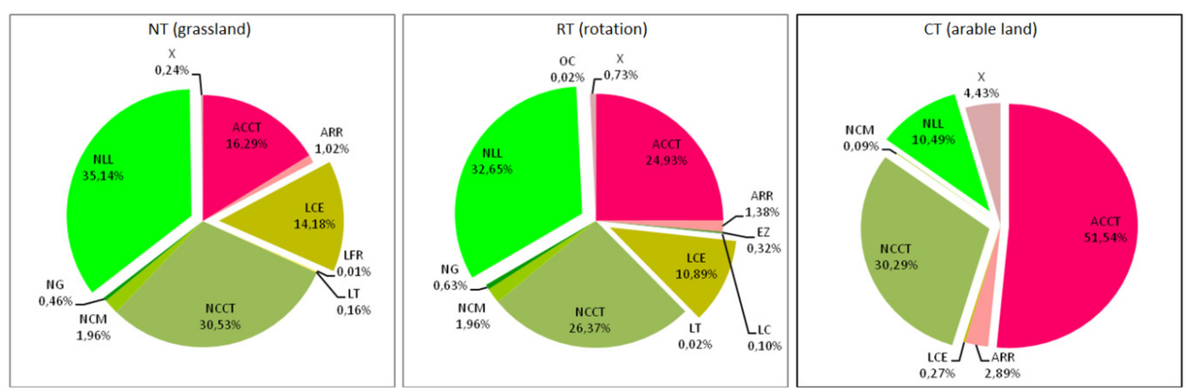

Figure 1. Community composition of earthworms by species biomass at the LTO Lusignan experiment, expressed for permanent grassland (T5), rotation with grass (T2), and for arable land (T1).

Anecics are considered very relevant for water infiltration, as these species construct vertical burrows that can form preferential flow paths for excessive rainfall, which penetrate any plough pan into great depths. Water discharges via this route can be significant (Bouché & Al-Addan 1997, Pitkänen & Nuutinen 1998), depending on tillage practices (Capowiez et al 2009). However, within this functional group, burrow morphology may vary between species with respect to the degree of burrow branching; thus drainage efficiency may still vary with species (Jégou *et al.*, 1999). In addition, this group will introduce plant litter into deeper soil layers, as a result of which soil organic matter can increase, which is beneficial for soil hydrology in terms of water retention capacity.

Epigeics can be relevant as well, as they construct superficial burrows and mitigate soil crusting. They also introduce plant litter into the soil, but only in surface soil layers, thus reducing hydrophobicity during drought and improving water retention capacity (Addison, 2009; Sánchez-de León *et al.*, 2014).

The group of endogeics is considered relatively less important for soil hydrology, as these species dwell the soil below the top soil without constructing permanent burrows or introducing organic matter into the soil.

Given the composition of the earthworm community in terms of species and their biomasses, for the parametrisation of functional biodiversity for the hydrological modelling module we have focussed on soil macropores constructed by anecic earthworms. Thus we made observations on burrow identification and quantification in the field at various depths along the soil profile, in order to acquire quantitative data for modelling parameters.

3. Earthworm burrows spatial structure at Lusignan

3.1. Recording of earthworm burrows

We employed a technique as previously reported (Poier and Richter, 1992; Lamandé *et al.*, 2011) for burrow identification and quantification, which shall be briefly summarized here. Successive horizontal planes at depths 10, 20, 30, 50 and 100 cm were exposed with an excavator shovel in order to prepare for macropore identification. After removal of the soil layer, the macropores were cleared with a vacuum cleaner, as they would otherwise be hidden by loose soil. Transparent plastic sheets, 50 by 100 cm, were placed on the cleared soil horizon. Then the perimeters of visible macropores were manually outlined and filled with a permanent marker on the transparent plastic sheets. Thus, very fine macropores, 0.075-1 mm, were not quantified, as they could not be reliably identified, while fine, 1-2 mm, medium, 2-5 mm, and coarse, >5 mm, were recorded. The plastic sheets were transported to the lab and digitally photographed using a Canon EOS 600D and the digitized images of the macropore dot drawings were automatically identified by thresholding using ImageJ image analysis software v 146b (Ferreira and Rasband, 2010). After inspecting the pictures for correspondence between the digitized dots and the dots on the original pictures, objects below 0.2 mm^2 were omitted from further analysis of macropore distribution and frequencies. Macropores were grouped into 5 diameter, ∅, size classes of 0.5-3, 3-5, 5-7, 7-9, 9-11 mm and their frequencies m^{-2} are shown in **Error! Reference source not found.**.

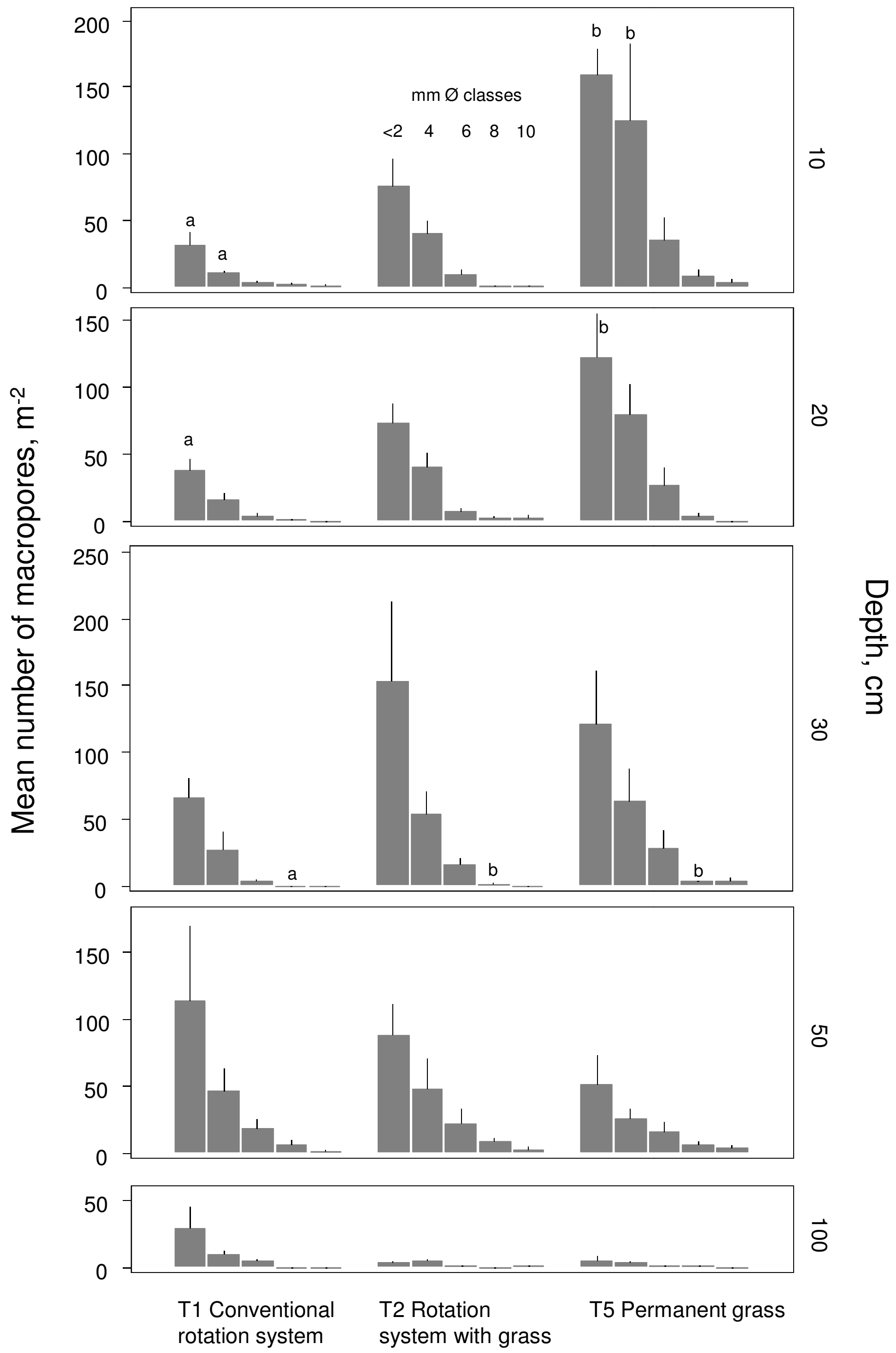

Fig. 2. Mean number of macropores for each depth and cropping system. Macropores are classified by their diameter, Ø: 0.5-3, 3-5, 5-7, 7-9, >9 mm. Vertical bars are standard errors of the mean, n=4. Significant differences between frequencies within size-classes across the three cropping systems are indicated by small letters (Tukey's test, transformed by log n+1).

3.2. Mean frequency, depth and hydrology of earthworm burrows

The following key figures requested for the hydrological modelling were derived from burrow data as presented in Annex 1.

	T1 Conventional rotation	T2 Rotation with grass	T5 Permanent grass
Freq. of burrows m^{-2}, at depth 10 cm, Ø>2 mm	16	50	170
Mean depth[1)], cm, 0-1 m	12	36	26
Burrows Ø>2 mm hydrologically active at 1 m depth[2)]	6	3	2

[1)] Calculated only for the large macropores with Ø>6 mm, assuming that they are continuous and runs vertically downwards.

[2)] Assumption: 50% of the burrows recorded at 1 m depth are active (van Schaik *et al.*, 2013).

4. Hydrological modelling

4.1. Objectives and approach

The objective was to incorporate a representation of the hydrological effect of earthworm burrows into the Joint UK Land Environment Simulator (JULES) model is a standalone version of the representation of the land surface, including water regulation, in the UK Met Office's Unified Model and thus is used in the Hadley Centre's Global Climate Model (GCM). It is capable of being run in a spatially distributed mode at scales that range from 1 km^2 to 10000 km^2, typically with a time step of one hour. As such it uses a relatively simple representation of the environmental processes. A full description of JULES can be found in Best *et al.* (2011) and Clark *et al.* (2011). The formulae used for the earthworm burrow hydrology are identical to those presented in these JULES papers and in DAISY papers (Mollerup, 2010; Abrahamsen, 2011; Hansen *et al.*, 2012).

4.2. Water flow domain covered

The soil hydrology module in JULES only considers the domain of the water in the matrix of a soil. It is based on a finite difference approximation to the Richards' equation (Richards, 1931) for unsaturated flow through porous media. The soil is divided into four vertical layers with thicknesses of 0.1, 0.25, 0.65 and 2 m in the operational implementation of the model. The van Genuchten *et al.* (1980) model, of the hydraulic conductivity and the soil water suction as a function of the soil water content, is used. The parameters required for the module are: the volumetric soil water contents at saturation and wilting point, the residual volumetric soil water content, the saturated hydraulic conductivity and the Van Genuchten parameters α and n. The distribution of roots, required for distributing the soil water loss to evaporation, is based on an exponential decrease with depth down to a defined maximum rooting depth.

4.3. Selection and adaption of model tools

In order to incorporate a representation of the effect of earthworm burrows on soil hydrology, a review was made of existing models, focussing on macropores, i.e. preferential flow along connected cavities greater than 75 μm in diameter. As a result the macropore module of the DAISY model (Mollerup, 2010) was selected on the basis of its being parsimonious in its computational demands and the number of parameters required. The representation is based on that used for groundwater wells in unconfined aquifers. Thus, the conceptual model is that the effect of earthworm burrows can be represented by an equivalent vertical cylindrical void. Consequently, the hydraulic properties of the earthworm burrows, which are measured in the field, cannot be used to specify the relevant model parameters. The flow of water between the macropores and the soil matrix is dominantly a function of the head of water in the macropores in relation to the soil water pressure in the soil matrix. The parameters used for this module are: the average density of macropores, the average diameter of the macropores, the average depth at which the macropores start and the average depth at which they terminate, the conductivity of the macropore wall relative to the surrounding matrix, the soil water pressure at which flow into macropores starts and the soil water pressure at which flow into macropores stops.

JULES is written in the FORTRAN 95 programming language, whilst DAISY is written in C++. Consequently, it was necessary to add computer code in FORTRAN 95, into the JULES soil hydrology module, based on the published equations for the DAISY macropore module. To simplify this task, the JULES soil hydrology module was extracted and set up as a stand-alone program with the input of the driving variables, precipitation and evaporation, read in from a file. In order to simplify the code, the starting and termination depths for the earthworm burrows were constrained to coincide with the interfaces between the soil model layers.

4.4. Model parameterization

In order to demonstrate the potential use of incorporating the hydrological effects of earthworm burrows into a large scale land surface model, it was decided to do a "proof of concept" exercise using data from the Lusignan LTO.

Model parameters for soil matrix hydrological characteristics were derived from the soil physical values, contained in the Harmonised World Soil Database (HWSD), using the HYPRES pedotransfer function (Wösten, 2000). The soil definition selected was that of the dominant soil from 1 km^2 which covers the location of the Lusignan site. For the macropore module, the first four parameters (the average density of macropores, the average diameter of the macropores, the average depth at which the macropores start and the average depth at which they terminate) were available from measurements described above. Values given in reports about the use DAISY were used for the remaining parameters. For the driving data, the rainfall values used were the hourly Lusignan data for 2005-2012; the evaporation values were the Penman-Monteith potential evaporation (PE) calculated using the Lusignan hourly meteorological data. PE can be considered as the evaporation from a permanent crop of short grass. It should be noted that no attempt was made to simulate the evaporation losses from different vegetation types. The model was initialised by running it for 10000 time steps without any driving variables input so that the soil water content stabilised at a value at which drainage had ceased. It was then run using the first year's driving variables so that the soil water contents would be reasonable of winter conditions at the start of the simulation

4.5. Description of scenarios

The model was run for three different scenarios: baseline (no earthworm burrows, i.e. only water flow through the matrix), low density of earthworm burrows (T1 conventional rotation) and a high density of earthworm burrows (T5 permanent grass). The results showed that there were only small differences in the simulated soil water contents between the first two scenarios, so no further analysis of the low density of earthworm burrows was carried out. The simulated volumetric soil water contents, as the daily average values, for the baseline and a high density of burrows scenarios are shown in Figure 3. There are very clear differences between the two scenarios. During the winter, when evaporation losses are small, the day to day fluctuations are dominated by rainfall. The presence of the earthworm burrows tends to reduce these fluctuations in the first two layers, compared to the baseline scenario, as the excess water is transferred rapidly to depth. However, during the summer this process allows excess water at the surface, and in the topmost layers, to be transferred to depth rapidly with the result that losses from evaporation are not replenished.

4.6. Links to agro-economy

A possible use of the model simulations of the soil water content could be to estimate the economic cost/benefit to a region. To illustrate this possibility, two metrics were calculated from the simulated soil water contents: trafficability and vegetation soil water stress.

4.6.1. Trafficability

The trafficability metric is based on the hypothesis that the soil loses cohesion at high levels of soil saturation, with the result that wheeled vehicles can no longer move over the surface without unacceptable detrimental consequences for soil structure. The metric was calculated for a soil depth of 0.35 m (corresponding to the two topmost model soil layers), using the daily average soil fraction of saturation. According to Müller and Schindler (1998) trafficability is possible at soil water contents below 30%, which is within the range of the field capacity of loamy soils. As a loamy soil has water content at water saturated conditions of fifty percent, i.e. water logging, we selected a fraction of 0.75 as the threshold above which traffic was excluded - this value corresponds approximately to the field capacity. Hence, this threshold of 0.75 was used and, if exceeded, would mean that farm vehicles would have considerable difficulty in maintaining traction. Given the local loamy soil type, this value is a realistic value for a tipping point in soil structure resilience, beyond which soil pores get water logged and the soil structure is more easily lost through compaction. The resulting metric has a value of 1 if trafficability is affected, and 0 if not. The results, depicted in Figure 4 show that the presence of earthworm burrows result in a reduced risk of trafficability affected vehicle operations. This is because the burrows serve to reduce the period of soil water logging by providing a more raid route for water to be transferred from the surface to depth. Obviously a more detailed analysis, involving the timing of specific crop management activities, is required in order to assess the probability of a realistic impact. The winter of 2012/13 was a good example where heavy rainfall affected crop management, in SE England, – harvests delayed by up to a month; ploughing and drilling impossible in the autumn and throughout the winter, which ended up with spring crops being planted late.

4.6.2. Soil water stress

The vegetation soil water stress metric uses an output from the model which is set to 1 when the soil water content is not constraining the transpiration and photosynthesis, via the stomata closing, and goes to 0 when these are effectively stopped. So this indicates periods when growth will be limited and hence, if these occur during the main growing period of the vegetation, yield will be reduced. The value of 0.5 was selected for the daily average vegetation soil water stress factor which is likely to have a measurable effect on the yield. The resulting metric has a value of 1 if vegetation growth is affected, and 0 if not. The results are shown in Figure 5 and suggest that the presence of earthworm burrows under these local conditions serves to increase the risk of vegetation stress arising from a lack of available soil water. This is because a portion of the precipitation from heavy rainfall events during the summer is transferred to depth more rapidly, bypassing the zone where the majority of roots are present. In practise, the phenomenon would only have an effect if the vegetation stress occurred during the main growth period of the crop.

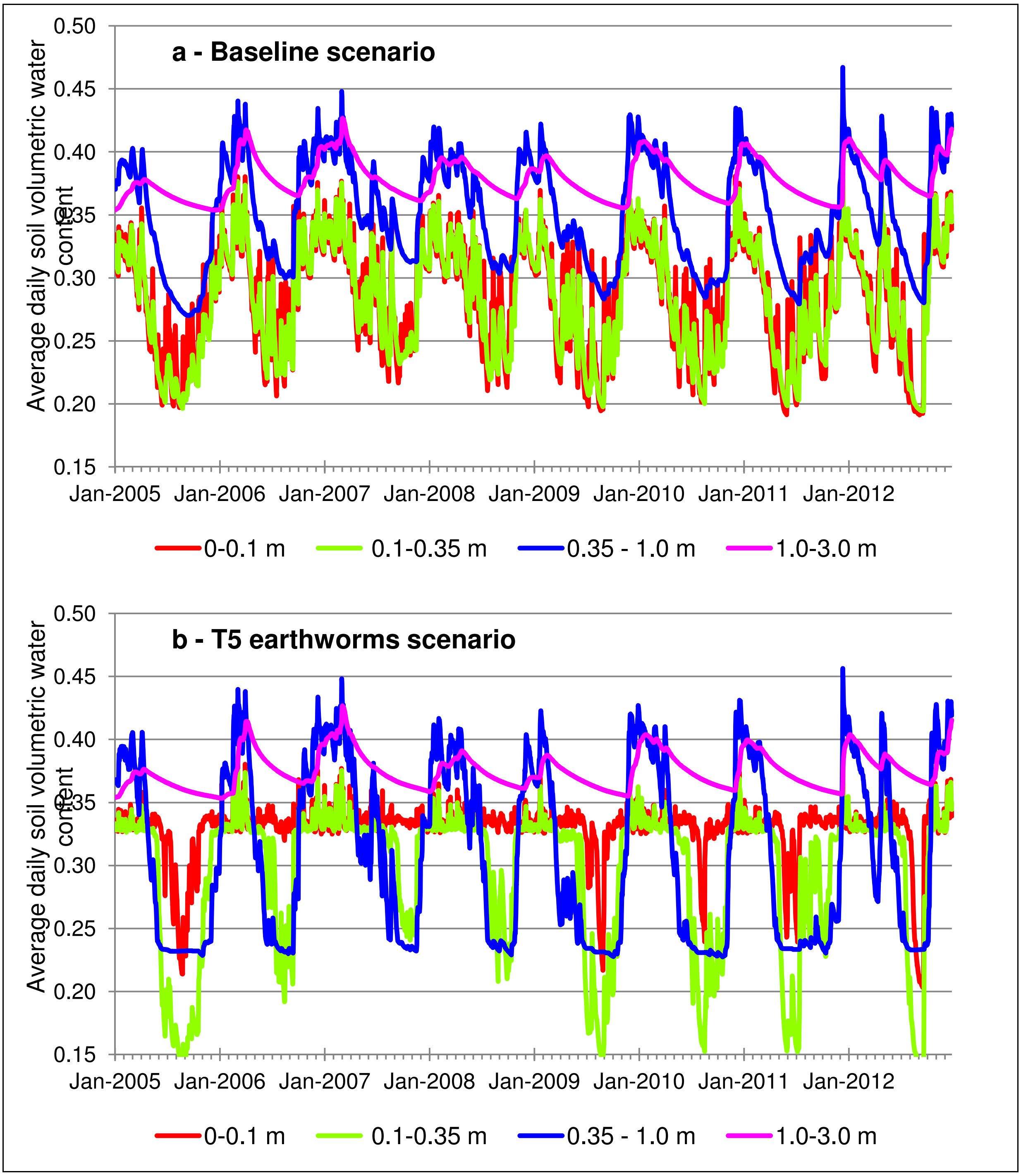

Fig. 3. Simulated volumetric soil water contents of the four model layers for the a - the baseline scenario (no earthworm burrows) and b – the permanent grassland earthworm burrows

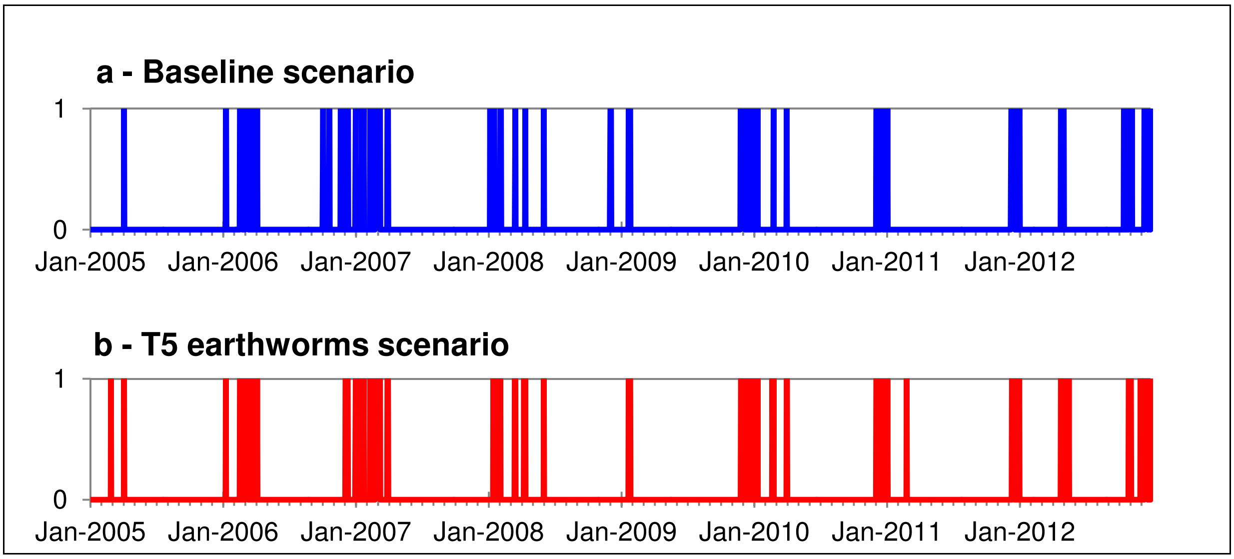

Fig. 4. Trafficability metric a - for the baseline scenario (no earthworm burrows) and b – for the permanent grassland earthworm burrows (1 = risk of damage, 0 = no risk of damage)

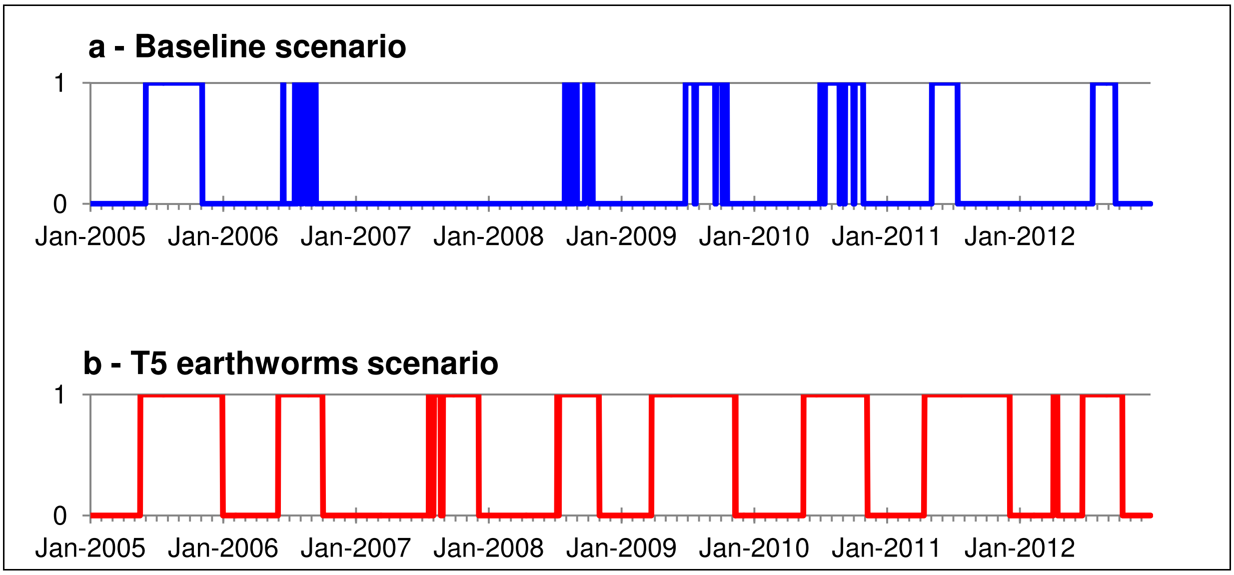

Fig. 5. Vegetation soil water stress metric a - for the baseline scenario (no earthworm burrows) and b – for the permanent grassland earthworm burrows (1 = risk of loss of yield, 0 = no risk of loss of yield)

5. Conclusion

A modelling module has been added to the existing JULES framework, using model subsets from the existing DAISY model. The approach has enabled the assessment of events of waterlogging and water deficiency in agricultural soils in real case scenarios, identifying the periods of risk in relation to earthworm burrowing.

Whilst the presence of burrows in relative high densities was shown to mitigate to some extent the risks for soil water logging and hence increase trafficability of the land, a trade-off was observed in a corresponding increase of the risk for water deficiency. This latter observation may be an artefact result, as water uptake by plant roots as related to crop type was not included in the model. Also, the impact of anecic earthworm burrows upon soil drainage capacity seems less dramatic than could be expected from some literature (Bouché and Al-Addan, 1997). No doubt, these results are associated to the local soil type and earthworm burrow architecture, being affected by the cropping and tillage system. Another sensitive aspect in our data may that the number of earthworm burrows that actually is conducive may vary with season. Burrows have to be open to the surface to effectively drain excess water, and therefore during cold or dry periods of earthworm inactivity maintenance may be insufficient and regulation of water movement is less effective (Eggleton *et al.*, 2009; Nuutinen and Butt, 2009).

The results of this study should not be extrapolated to other soil types or land uses and management. For extrapolation purposes further research would be required. The scope of this present study was only to develop the modelling framework as a proof of concept.

The output of the modelling can be used for economic assessment, e.g. by quantitatively assessing the occurrences of soil water deficiency and water logging as risk to farmers' income stability as a result of reduced yields or loss of entire crops. To this extend, follow-up studies will be undertaken in WP5. This activity too, however, will be undertaken on the preliminary basis of "proof of concept".

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ANNEX I

Selected burrow data collected at the Lusignan field campaign, October 10-12, 2011.

		Burrow diameter			
		>6 mm		>2 mm	
	Depth	Freq. m^{-2}	95% C.L.	Freq. m^{-2}	95% C.L.
T1 Conventional rotation	10	3	[-2.5–8.5]	16.5	[6.0–27.0]
	20	0.5	[-1.1–2.1]	18.5	[-3.9–40.9]
	30	0	.	30	[-19.3–79.3]
	50	6.5	[-8.5–21.5]	70	[-12.0–152.0]
	100	0	[.–.]	13	[1.2–24.8]
T2 Rotation with grass	10	1	[-2.2–4.2]	50	[7.4–92.6]
	20	4.5	[-5.7–14.7]	50.5	[4.6–96.4]
	30	1.5	[-0.1–3.1]	71	[6.8–135.2]
	50	10	[-4.0–24.0]	79	[-41.5–199.5]
	100	0.5	[-1.1–2.1]	6	[3.4–8.6]
T5 Permanent grass	10	11.5	[-9.7–32.7]	172	[-80.9–424.9]
	20	3.5	[-4.0–11.0]	110	[-1.2–221.2]
	30	6	[-2.6–14.6]	97	[-24.5–218.5]
	50	9.5	[-3.1–22.1]	49.5	[-10.5–109.5]
	100	0.5	[-1.1–2.1]	4	[-2.9–10.9]