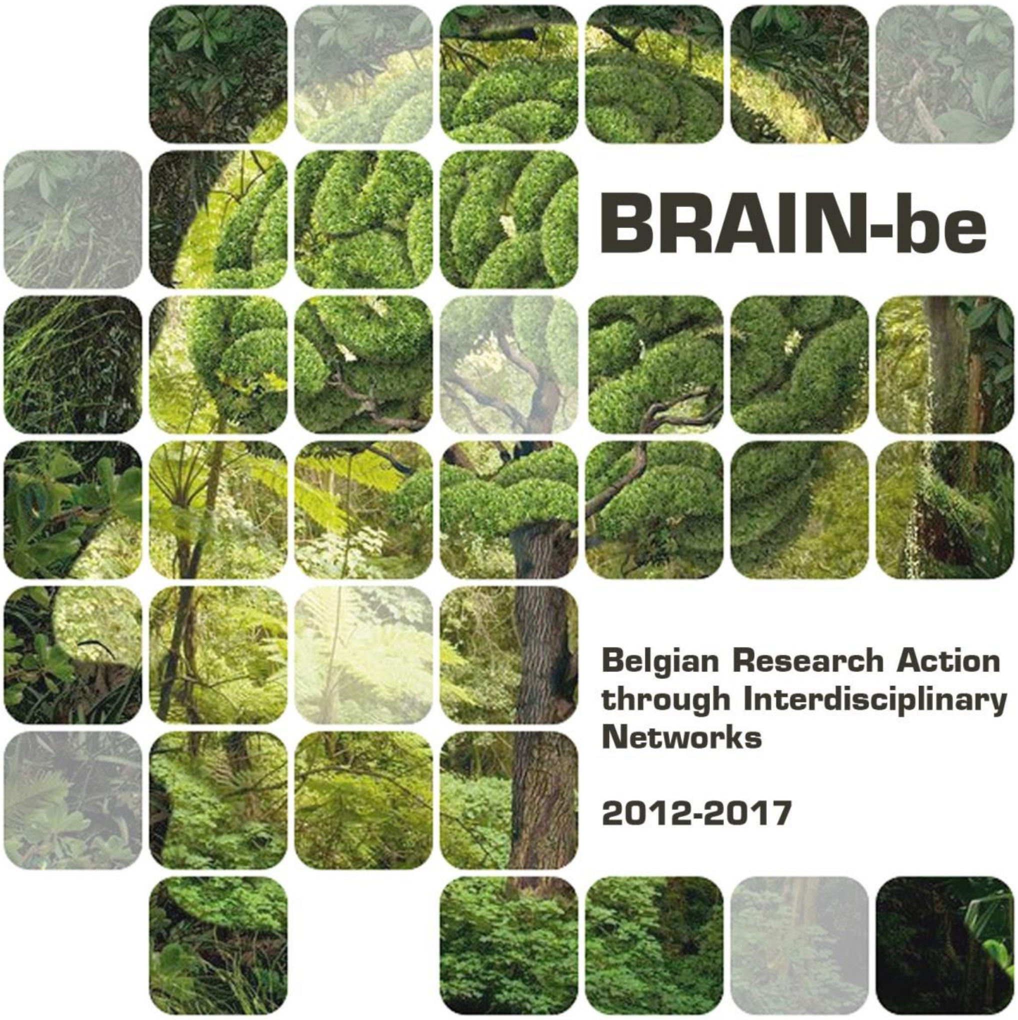

ForestFlow

Opgeloste koolstoffluxen in bosbodems onder toekomstige regenregimes

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NETWORK PROJECT

ForestFlow
Opgeloste koolstoffluxen in bosbodems onder toekomstige regenregimes

Contract - BR/175/A1/ForestFlow

FINAL REPORT

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ABSTRACT

Context

The relative importance of dissolved and gaseous export of carbon from forests under different precipitation regimes remains largely unexplored, partly because of technical constraints to accurately measuring dissolved export fluxes, and partly due to a strong focus on greenhouse gas balances in current research infrastructures.

Objectives

Forestflow aimed to:

-Quantify dissolved organic carbon export from deciduous and coniferous forest, and hereby close ecosystem carbon balances in two Belgian ICOS-sites

-Quantify the seasonality in dissolved vs. gaseous carbon export from forests: tree phenology and rain regime are hypothesized to be the main control factors

-Investigate whether shifts in gaseous vs. dissolved carbon export occur during rain events and persistent drought

-Model future alterations in the forest carbon balance, by implementing the results in coupled climate, hydrological and forest ecosystem biogeochemical models.

Conclusions

ForestFlow was not able to overcome the complete challenges as set above. The IFlux sampler proved not to be capable as of yet to perform as expected under non-saturated soil conditions. Sufficient time to redevelop the sampler was not available, so the decision was taken to develop new 3D printed lysimeters. The methodological advances here allowed to assess DOC fluxes during extreme rainfall for the first time. The advances also proved to be valuable for other researchers, and a methodological paper was published. It is clear from the results that current DOC export estimates from forest soils, based on conditions during 'normal' weather, cannot stand under future climate regimes. During only on extreme rain event only, more DOC is exported on a daily basis, than current estimates for monthly DOC export subsoil based on earlier studies. Despite the major challenges we were confronted with (extreme droughts, COVID-19 and an unexpected need to develop a new sample), ForestFlow results clearly indicate that shifting DOC fluxes could be crucial for the forest carbon balance, potentially shifting soil storage from a net sink to a net carbon source.

Keywords

Forests; carbon; dissolved carbon export; future climate; extreme rain events; soil lysimeter

1. INTRODUCTION

Future climate conditions involve increased temporal variability, with both increases in precipitation intensity and changes in the number of rain storms (more rainfall events in the wet winter periods and less rain in the dry summer periods). These changes lead to an intensification of the hydrological cycle, with higher runoff flows in the wet periods and stronger dry-out of the soils during the longer drought periods. Such alterations in precipitation patterns will cause large changes in the forest carbon balance. Hydrological conditions are the main driver of DOC leaching, both on intra-annual and inter-annual timescale. Longer periods of drought, and occasional strong precipitation events, could cause a more event-driven carbon export from soils through dissolved losses.

Still, the relative importance of dissolved and gaseous export under different precipitation regimes remains largely unexplored, partly because of technical constraints to accurately measuring dissolved export fluxes, and partly due to a strong focus on greenhouse gas balances in current research infrastructures. It is the understudied interaction between the biological component (“phenology”), the climate component and the hydrological component, and how it affects DOC export fluxes that is targeted specifically in our project. In this project, we will thus fill a gap in the research at the (Belgian) ICOS stations, namely the export of dissolved carbon from soils.

To reach these challenging goals, we initiated a highly multidisciplinary research study, where state-of-the-art phenological and biogeochemical measurements were performed. These are subsequently linked to the detailed climatic observations at the ICOS stations. We thus achieve an empirical coupling of DOC fluxes to forest phenology and climate. This enabled us to assess whether a shift occurs in gaseous vs. dissolved carbon with changing rain regimes.

In order to allow these site-specific empirical findings to be extrapolated to the larger spatial scales, and to assess future impacts under changing climate conditions, hydrological modelling have been applied. A novel hydrological modelling approach was implemented and applied, to conduct the hydrological impact investigations. Particular focus was given to the spatial resolution of the model. The approach allows a direct coupling to climate change scenario analysis, hydrological and phenological characterization and the biogeochemical assessment of dissolved carbon fluxes. On the one hand, there is a high spatial resolution required for studying the surface hydrological processes of the local study plots around the ICOS sites. On the other hand, to model the role of the groundwater a larger scale model covering the entire watershed is required.

The fine resolution model at the local scale has been nested in the coarse resolution model at the larger scale. This project thus applied an innovative ‘‘method of multiple working hypotheses’’ where the model structure is adjusted or inferred from data and field evidence.

2. STATE OF THE ART AND OBJECTIVES

Forestflow aimed to:
-Quantify dissolved organic carbon export from deciduous and coniferous forest, and hereby close ecosystem carbon balances in two Belgian ICOS-sites
-Quantify the seasonality in dissolved vs. gaseous carbon export from forests: tree phenology and rain regime are hypothesized to be the main control factors
-Investigate whether shifts in gaseous vs. dissolved carbon export occur during rain events and persistent drought
-Model future alterations in the forest carbon balance, by implementing the results in coupled climate, hydrological and forest ecosystem biogeochemical models.

Forest ecosystems play an essential role in the global carbon cycle (e.g. Bonan et al. 2008). Trees take up CO_2 during photosynthesis, and part of this carbon is eventually stored in the soil. The strength of the soil carbon sink is largely dependent on the climate. Climate impacts, among others, forest production, decomposition processes and hydrological balances.
To determine the stability of the carbon sink, the role of future precipitation patterns is therefore crucial. Altered soil water content (drought events, excessive wetness), more extreme meteorological events, and alterations in seasonal water redistribution have strong effects on forest water balances, depending on soil properties, microclimate and plant functional type (e.g. Kucharik et al. 2000). Increasing evidence suggests that variability and extremes in precipitation are more important drivers of ecosystem processes than mean conditions (Knapp et al. 2008).

Future climate conditions involve increased temporal variability, with both increases in precipitation intensity and changes in the number of rain storms (more rainfall events in the wet winter periods and less rain in the dry summer periods). These changes lead to an intensification of the hydrological cycle, with higher runoff flows in the wet periods and stronger dry-out of the soils during the longer drought periods (Knapp et al. 2011).
Such alterations in precipitation patterns will cause large changes in the forest carbon balance. Hydrological conditions are the main driver of DOC leaching, both on intra-annual and inter-annual timescale (e.g. Don and Schulze 2008; Gielen et al., 2011). Longer periods of drought, and occasional strong precipitation events, could cause a more event-driven carbon export from soils through dissolved losses.

Still, the relative importance of dissolved and gaseous export under different precipitation regimes remains largely unexplored, partly because of technical constraints to accurately measuring dissolved export fluxes (e.g. Verreydt 2012), and partly due to a strong focus on greenhouse gas balances in current research infrastructures (Knapp et al. 2008; Gielen et al. 2011). It is the understudied interaction between the biological component ("phenology"), the climate component and the hydrological component, and how it affects DOC export fluxes, that is targeted specifically in our project.

We have quantified hydrologically controlled fluxes of forest dissolved carbon towards rivers and confined aquifers. Anthropogenic and global changes impact on surface soils: it is here that the amount of potential leaching is set. Forest characteristics and phenology put a major control on the water flux that reaches the soil. Our project fits within the specific objective to better confine the pathways of dissolved terrestrial material fluxes under future predicted climate changes. We have specifically applied an entirely novel method to assess dissolved fluxes in detail. We have also targeted to fill a gap in the research at the (Belgian) ICOS stations, namely the export of dissolved carbon from soils.

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3. METHODOLOGY

WP1: Hydrological Site Characterisation

Collection of Historical Data

Historical observations for temporal and spatial data were collected at local scale for Brasschaat and Vielsalm ICOS sites, and at basin scale for Schjin and Upper Amblève, respectively. There were multiple sources and variables of interest as it is shown in Table No. 1. Additionally, for the case study Brasschaat, due to the quality and availability of data, two water level pressure sensors HOBO were installed downstream Brasschaat in March 2019 until February 2021.

Table I: Summary of variables per source per basin and ICOS site

Basin/ICOS site	**Sources**	**Variables**
Schijn, Brasschaat	RMI, WATERINFO, EUROFLUX Pluviometers Antwerpen, INBO	Precipitation: Deurne, FLX, Wilrijk, Herentals, Kapellen, Loenhout, Melsene, Vosselaar, pluviometers Antwerpen P1-P12 Rainfall and Throughfall: INBO data for Brasschaat
	WATERINFO, RMI, KNMI-Nederland	Evapotranspiration: Herentals, Melsene, Liedekerke, Uccle, Westdorpe, Hansweert, Tholen, Woensdrecht, Gilze-Rijen, Eindhoven FLX measurements of latent heat flux: for Brasschaat
	WATERINFO, Provincie Antwerpen, Field Measurements in this study	Discharge: Wijnegem Groot Schijn, Wijnegem Afvoergracht Waterlevel: Ekeren Water Level at Laarse Beek by Antwerpen authority: stations 06 & 09 Water Level & discharge: HOBO SENSOR 20474115 & HOBO SENSOR 20474116
	VMM	Effluents: 26 sites
	WATERINFO, INBO, UAntwerpen-Cristina	Soil moisture (Loenhout) Soil moisture TDRs 1995-2013, variable depth 25 to 175 cm: for Brasschaat
	INBO, DOV	Groundwater level for Brasschaat Groundwater level basin: 169 piezometers (Schijn basin)
	DOV	Groundwater abstractions: 42 sites
	AGIV, Uantwepen, DOV, CORINE, GLOBELAND30	Basin and Brasschaat site delimitation, DEM, land dover, soil texture, hydrological units, geological units
	Waterinfo, Euroflux	Temperature: Herentals, Melsene
	Euroflux	RECO
	Literature, SoilGrids, FAO, DOV	Soil Organic Carbon
	MODIS	Net Primary Productivity, Land Cover

Basin/ICOS site	Sources	Variables
Amblève, Vielsalm	SPW Aqualim	Discharge: L5580, L6070, L6510, L6520, L7160, L7280, L7670
	PAMESEB, RMI, Fluxnet	Evapotranspiration: Ferrières, Bergeval, Elseborn, Emmels, Jevoumont, Spa, MontRigi Fluxnet measurements FLX latent heat flux for Vielsalm
	PIEZEAU	Groundwater: PZ2016, PZ5180, PZ5721, PZ6840, PZ7066, PZ7067, PZ7172
	SPW, PAMESEB, RMI, Fluxnet	Precipitation: 65370015, 68480015, 68580015, 69580015, 9670015, 99220015, Ferrières, Emmerls, Bergeval, Elsenborn, Spa, FLX
	Euroflux	Temperature RECO
	SPW, USGS, GLOBELAND30	Land Use, soil texture, geology, DEM
	Literature, SPW, SoilGrids, FAO	SOC stocks

Processing of data

These data were pre-processed using semi-automatic algorithms built for this purpose. Then, the processed data were used in a second step for a better insight of the hydrological system, for example to determine the quick/slow hydrological flow responses, the influence of the effluents, the water abstractions and others. To evaluate the flow components and their response times separately, a generalization of the numerical Chapman-filter was applied. In addition, events were separated with the identification of peak and low flows using the Peak-Over-Threshold method.

Analysis of data

Seasonality as well as temporal and spatial variability were analyzed for the mentioned historical variables in combination with the spatial physical characteristics. Finally, based on the primary and secondary data collected, the dominant hydrological processes to be accounted for in the modelling were identified.

WP2 and WP3 combined: Biogeochemistry and tree phenology as mediator of soil water fluxes

In order to quantify Dissolved Organic Carbon export from the ICOS station of Brasschaat in Belgium, we had as a first objective the adaptation of the structural design of the iFLUX sampler® to enable it to measure vertical instead of horizontal fluxes in an unsaturated environment. Unfortunately, the adaptation of the iFLUX sampler® was not successful, and for this reason, the methodological objective of this study was revised from adapting the iFLUX sampler® to the creation and design of a Zero Tension Lysimeter (ZTL). Therefore, we designed a new and 3D-printed ZTL aimed at quantitatively collecting leaching water at several depths. We aimed to develop a novel generation DOC sampler that would simultaneously measure water and DOC fluxes, and second, we wanted to use this new sampler to study the impact of climate extremes on DOC leaching in forests.

The initial experimental set-up was installed in two ICOS sites, Brasschaat and Vielsalm. The follow-up of the measurements and analysis was done at both sites, but as the ZTL and rhizons collected solutions erratically in Vielsalm, in part due to the type of soil (silty clay soil with a significant stony content), it was finally decided to focus the project on the Brasschaat site.

Site description

The experimental site is located in the forest ‘De Inslag’ in Brasschaat near Antwerp, Belgium (51°18'27.1"N 4°31'18.9"E). The experiment is hosted in the vicinity of the ICOS ecosystem monitoring station of Brasschaat (www.icos-ri.be) (Franz et al., 2018; Heiskanen et al., 2021), co-located with an ICP forest intensive monitoring level II plot (Neirynck et al., 2008). The location of this research is mainly covered by an even-aged Scots pine plantation (*Pinus sylvestris* L., planted in 1929), while the larger area can be characterized as a mixed coniferous/deciduous forest. The mean annual temperature at the site is 10.8 °C, with a mean annual precipitation of 1011 mm, with drier periods for the years 2004 (897 mm), 2011 (888 mm), 2013 (867 mm) (Horemans et al., 2020) and 2019 (798 mm). The herb layer of the Scots pine stand is dominated by *Molinia caerulea* (L.) Moench, followed by saplings of *Sorbus aucuparia* L., *Rubus* species and *Dryopteris* ferns (Gielen et al., 2011). The site is characterized by moderately wet sandy soil, rarely saturated, high hydraulic conductivity in the upper layers and distinct humus and/or iron B horizon. The soil is classified as Endogleyic Brunic, Albic Hypoluvic, Arenosol (Dystric) according to IUSS Working Group (IUSS Working Group WRB, 2007) with a C:N ratio of 30 in the organic layer.

Clay lenses of variable thickness locally hamper the infiltration of water at 50–125 cm depth, and pH values of the soil water range from 3.1-3.9 (Janssens et al., 1999; Verstraeten, 2018).

Sampler design and installation

The sampler designed received the name of Zero Tension Lysimeter (ZTL3D) and was created by Selective Laser Sintering (SLS) using Nylon 12. The technic was chosen for extreme accuracy in small details in the design. Printing was done on a Multi Jef Fusion 3D printer HP. The material chosen to SLS print was the high molecular weight Polyamide 12 or Nylon 12, which is characterized by low moisture absorption, exceptional impact and notched impact strength, resistance to extreme temperatures and resistance against greases, oils, and other chemicals.

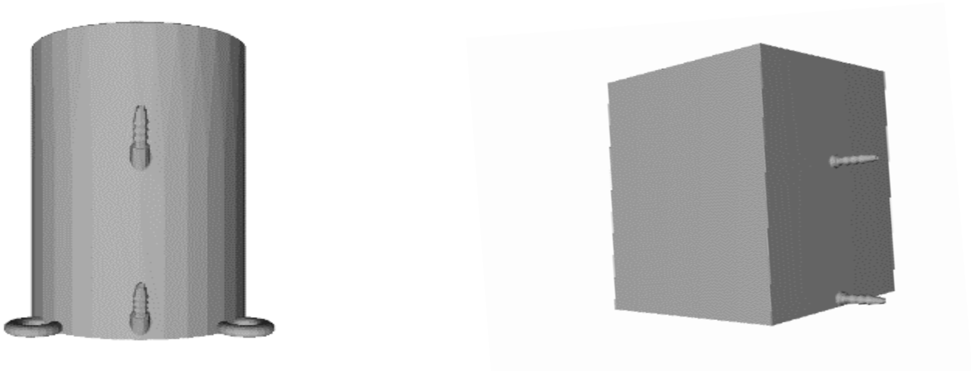

Figure 1: Round and Square samplers for vertical and horizontal installation.

We designed two models of the ZTLs3D. One is formed by one single cylindrical volume of 13 cm height and 8 cm diameter and has a water collection capacity of ~350 ml. The second one is a square prism of 13 cm height and 8.5 cm width, with a capacity of ~450 ml (Fig.1). The cylindrical ZTLs3D fit in a cylindrical hole made by soil coring from the soil's surface, hereafter referred to as vertical installation. The square ZTLs3D are fit for installation in a cubic hole made in a trench wall, hereafter referred to as horizontal installation.

The figure above represents the field set up constructed for the research study. In total, 96 square ZTLs3D were installed in the 16 monoliths at 2, 30 and 75 cm depth (Fig.2). After this type of installation, monoliths were individually isolated (Fig.3), wrapped (except the surface) with two foils, the first one a strong plastic foil that acts as a barrier to prevent the water from leaving or entering, the second foil being a cloth that protects the monoliths from roots growing in.

Once this step was finished, the trenches were refilled and in the same monoliths, 96 round ZTLs3D were installed in the 16 monoliths at the same depths. In summary, 12 ZTLs3D per monolith were installed, each at least 50 cm apart, two replicates per depth and per type of installation (vertical or horizontal), creating a total of 64 samplers per depth. Furthermore, apart from the ZTLs3D, every monolith was equipped with four TDRs, at 16 cm, 30 cm, 50 cm and 75 cm (CS605-L-3-Rod TDR Probe with RG58 Cable, Campbell Scientific, Logan, USA) and five handmade pluviometers were randomly positioned around every group of four monoliths.

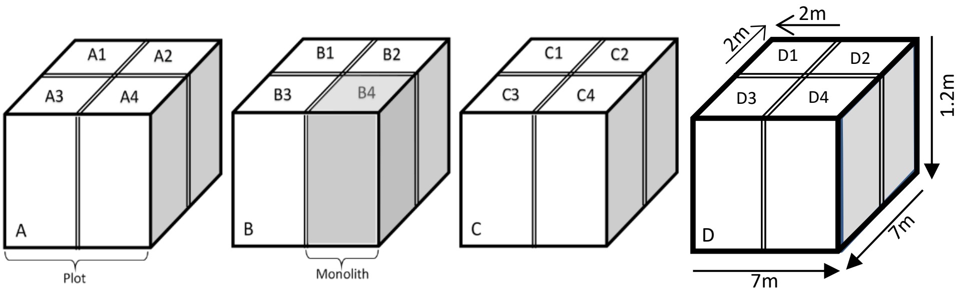

Figure 2: Plot scheme representation of the field experiments set up. Plots are named A-D. Every plot of 14 m^2 contains four isolated monoliths of $4m^2$ each.

Figure 3: Visualization of the plot installation

Figure 4 shows a finalized plot once the vertical and the horizontal installation was finished in the pine forest of Brasschaat.

Figure 5: Visualization of a finalized plot. The little layer within the monoliths shows very little destruction while the surrounding of the monoliths suffered a big impact. In the middle of the plot there is the power station for TDRs functioning and data logging.

Irrigation setup

Water collection started in February 2019. Natural rain events were intended to be collected biweekly, but this was not feasible due to the severe drought in spring 2019. Consequently, sampling was done after every 'collectable' rain even. After that, more frequent water collection was made possible by the installation of an irrigation system. It consisted of 100 irrigation lines per monolith of 4 m^2, positioned every 20 cm for homogenous soil irrigation. Lines were directly installed on the surface of the soil. Water input was regulated by the irrigation system's valves with a velocity of 10 L min^{-1}. Sixteen flowmeters traced the amount of water added to every single monolith. From July 2019 onwards, this irrigation system was used to simulate rain events of different intensities. These rainfall simulation experiments were conducted in July, August, September, November 2019 and March 2020. The rain simulations applied had different objectives:

1. To allow a more frequent collection of element leaching by the ZTLs3D,
2. The evaluation of the two types of ZTLs3D soil installations,
3. The study of element leaching under future climate conditions.
4. The trace of element leaching through depth in all climate scenarios. To achieve these goals, we simulated different rain intensities by adding 9-75 mm of irrigation water.

We validated the water collection by the ZTLs3D using a Water Bucket Model (WBM), driven by water inputs via irrigation and precipitation (Pr), and water losses via evapotranspiration (ET) and infiltration rate (IR). The atmospheric data was used from the ICOS tower in Brasschaat.

Rain Simulations specifications

Between July and September 2019, we applied two Rain Simulations (RSs) at the experimental site. The RSs included different irrigation intensities in order to test different research questions; here, we refer to them as Rain Simulation number 1 (RS1) and Rain Simulation number 2 (RS2). A monolith from each plot (Fig. 2) received a different treatment, having a total of four treatments within one plot with four replicates since we had four plots.

RS1, which ran from the end of July to the beginning of August 2019, was sub-divided into three phases; the first two phases had equal amounts of water applied to all treatments, except a drought treatment. Finally, at the end of September 2019, when soil water contents had been similar across the three irrigation treatments for several weeks, RS2 was conducted. RS2 consisted of a single and intense irrigation event that added equal water to all monoliths, including the droughted treatment. Its purpose was to study the legacy effects of the previous third phase of RS1, where three treatments received different amounts of water, and to evaluate the effect of the previous extreme drought event.

From November 2019 until March 2020, we performed two more Rain Simulations (RSs). Their characteristics were the same, with equal total amounts of water added over a variable time period, with the only difference between the two RSs being the season in which we applied them. Leaf litterfall at the site typically peaks in September-October, and we, therefore, conducted the first RS at the beginning of November 2019 when soil drainage had started again and the freshly fallen litter was likely leaching large amounts of DOC.

The second RS was conducted in March 2020, when most plants were still dormant. The repetition of the RSs in different seasons allowed us to study the effect of fresh litter inputs on the production and leaching of DOC. We refer to these as Rain Simulation in Autumn (RSA) and Rain Simulation at the end of Winter (RSW). Both RSs applied the same total amount of water, but distributed across different time durations to test whether the intensity of rain affects the leaching of DOC through depth.

We collected soil leachates on average 24 hours after every RS. A pump was manually attached to each ZTL3D to suck up the captured leachates through Teflon tubes into glass vials. Then, we quantified the total amount of water captured by each ZTL3D. Sampling was performed twice after each RS per ZTL3D. Before the samples were brought to the laboratory, we filtered them with a Polyester (PET) filter syringe of 0.45 µm and stored them in glass vials for DOC analysis or plastic vials for nutrient analysis. The nutrients analysed included nitrate (NO3--N/L), ammonium (NH_4^+-N/L) and phosphate (PO_4^{3-}-P/L).

WP4: Hydrological modelling

Modelling tasks include three main steps, where each step is built based on the results obtained in the previous steps.

Lumped modelling for Schijn and Upper Amblève

The VHM model was used in the first step, which is a conceptual model based on the distribution of precipitation to the different flow components (overland flow, interflow, and baseflow), after the representation of some losses by evapotranspiration and infiltration.

The VHM model was calibrated and validated as a preliminary step before applying the flexible hydrological distributed model. The calibration of lumped model was done in a stepwise way, based on multiple objective functions and graphical criteria for model performance evaluation. Initially, the model was calibrated for the Lower Schijn and Salm basin. However, due to data availability and quality, the basin delimitation was extended to larger areas denominated as the Schijn and Upper Amblève basins. As a result, flow records used in the modelling during the first year of the project such as Groot Schijn station (nearby basin) and L6070 have been replace with Wijnegem Afvoergracht (nearby basin) and L7670 for Schjin and Upper Amblève, respectively. Furthermore, a disaggregation of the calibrated lumped conceptual model parameters was performed.

Distributed modelling for Schijn and Upper Amblève

Preliminary calibrated parameters obtained from the lumped conceptual model (VHM) were disaggregated. This disaggregation is based on relationships of parameters with physical attributes of the catchment using PCRASTER-PHYTON environmental software. The resulting maps together with meteorological data collected in WP1 and lookup tables from literature were used as input for the flexible distributed model. This distributed model was calibrated using an automatic algorithm SCEUA for both basins, Schijn and Upper Amblève, where Brasschaat and Vielsalm ICOS are located, respectively.

The initial phase of calibration considered a single station, for example, internal flow gauging station Wijnegem Afvoergracht for the Schijn basin, and L7670 station at the outlet of the Upper Amblève basin.

The second phase included also internal stations. It is important to consider that in the Schijn basin there is only one extra station with available historical discharge data for calibration, Wijnegem. Therefore, some discharge data were estimated from water level data at stations Ekeren, 09 and 26. Consequently, there is a lot of uncertainty in the measurements at the internal stations of the Schijn Basin, while in the Upper Amblève this is not the case because there are historical data available also for the internal stations.

Other variables, such as actual evapotranspiration and groundwater levels, obtained from the distributed model, were analyzed to evaluate the response of other processes. Subsequently, results were also validated using data in a separated period. For the Schijn basin, discharge data for internal stations were calculated using a discharge – water level rating curve that was built with field measurements of two water level sensors installed for this project (HOBO 20474115 and HOBO 20474116). Similarly, in Vielsalm, validation was done using discharge data available for internal stations. The performance of the model was evaluated using goodness-of-fit statistics for model residuals, flow hydrographs, scatterplots of simulated versus observed peak flows, low flows and seasonal changes. Some modifications were made to the algorithm of the main model VHM to avoid those variables take illogical values, and to be able to apply the concept of disaggregation data based on an internal station instead of the outlet basin.

Soil organic carbon modelling by RothC and DOC modelling

Figure 5 shows the structure of the carbon model considered. This model has two main submodules, one for modelling soil organic carbon and the other one for estimating dissolved organic carbon (DOC). We used as reference the ROTHC version 26.3, which is a process-oriented, multi compartment model, and empirical in nature for calculating soil organic matter turnover. The compartmentalization is based on kinetically homogeneous pools and its turnover times rates (Coleman & Jenkinson 2014). Therefore, RothC was implemented using some first-order decay equations to represents litter and carbon pools and it was linked to soil moisture through its parameter “b”. First, it was implemented using a single soil layer (30cm), where the vertical distribution is assumed homogeneous, and in the next stage, soil layers were considered, covering a range from 0 to 200cm.

The soil organic model was run at equilibrium, and results of CO_2 at the Brasschaat site (cell of 250 * 250m) were compared with the modified RECO values collected in this ICOS site. In addition, spatial distribution of soil organic carbon was compared with available maps for evaluation of the model.

The DOC submodule was implemented based on the JULES-DOCM and ORCHIDEE-SOM conceptualization. We considered production and decomposition processes of SOC and DOC, as well as DOC leaching per user-defined layer. Carbon dynamics are simulated up to 2m depth, considering the global available data per depth such as soil texture and root distribution. This consideration of depth distribution is important for the coupling of this module to the soil moisture module based on Aquacrop, and for accounting the vertical distribution of soil moisture and drainage.

It is important to notice that the model does not include a dynamic vegetation model, but it considers the inclusion of the seasonal and vertical distribution of plant residues based on literature values.

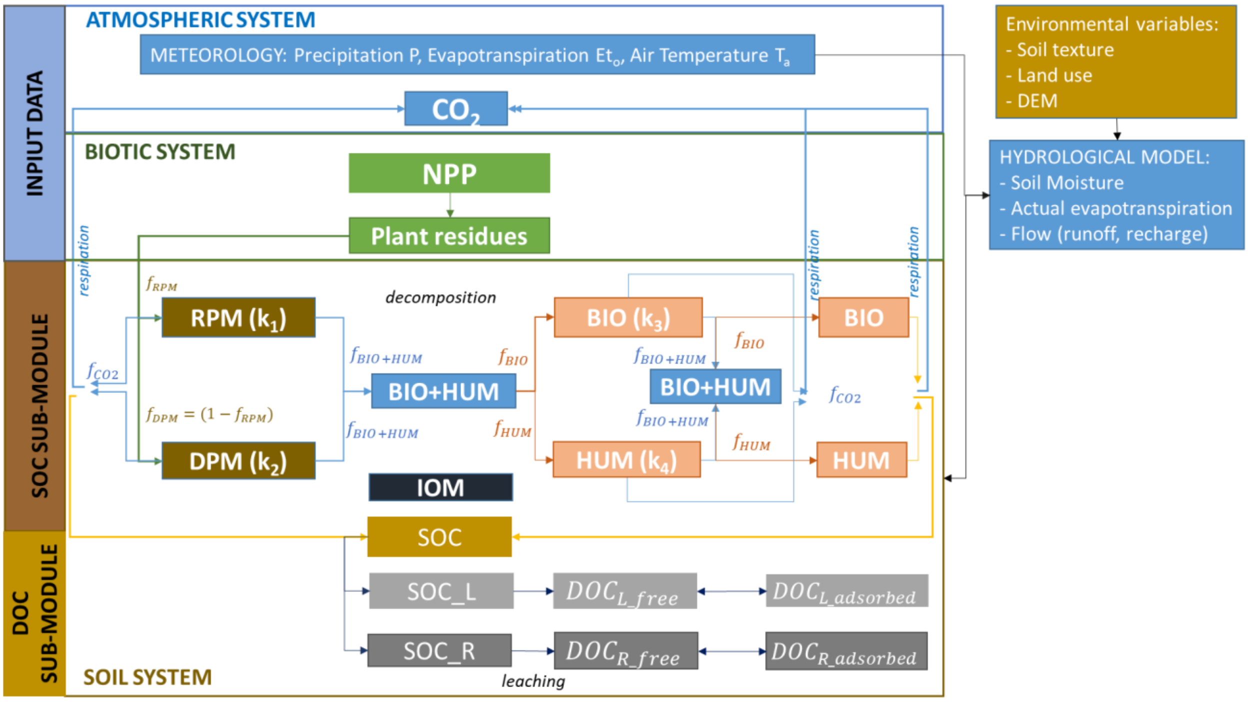

Figure 5: Structure of carbon model with soil organic carbon (SOC), by Roth C, and DOC sub-modules. Litter pools are decomposable plant material (DPM) and resistant plant material (RPM), and soil organic matter pools are microbial biomass (BIO) and humified organic matter (HUM), CO2 is result of decomposition (heterotrophic respiration), IOM is the inorganic pool considered constant. SOC_L and SOC_R are the labile (L) and recalcitrant (R) components, DOC is the dissolved organic carbon that can be free of being absorbed in the soil. The fractions are represented by an initial (f) followed by the pool that receives the material.

WP5: Climate scenario analysis

Climate scenarios with a regional climate model are usually going along with several simulations over past periods. Those include verification runs, where up-to-date reanalyses are used as lateral boundary conditions (LBC) for the regional climate model, and a historical run, using the general circulation model used as LBC for past period. There should be as many historical runs than GCM used for scenarios. Two verification runs have been done at KMI with the ALARO-0 climate model using reanalyses from the European Center for Medium range Weather Forecasts (ECMWF): ERA-Interim for a run until 2006 (already used in the BELSPO project CORDEX.BE), and a complete reprocessing using ERA5 until 2018, both simulations are done over the Belgian domain at 4 km resolution. For historical and future scenarios (especially the RCP8.5 – the business-as-usual radiative scenario from the IPCC AR5), the CNRM CM5 global climate model runs (Voldoire et al, 2013) have been used. While past studies have evaluated parts of the evaluation run using ERA-Interim as boundary condition (eg Giot et al, 2016), we have continued the effort in evaluating the ERA5-based downscaling using ALARO-0 over the Belgian domain and in particular over the two regions close to the project test sites, using available observational datasets available at KMI (see Table II). The question to be answered is twofold: Can ALARO-0 model provide sufficiently accurate climate information to be used by land model applications? Are the historical runs compatible with the verification runs or is there need for a correction? To answer those questions, we have focused on the two key variables driving most of the dynamics of land surface models: precipitation and surface solar radiation. Air temperature and wind speed are also necessary for land surface models. The validation will be pursued beyond the project.

Table II: Source of observations for the evaluation of ALARO-0/ERA5 verification run.

Variable	Source	Locations
Surface Total solar radiation	KMI – CLIMATE-GRID	Belgium (5 km grid)
Air temperature, Surface pressure, Wind speed	KMI - SYNOP	2 sites: Spa-Aerodrome (50.48N 5.91E), Deurne (51.22N, 4.46E)
Daily Precipitation	KMI - SYNOP/UAntwerpen	2 sites: Spa-Aerodrome (50.48N 5.91E), Brasschaat

SURFEX is the land surface model used at KMI. It includes several modules specific for different types of surface: ISBA is designed for vegetation, TEB for urban environment, FLAKE for open water. SURFEX can be used online, coupled to the RCM ALARO and off-line to zoom for impact studies to obtain air surface temperature and humidity, soil temperature and moisture, carbon, water and heat fluxes at higher resolution, e.g. 1 km. Land surface models need information on land cover classification to select the physics and specific parameters to be used to estimate the fluxes of heat, water and carbon between soil-biosphere/urban materials-atmosphere.

This offline capacity to zoom is partly imputable to the resolution of the land cover map, in addition to the spatial resolution and quality of the forcing. ECOCLIMAP database has been used so far by SURFEX until version 8.0 in all offline/online applications: it is composed of a land cover map, for which each class corresponding to a complex landscape (eg Spanish complex cultivation), is associated to structural vegetation parameters (eg albedo, vegetation fraction, leaf area index, vegetation roughness). The number of classes has been growing in three successive versions of the database (v1, v1.5 and v2). Each of the classes were further decomposed into the 4 tiles corresponding to the different models, and in turn into Plant Functional Types (PFT, eg permanent grass, evergreen coniferous forest) processed by ISBA model. The decomposition into PFTs was largely based on averaged statistics generalized from reports and publications, and is prone to sometimes large uncertainties.

So far, the SURFEX versions used for impact studies have not include the carbon allocation modules, and have been used to derive the climate signature of urban areas (eg Duchêne et al, 2020). In the ForestFlow project, the use of SURFEX v8 is evaluated in its ability to deliver the evolution of biomass and carbon pools/fluxes evolution, while maintaining a good accuracy of water cycle related variables. SURFEX v8 integrates the ISBA_CC model for “natural” patches, which integrates a modeling of the photosynthesis and carbon allocation within the different parts of the soil/vegetation. Nitrogen dilution is parameterized and soil organic carbon is prescribed. Key output variables have been investigated.

As the land use/land cover directly affects the evaluation of the surface variables, and especially the carbon cycle, a review of the existing LCLU maps over Belgium and the datasets providing future scenarios has been done in order to prospect the potential for further impact studies and regional earth system modelling activities (to be pursued beyond the project). Over the two forested project sites, SURFEX v8 has been tested in the configuration used in De Pue et al (2022), from the BELSPO ECOPROPHET project.

Point-wise simulations using ISBA-CC scheme, with an activation of the MEB module (Multiple Energy Balance), the prognostic LAI scheme and the scheme of radiative transfer through the canopy layers. Twelve layers of soil have been used as well.

We have compared to existing datasets to evaluate soil moisture and gross primary productivity. Several configurations of coupling of SURFEX v8 have been reviewed, especially the coupling with the hydrological module C-TRIP (Decharme et al, 2019), which could allow the transport of dissolved soil carbon in the rivers network if further developed for Belgium.

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4. SCIENTIFIC RESULTS AND RECOMMENDATIONS

WP1: Hydrological Site Characterisation

Schijn Basin and Upper Amblève basin

Table III shows the main physical characteristics of the Schijn and Upper Amblève basins. The Upper Amblève basin covers a surface of 775 km^2 and with an elevation that ranges from 209 to 700 m.a.s.l. The dominant soil in the area is characterized by soil complexes with stony content “G class” with almost 90% of coverage. There are three sub-classes of G soil according to the volume of coarse material. The class “loamy-stony soil” with 15-50% of rock fragments covers about 70% of the basin; other soil complexes without stony load and artificial soils cover around 4.5%, while the rest is peat soils (1.1%). Other simple textures such as silt, loam, clay are present in less than 0.1% or they are absent. The dominant land cover is forest with 50% coverage, from which 22% is evergreen forest, 19% is deciduous forest and 9% is mixed forest. Grasslands is present in 22% of the basin area and croplands in 13%. Water bodies are present in less than 0.1% and build up areas covers the 6% of the basin. Other types of land cover such as shrub lands, bare soils, wetlands are present in less than 10%.

The Schijn basin has a surface of 358 km^2, with an elevation that ranges from -1.2 to 56 m.a.s.l. The dominant soil is sand for 66% of the basin area, followed by loamy sand for 22% of the basin area, clay soils in less than 3%, and peat soils for around 0.12%. The dominant land cover, which is based on the land cover map (BBK, 5m) after re-classification to classes used in IGBP classification, is mixed forest with 38%, then build-up area with 22%, croplands 17% and grassland 16%. Water bodies, natural vegetation and barren soils are present in less than 2% of the basin area.

The hydrology of the Schijn basin, upstream of the Brasschaat site, is characterized by small channels distributed along the Inslang forest, which are mostly dry thought the year, even upstream. In addition, at local/basin scale there are multiple hydraulic infrastructure in place that strongly influence the hydrology in the area.

The results of the flow components analysis showed that the major flow component is baseflow (slow groundwater runoff) for Brasschaat (>63%) and interflow for Vielsalm (>41%). Nevertheless, the baseflow also contributes with an important fraction to the total discharge for Vielsalm.

Table III. Main physical characteristics of the Schijn and Upper Amblève basins

Variable	**Brasschaat (Schijn basin)**	**Vielsalm (Upper Amblève basin)**
P [mm]	830	952
PET [mm]	596	489
Q [mm]	174	550
Area [km2]	358.43	775.88
LU_dominant	Mixed Forest 38% Build-Up 22.7%	Mixed Forest 50% Grasslands 22%
ST_dominant	Sand 66%	Loamy-stony 70%

WP2 and WP3 combined: Biogeochemistry and tree phenology as mediator of soil water fluxes

The scientific results for this study can be divided in two sections. First, the results found on the performance of the new Zero Tension Lysimeter design and second, the results on the Dissolved Organic Carbon export under future rain regimes.

Performance of the ZTL3D

The design of a sampler that could represent the water flux of the forest was an essential tool for this study. The ZTL3D used for collecting leaching water and afterwards analyse DOC concentrations, was together with the Water Bucket Model (WBM), the base method of a validated DOC flux for the rain simulations performed during this research.

Much research is available on specific types of lysimeters, including reviews of different types or comparison of lysimeters with other methods (Abdulkareem et al., 2015), but there is very little research that focuses on the differences between two types of installation of the same Zero Tension Lysimeter. We observed that the amount of water collected depended on the type of installation. Vertically installed ZTLs3D collected larger amounts of water than horizontally installed ZTLs3D throughout the entire study, independent of whether water drainage was caused by natural rain events or by simulations (Fig.6).

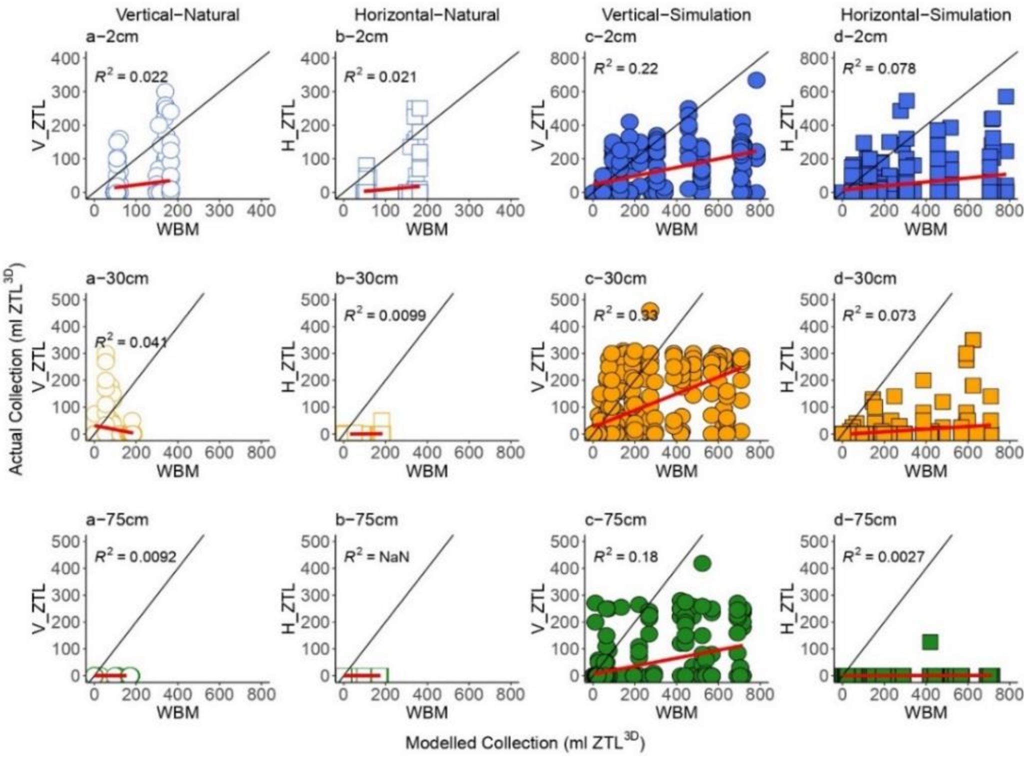

Figure 6: Identity lines comparison from ZTLs^{3D} collections (ordinates axes) versus modelled collections by the WBM (abscissa axes). Natural rain collections are represented by empty markers (ml/ZTL^{3D}). Rain simulation collections are represented by filled markers (ml/ZTL^{3D}). Every data point represents the collection by a single ZTLs^{3D}.Circular markers represent vertical installation while square markers represent horizontal installation. Red lines show the agreement with the 1:1 line per depth, type of rain event and type of installation. Each combination has a different name: Vertical installation during Natural collection – "a". Horizontal installation during natural collections –"b". Vertical installation during rain simulations – "c. Horizontal installation during rain simulations – "d". Every row represents a different depth.

The difference in the amount of leaching water collected by both installations could be explained by the influence of different types of preferential flow pathways and the effects of the two types of installations performed, for instance, the compaction created in the soil only by horizontal installation deviated in some cases the leaching water from going through the sampler to passing around it. Since both installations had different performances, we needed a tool to validate the correct amount of water passing from horizon to horizon, for that, we created a Water Bucket Model (WBM) for four depths which was simultaneously validated with the soil moisture sensors (TDRs) installed in each monolith.

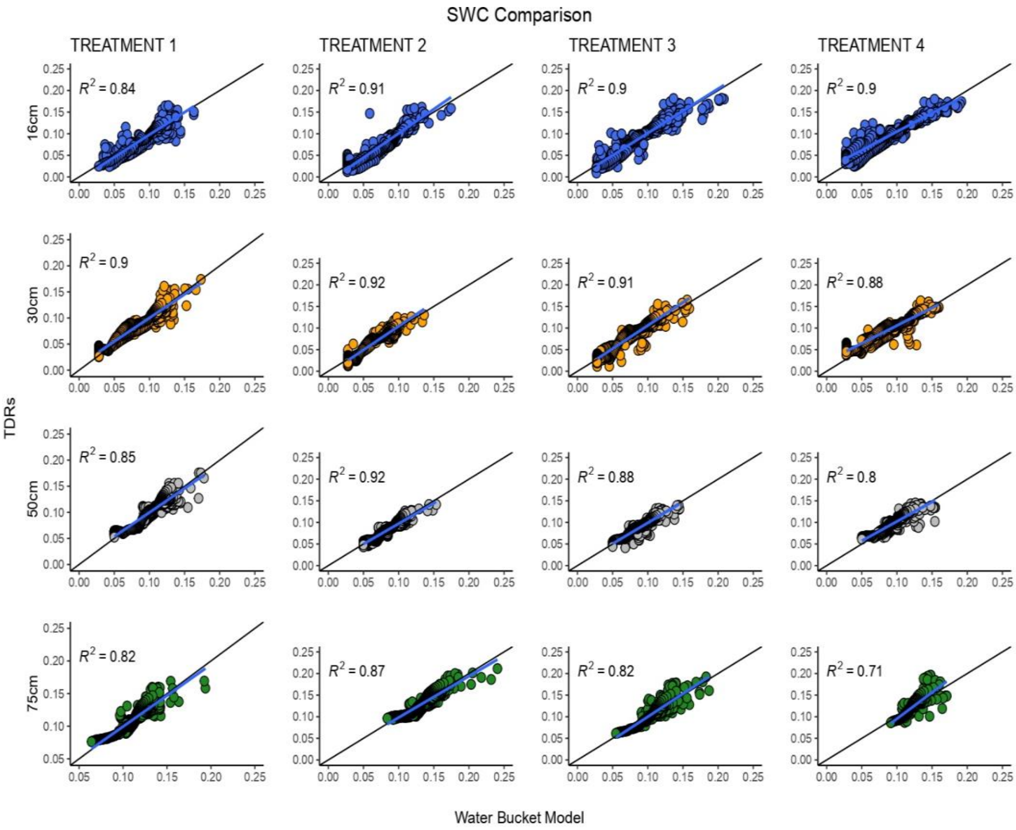

Figure 7: Daily average soil water content comparison between Water Bucket Model and TDRs data. Columns represent treatments while colours represent depths. Blue lines (regression lines) show the agreement with the 1:1 line per depth and treatment.

The soil water content simulated with the WBM agreed very well with the TDR measurements in the same plots during the entire study period (Fig.7). However, a lesser agreement was found with extreme soil water contents (SWC), especially below 0.05 m3m-3 and when ~75 mm water day-1 were added as extreme rain simulation experiments. Nevertheless, the lesser agreement for the low SWC did not affect the results of this research as its objective was to compare amounts of water leaching predicted by the model and the actual water leaching collected by the ZTLs3D, which only occurs at higher levels of soil water content above field capacity.

The lesser agreement for the very high SWC is most likely related to the layers' infiltration rates and evapotranspiration. Infiltration rates calculated by the model resulted in a delay of the leachate, mainly at the deepest depths (30 - 75 cm). The bigger the rain simulation, the longer the leachate continues at deeper layers. The most extreme irrigation events led to underestimated drainage when looking at the results right after the irrigation. According to the WBM, the total drainage at deeper layers was still happening days after the rain simulation, as in reality, the collection with ZTLs3D had already occurred.

To account for the infiltration's delay, the total leachate per rain simulation experiment was cumulatively calculated. Differently, in natural rain events, the WBM performed excellent and cumulative collections were not needed.

In conclusion for the ZTL3D design and study, we found that:

-The novel 3D-printed design for Zero Tension Lysimeters allowed collecting leaching water at different depths. Its inert material after an ultrasonic bath allowed accurate chemical analysis.

-A Water Bucket Model successfully reproduced temporal and spatial variation in soil water content. However, its calculated water fluxes, in general, exceeded the volumes collected by the ZTLs3D, indicating that our new ZTLs3D design underestimated the amount of drainage water.

-Vertically installed ZTLs3D more frequently collected drainage water and typically underestimated drainage water fluxes much less than horizontally installed ZTLs3D, independently of the event or depth. This difference could be due to disturbance during installation and soil properties.

-Preferential flow pathways created by vertical coring would lead to an overestimation as long as the soil has not fully restabilized, whereas compaction and edge effects would underestimate the water flow. Given the potential of the 3D-printed ZTLs, future research should identify the main causes of the low collection efficiency and resolve these artefacts.

Dissolved Organic Carbon export under future rainfall regimes

The results found affecting DOC under future climate scenarios focus on first, the importance of the soil state prior a heavy rain simulation, and the different effects on DOC exports under different intensities of rain during the autumn and winter seasons. During the RS1 and RS2, we conducted rain simulations in which we varied the precipitation, from droughted treatments (representing dry-wet cycles) to high intensity rain events (representing the intensification of the hydrological cycle). The intensity of the rain simulation applied had a clear impact on DOC. Concentrations and fluxes were similar during the treatments with the same water additions, and started to change as soon as we performed different rain simulations intensities. Once the heavy rain simulation was applied also to the droughted treatment, it was found that with preceded dry conditions, the DOC flux produced after a heavy rain simulation (as the representation of long drought followed by strong rain events) was the biggest at 2 cm depth compared to other treatments that were receiving rain additions instead of being dry (Fig.8) .

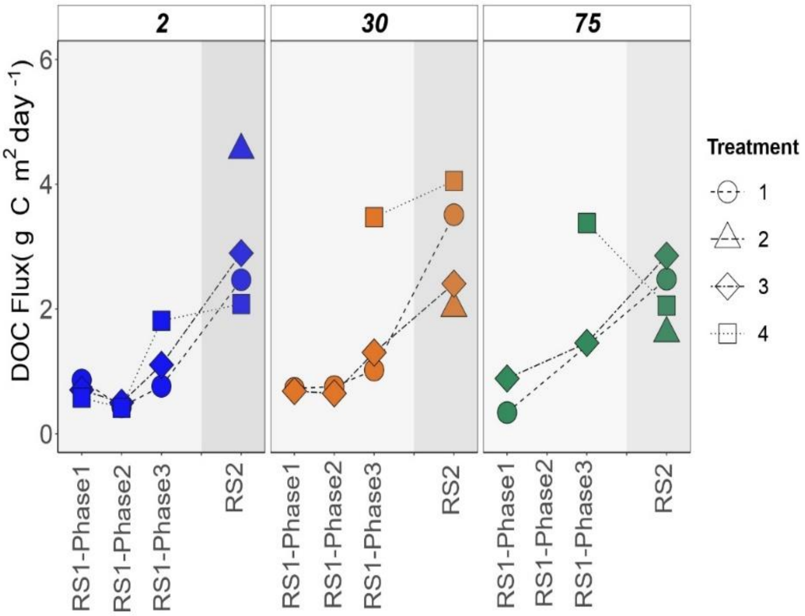

Figure 8: Representation of averaged fluxes at 2, 30 and 75 cm depth in four treatments under different irrigation intensities. Abscissa axes represent the exact days of collection. Ordinates axes represent the flux of DOC in g C m^2 day^{-1}. Colors represent depths while marker shapes

In addition, the treatments that received water previously, showed an increase of DOC flux with depth, mostly at 30 cm depth. When compared to previous studies of DOC fluxes on the same site, an average DOC flux of 10 g C m-2 year-1 was reported by Gielen et al., 2011 in a seven year study from 2000-2006 in the same forest, under natural rain events with no RSs performed. We found a total export ranging from 4.5-7.5 g C m-2 for the rain simulation period, depending on the T and depth; which represented 45-75 % of the yearly export under natural rain conditions reported by Gielen et al., 2011.

In conclusion for RS1 and RS2, we found that:

-The phase 3 of Rain Simulation 1 (RS1-Phase 3) showed a clear influence on the exponential increase of DOC fluxes with depth seen in Treatment 4 mostly at 30 and 75 cm depth.

-During Rain Simulation 2, the drought treatment followed by a heavy rain event produced the highest DOC concentrations and fluxes compared to other treatments with previous water applications at 2 cm depth. However, at 30 and 75 cm, depth showed a strong influence, where DOC fluxes from droughted treatments showed one of the lowest concentrations and smallest fluxes.

-Compared to previous studies in the same forest, the performed rain simulations caused higher DOC concentrations and bigger flux fluctuations. Furthermore, the total DOC export in this study (three months) covered from 45-75% of the annual export in the same forest under natural conditions.

-We conclude that water flux, DOC transport, texture, soil structure, and microbial decomposition are interrelated factors that affect DOC concentrations and leaching and their movement/production through depths.

During RSA and RSW, we simulated four treatments that applied equal amounts of water, distributed over different time periods and thereby creating different RSs intensities. RSs aimed to prove that future climate scenarios could impact DOC leaching. One of our hypotheses aimed to demonstrate the effect of heavy rain events on the DOC concentrations. We initially assumed that more distributed RSs would produce higher DOC concentrations than more intense RSs. However, our results showed the opposite: Large amounts of rain (T1 or T2) can cause higher DOC concentrations (Fig.9) and fluxes (Fig.10) compared to smaller and continued rain events (T3 or T4). This suggests that DOC concentrations and fluxes variability is determined by precipitation and therefore future and extreme climate conditions can potentially change DOC dynamics.

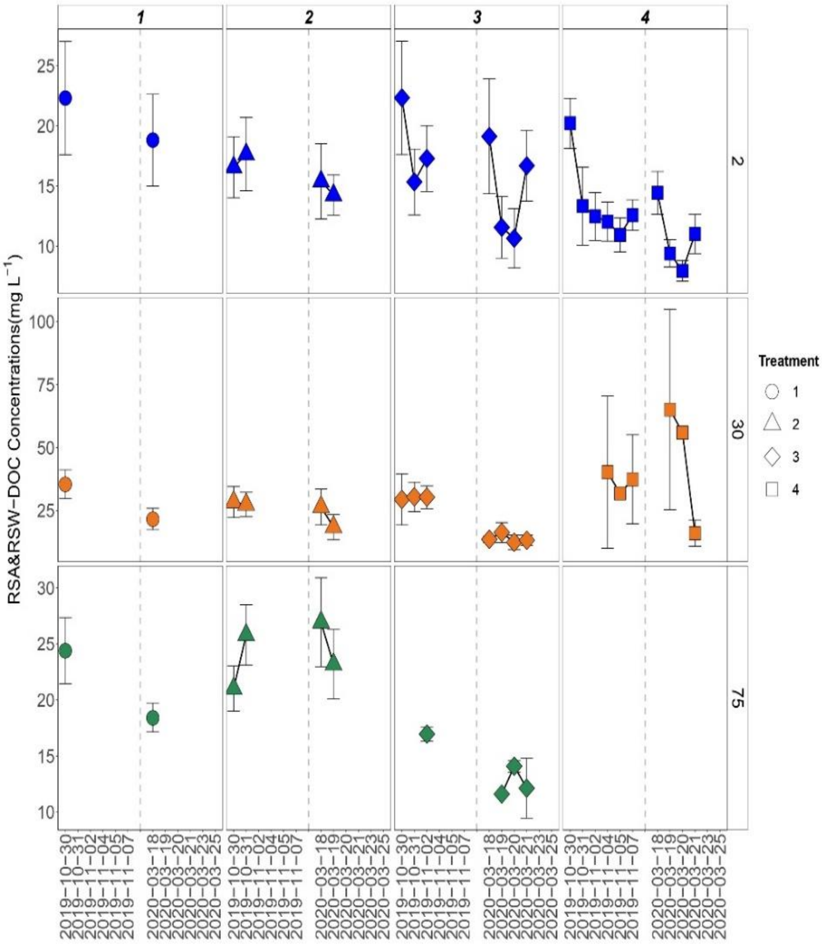

Figure 9: Evolution of DOC concentrations (mg C l -1) during RSA and RSW. Abscissa represents the collection dates whiles the ordinate represents DOC concentrations, with different scales for the 3 depths. Vertically, the panels (1-4) refer to specific Treatment (T). Horizontally, panels (2, 30, 50 and 75) refer to each depth. Dotted vertical lines separate RSA (on the left) from RSW (on the right) in each panel. Error bars represent the Standard Error.

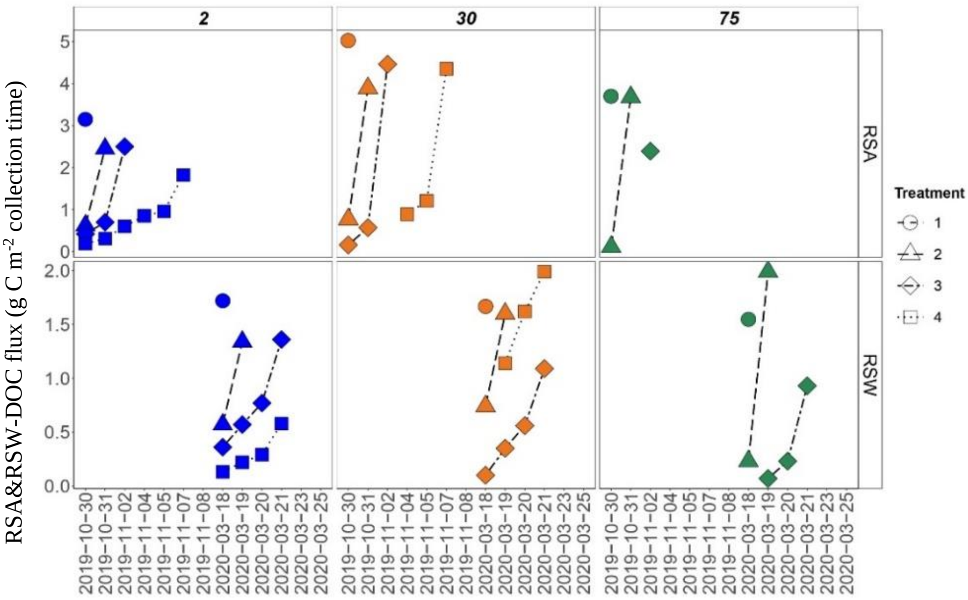

Figure 10: Cumulative Dissolved Organic Carbon fluxes (g C m²) from RSA represented by four different Ts. On the abscissa, the days of collection per T. On the ordinate, the amount of DOC Flux captured (g C m²). Symbols show the different Ts while colors are linked to the depths studied.

We also hypothesized that DOC concentration and fluxes would decrease during wintertime. In agreement, our results showed a large decrease in DOC concentrations and fluxes during winter (RSW) compared to autumn (RSA). Such decrease contrasts with an increase in soil moisture for the wintertime period, even though the addition of water was the same for both RSs. We concluded that precipitation by itself cannot explain the general decrease in RSW because soil moisture during the winter period was higher than during autumn. Instead, we hypothesized that the grasses' senescence and littler decomposition is the main cause of the decrease in all forms of DOC during RSW.

Litter decomposition combined with the grassroots exudates, which predominate our plots, might explain the seasons' different behavior. RSA might be influenced by the end of the grasses growing season, which apport fresh carbon through root turnover and exudate (Sanderman et al., 2008) but would be dormant during winter. During autumn (RSA), the soil moisture at deeper layers might not have reached field capacity and previous soil moisture state per layer might influence the transport and sorption of DOC, leading to a higher retention/production of DOC in deeper layers where soil moisture is higher.

The fast water movement created by the intense treatments in the RSs, together with the previously mentioned soil conditions, could decrease the sorption and the microbial processing in the surface and bring down the litter derived dissolved organic matter into the subsoil (Kaiser and Kalbitz, 2012), showing an increase in DOC through depth from 2 to 75 cm depth during RSA, more extremely seen at 30 cm depth. During RSW, all layers might have reached field capacity, grasses would be dormant, and the litter decomposition might be smaller together with a higher fraction transported through depth due to more homogeneous soil moisture in all layers, resulting in smaller DOC fluxes but more homogenous through depth than compared to RSA.

In conclusion for the RSA and RSW we found that:

- The effect of the rain simulation on DOC concentrations and fluxes increased together with the intensity of the event.
- DOC concentrations decreased for all treatments compared to previous natural rain collections while DOC fluxes showed a clear link between concentration and water drainage which was directly influenced by the RS' intensity.
- The three depths studied showed significant statistical results when studying the relation between intensity of event and DOC flux produced. The same effect was found for DOC concentrations at 2 cm depth.
- Season showed to have a clear impact on DOC concentrations and fluxes where litter decomposition and roots exudates played an important role during autumn.

Future research recommendations

We recommend vertical installation according to our findings. The surrounding forest and the area around the samplers will not be disturbed. Furthermore, the absence of compaction in this type of installation grants a more frequent leaching collection. An improvement of the ZTL3D could focus on simply making it much bigger, it would allow more frequent collections since the possibility of encountering preferential flows would decrease. The compaction created during horizontal installation could be studied further, some plots could be re-opened for total access to the monolith wall. The addition of coloured trace components to the irrigation water could highlight the presence of compaction for the horizontal installation or discover preferential flow pathways that could have interfered with the collections.

The manipulation experiments carried out in this study could be extended to the full field capacity, meaning that instead of having replicates for different treatments, certain events could be represented in all monoliths simultaneously. This approach could bring two advantages; First, the number of samplers that would collect water would be much higher since there would be 16 monoliths receiving the same treatment, and thus, more replicates would be available and less chance of missing certain collections. Second, the field would be under the same condition for the next experiment.

On the other hand, future research could also focus on repeating the drought followed by a rewetting of different intensities with monthly rain simulations. For example, each plot would represent a rain intensity thought the year and keep one monolith as drought. This would allow studying DOC concentrations and fluxes yearly, with the effect of four different rewetting. First, this would allow us to compare monthly and yearly DOC fluxes with Gielen 2011. Secondly, it could study whether DOC fluxes under extreme events are compensated by smaller fluxes afterwards since the rain simulation would be on a long term and not only short and extreme. Thirdly, it would allow understanding the ecosystem’s limits when switching from sink to C source (Sowerby et al., 2010) by studying droughts with different rewetting intensities.

It would be interesting to focus on studying the mechanisms of conditioning DOC in depth. Specific research on the link between DOC measurements and soil enzymes and decomposition rates, microbial respiration and growth and the effect of soil texture and structure would enable to validate the SOM-models like Orchidee-C and compare them with soil measurements. Furthermore, analysis of the DOC quality would explain the origin of DOC in each layer, helping to understand the vertical redistribution of DOC through depth under extreme rain events.

Further knowledge of how DOC travels through depth under extreme events and the biological processes involved would improve the C balance estimation of the ecosystem at a local and global scale. In addition, the representation of the C balance with two DOC exports as the representation of normal weather conditions and extreme weather conditions could also help to understand future climate scenarios effects on soil C.

WP4: Hydrological modelling

Lumped conceptual hydrological modelling

The VHM model calibration for Wijnegem Afvoergracht showed a satisfactory model performance with a Nash-Sutcliffe goodness-of-fit statistic value of NSE=0.71 after calibration and NSE=0.80 after validation. In addition, the calibration for Vielsalm case showed an NSE=0.74.

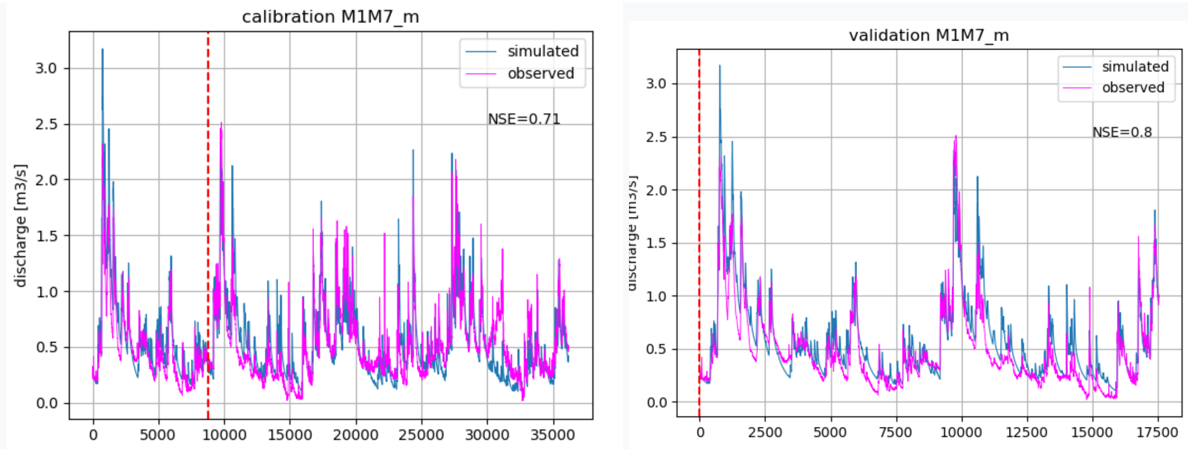

Figure 11. Example of calibration and validation results for the lumped VHM model, at Wijnegem Afvoergracht station; case study of the Schijn basin.

Spatially distributed hydrological modelling

Based on the performance rating given by Moriasi et al 2007, the Upper Amblève basin showed satisfactory model performance at the outlet (L7670) with NSE (PBIAS) = 0.78 (-3.97) after calibration and NSE (PBIAS) = 0.76 (6.98) after validation. This shows an improvement compared to the lumped model (NSE=0.75) for both calibration and validation. In addition, internal stations showed acceptable performance (NSE=0.55 - 0.80) as also shown in Figure 12, left. Specifically, the Salm basin, in which the Vielsalm site is located shows very good performance for calibration with NSE (PBIAS) = 0.74 (-10.1) as is shown in Figure 12, right, and for validation with NSE (PBIAS) = 0.79 (-14.1).

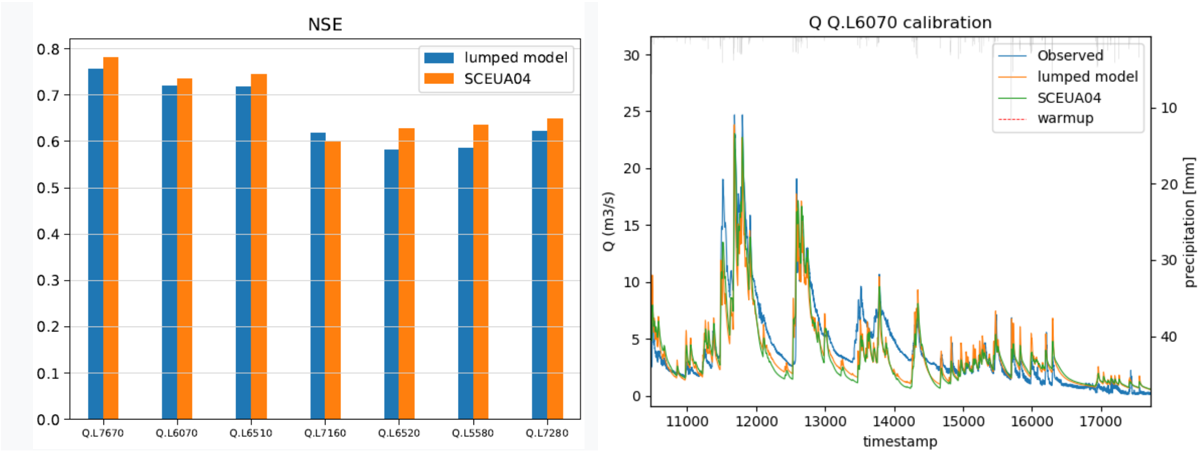

Figure 12 Observed and simulated hydrographs in m3/s for the Salm basin (station L6070) (right), in which the Vielsalm site is located, and NSE model goodness-of-fit statistics at the outlet and internal stations (left)

Similar results were observed for the outlet of the Schijn basin for calibration with a NSE (PBIAS) = 0.77 (-5.42), but there was a lower performance for validation with a NSE (PBIAS) = 0.52 (10.42). Unfortunately, the results for the internal stations did not show an improvement in the performance, even they report negative NSE values as we can see in the Figure 13.

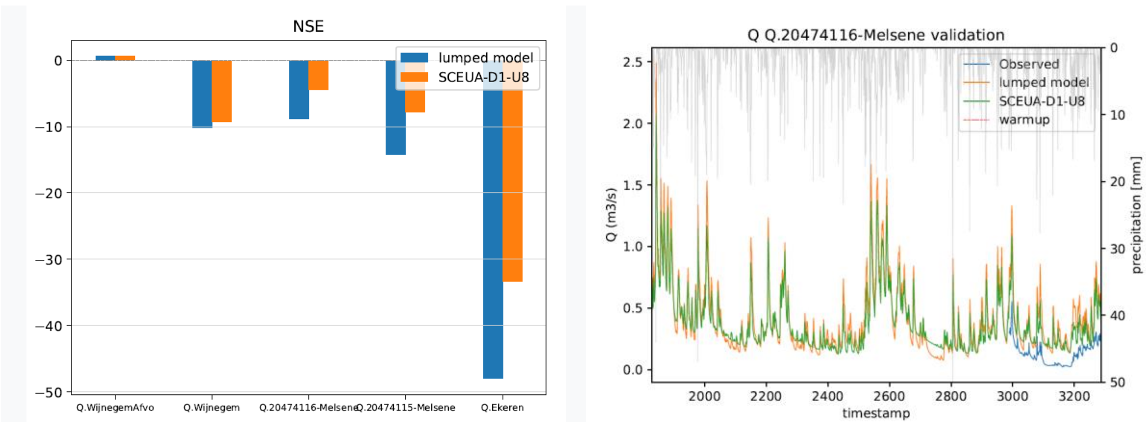

Figure 13. Observed and simulated hydrograph in m3/s for the nested Schijn basin at the upper internal station (HOBO 20474116), in an area where the Brasschaat site is located (right) and NSE model goodness-of-fit statistics at the outlet and internal stations (right)

This effect could be attributed to limitations of the disaggregation method. For example, some parameters in soil moisture calculation were kept constant, but they change with the variation of other parameters that were disaggregated, or simply the hydrological variability is not well represented with the physical characteristics used in the model. It is recommended to analyze further the complex relationship with the thickness, depth and texture of aquifers and the hydrological response, which were not accounted for in the disaggregation, but which could influence model performance.

Also, there is uncertainty in the data collected for the internal stations because discharge was estimated from water levels using limited information. Other sources of uncertainty are the exceptionally long periods without rain and the high temperatures in the summer season when we did the field monitoring. These dry conditions caused complete dryness downstream the Laarse river monitored in this project, as well as the presence of some local sediment dunes and meanders that caused backwater effects, which influence the accuracy of low flow measurements carried out in Brasschaat.

In addition, uncertainty may also have been induced through the different sources of data, or due to anthropogenic interventions such as blockage infrastructure in the rivers or management measurements in the surroundings, which may have affected catchment hydrology. These are not considered explicitly in the model, so is advised to analyze those potential effects in more detail, which may require hydraulic river and urban drainage models to be considered.

Soil organic carbon modelling by RothC and DOC modelling

Initial soil organic carbon results at 30cm depth show that the spatial patterns of SOC, from which DOC is derived, are in accordance with SOC patterns observed for regional and global maps, such as the Soil Grids produced by local authorities such as DOV.

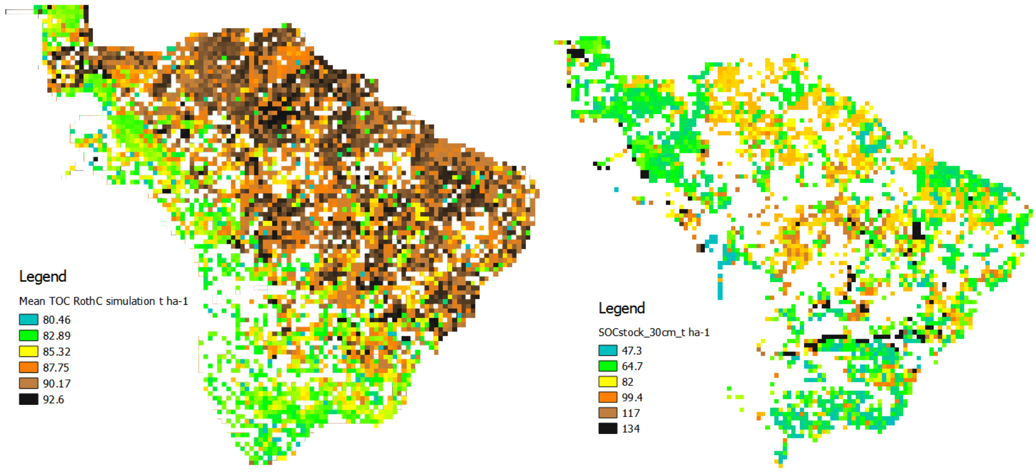

Figure 14. Spatial distribution of SOC stocks at 30 cm simulated by RothC (left) in comparison to reference maps provided by DOV, 2017

Furthermore, results for Brasschaat show that the magnitude and seasonal distribution of heterotrophic respiration, actual evapotranspiration and to some degree soil moisture, are in accordance with field observations. It is important to notice that monthly variability of mean values of simulated CO2 and RECO observations showed an overestimation from January to March, and from October to December, and an underestimation from April to September as we can see in Figure 15. The results in that figure show that the seasonal variation is misrepresented in certain degree, which could be due to the misrepresentation of seasonal variation of some input variables such as plant residues, temperatures or soil moisture.

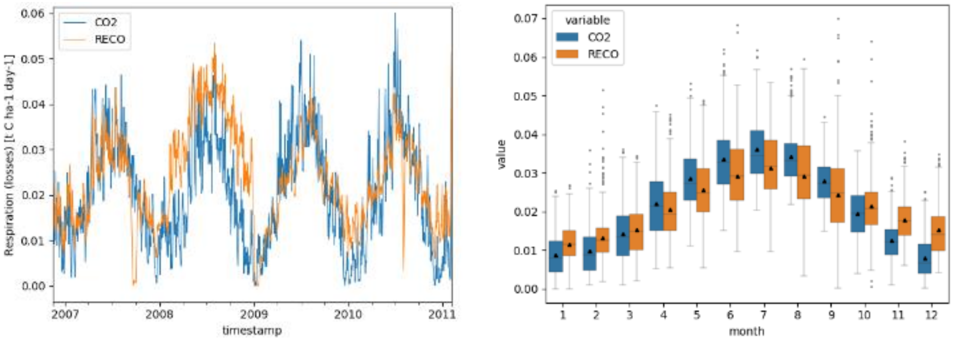

Figure 15. Temporal variability of CO2 loss simulations and observations (RECO) for Brasschaat. Average values per day (left) and month (right) in t C ha-1 day-1. RothC simulations for soil depth = 30 cm

The vertical distribution of soil moisture measured in the field by the project partner of UAntwerp, and the simulations obtained in the distributed hydrological model are shown in Figure 16 for 5 layers (L1 to L5) for irrigation experiment T3. Figure No. 7 shows a comparison of results for the variation of groundwater levels, which has a notably influence on soil moisture. Mean values are reproduced by the Aquacrop model, but the variability of moisture is represented with some limitations, which could be explained by the assumption of constant values in field capacity or wilting point in function of physical characteristics, which controls how soil moisture responds towards the upper and lower limits.

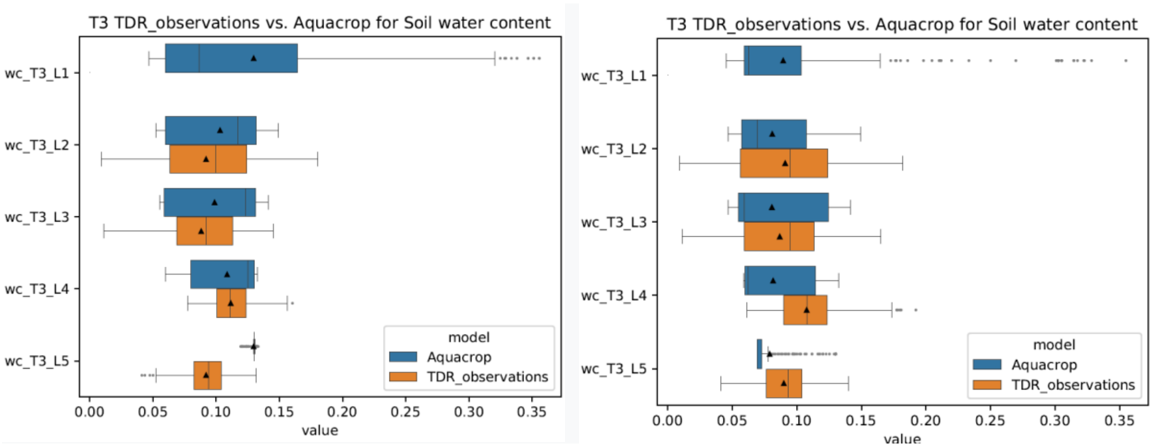

Figure 16. Boxplot of soil moisture in soil layers (L1 to L5) considering a groundwater level of -2m (left) and -99m (right).

WP5: Climate scenario analysis

Evaluation of the climate runs from ALARO-0

Global solar radiation at the surface from the ALARO-0 verification run has been compared to the observations from the CLIMATE-GRID (Journee et al, 2019) from KMI. A high spatial consistency is achieved. However, patterns (not seen in the CLIMATE_GRID dataset) of lower annual radiation over major cities and over the Ardennes relief is slightly noticeable (see Figure 17). Further checks are necessary to see if the partition between the direct and diffuse radiation is not biased. New observational datasets from KMI and from satellite (LSA-SAF, Meteosat) may help in evaluating both radiation components. We have also compared the histograms of the fraction of clear sky radiation for both datasets (here, illustrated over one year). The distribution is very similar for fractions over 0.5, but differ for lower fractions, with a large difference for overcast sky. Again, the impact on the absolute global radiation is weak, as it concerns only low radiation, but it may indicate spaces for improvement in the model.

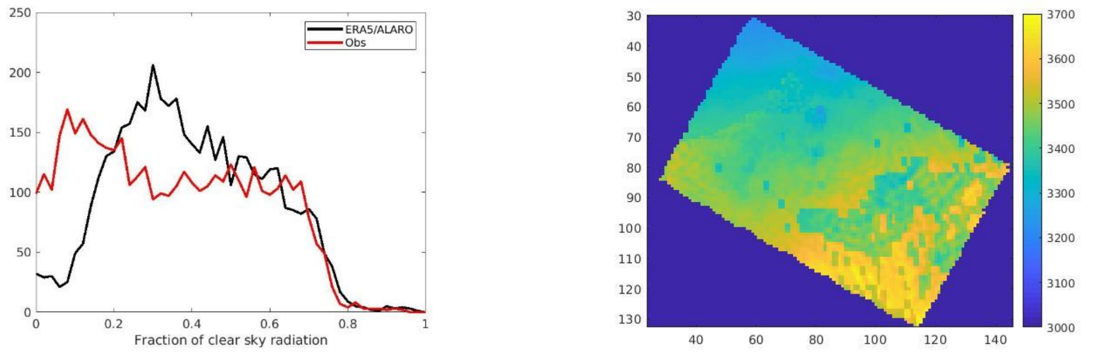

Figure 17: Comparison between verification (LBC: ERA5) from ALARO-0 and CLIMATE_GRID solar radiation over the Belgian domain: histogram of the calculated fraction of clear sky radiation at one pixel (left). Cumulated annual global radiation from ALARO-0 for 2018 (right).

Comparison of air temperature, surface pressure, wind speed and daily precipitation is done locally at Deurne and Spa-Aerodrome, both synop stations of KMI. As an example of results, we found at Spa, the standard deviation on the mean, maximum and minimum daily are 1.05, 1.4 and 1.6 K respectively, with a correlation of 0.99. Very high correlation of 0.99 is also found for daily surface pressure with a standard deviation of 1.2 hPa, while scores are a little bit lower for wind speed (correlation 0.68, standard deviation of 1.3 m.s-1). In this project, the daily precipitation is important, as it is a direct forcing of the infiltration of water into the soil.

For Spa, the cumulated precipitation of ALARO-0 is overestimated by 25% compared to the observations, while the timing of precipitation is relatively well represented (correlation of 0.77, if the extreme observed precipitation of 99.6 mm of is removed).

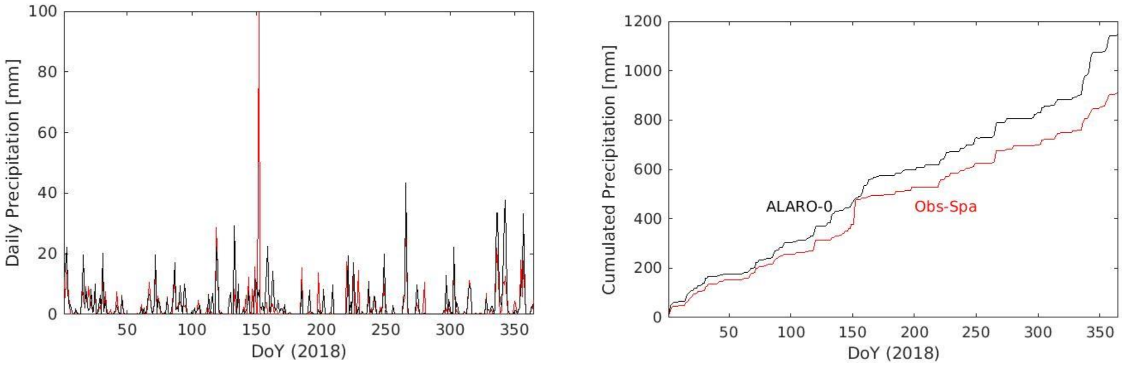

Figure 18: Comparison between verification (LBC: ERA5) from ALARO-0 and SYNOP Observations (daily sum). Time series for 2018 (left) and cumulative distribution for Spa-Aerodrome (right).

The consistency between the historical run and the verification run is done by comparing the spatial distribution of the annual averaged or cumulated variables. For precipitation, annual totals show almost no bias over Belgium and a very consistent spatial pattern. When looking at the number of precipitation days (P>1 mm.day-1), the pattern is consistent, but there is a lower number of wet days in the historical run. This may be caused by a slightly lower moisture advected through the lateral boundaries in the domain.

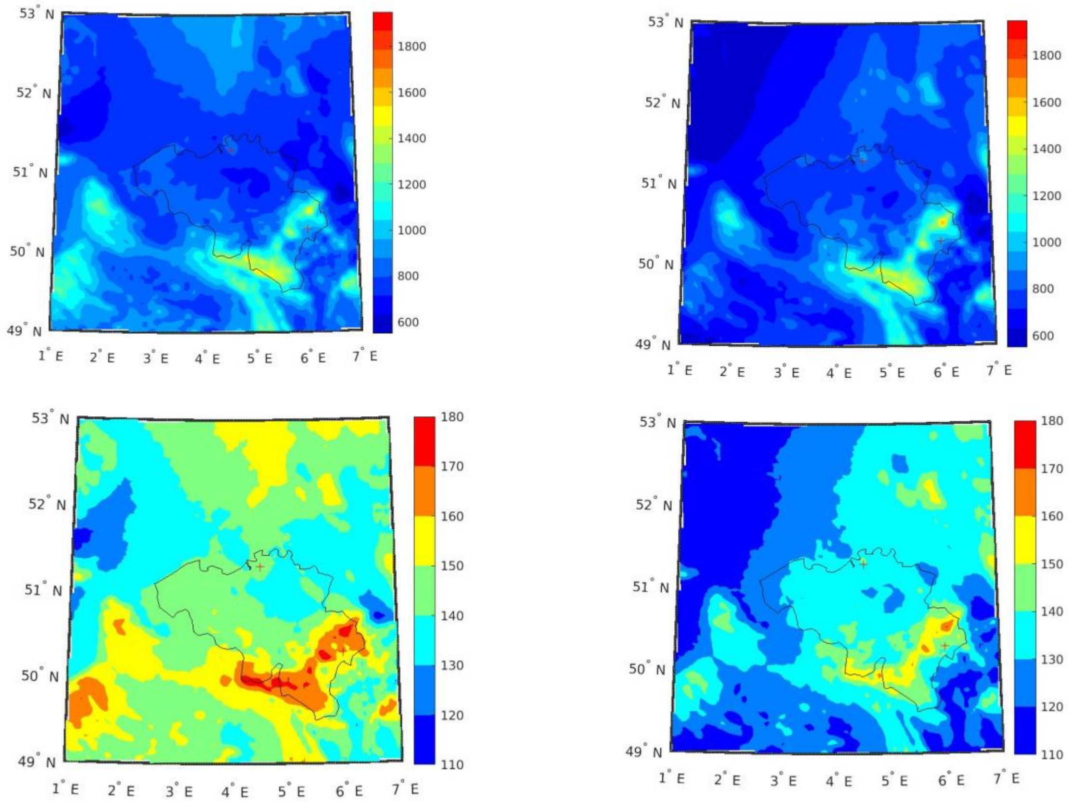

Figure 19: Comparison between verification (LBC: ERA5) and historical (LBC: CNRM CM5) runs from ALARO-0 for annual precipitation over the Belgian domain

Concerning total solar surface radiation, the spatial patterns of annual means are very consistent and no bias is observed. The two sites corresponds to zones with respectively low annual solar radiation (Brasschaat), and high radiation (Vielsalm). This verification test shows that no further bias correction is necessary to make the scenarios compatible with the verification run.

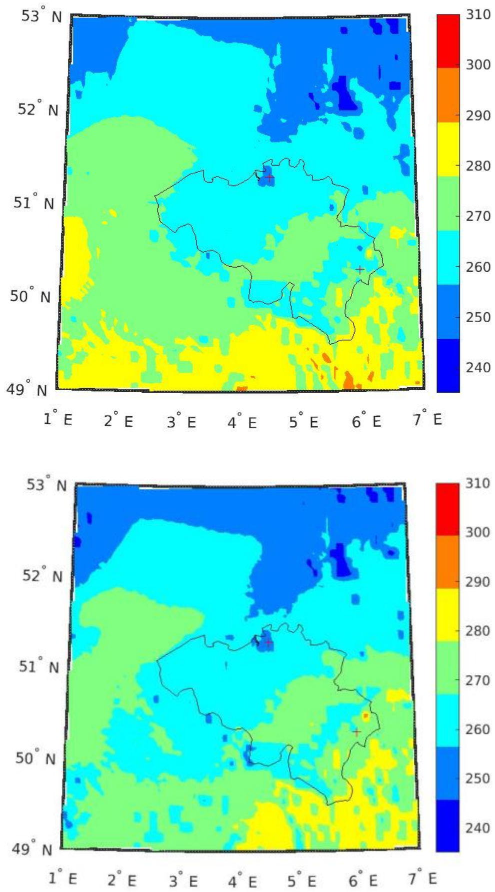

Figure 20: Comparison between verification (LBC: ERA5) and historical (LBC: CNRM CM5) runs from ALARO-0 for annual averaged global solar radiation at the surface over the Belgian domain

We found satisfactory scores for the driving climate variables provided by ALARO-0 model. Precipitation scores are a bit lower, especiallly when it comes to yearly accumulation. Time correlation is however relatively high, which is important for the impact studies at short time scales at the surface. The historical runs are compatible with the verification runs, giving confidence in using the future scenarios from CNRM-CM5 without regional bias correction.

Review of Land use/Land cover maps for Belgian domain

Land surface models need information on land cover classification to select the physics and specific parameters to be used to estimate the fluxes of heat, water and carbon between soil-biosphere/urban materials-atmosphere. ECOCLIMAP database has been used so far by SURFEX until version 8.0. From SURFEXv8.1 onward, the model supports the new version of ECOCLIMAP (SG, for second generation), which presents a simplification in the process of decomposition. Each of the 300m grid point land cover map is associated only to one tile and 1 PFT.

It simplifies greatly the pre-processing and allows an easy zoom at 300 m resolution. Thanks to this simplification, replacement of ECOCLIMAP by a higher resolution land cover map is made easier, as the conversion is straightforward (see Table IIII).

Table IIII: Legend of the ECOCLIMAP_SG land cover map. "Natural" classes available for Belgium are coloured.

1. sea and oceans	12. boreal needleleaf evergreen	23. flooded grassland
2. lakes	13. temperate needleleaf evergreen	24. LCZ1: compact high-rise
3. rivers	14. boreal needleleaf deciduous	25. LCZ2: compact midrise
4. bare land	15. shrubs	26. LCZ3: compact low-rise
5. bare rock	16. boreal grassland	27. LCZ4: open high-rise
6. permanent snow	17. temperate grassland	28. LCZ5: open midrise
7. boreal broadleaf deciduous	18. tropical grassland	29: LCZ6: open low-rise
8. temperate broadleaf deciduous	19. winter C3 crops	30: LCZ7: lightweight low-rise
9. tropical broadleaf deciduous	20. summer C3 crops	31: LCZ8: large low-rise
10. temperate broadleaf evergreen	21. C4 crops	32: LCZ9: sparsely built
11. tropical broadleaf evergreen	22. flooded trees	33: LCZ10: heavy industry

The advantages of using ECOCLIMAP SG in SURFEXv8.1 (and later versions) in replacement to ECOCLIMAP (v1, v1.5 or v2) for present days studies are 1) higher resolution (1000 m → 300 m), 2) easier construction of the physiographic files, and 3) easy replacement by other land cover maps for other uses. While ECOCLIMAP SG improves the representation at 1 km resolution, simulations at finer resolution might suffer from an incomplete classification (eg Ghilain et al, 2014 for an effect of accuracy on surface heat fluxes), as only the dominant PFT is selected. New LCLU maps available are based on another paradigm based on the "object" detection, allowed by the increased spatial resolution of satellite/airborne imagery. While coarse resolution maps were classified in ecosystems, finer resolution could move to homogeneous patch of vegetation, to landscape objects detection. It is why we have reviewed land use/land cover maps available for SURFEX impact studies over Belgium with their characteristics for applications in 1) present days at higher resolution, 2) historical period (past decades) and 3) future scenarios.

We see an interest in the dynamical LCLU maps as large changes can occur at the climate scales, e.g. urbanization, and also to later test the sensitivity of the climate to land use change in coupled configurations for regional earth system modelling.

Table V: Land use/Land cover datasets available for climate modeling over Belgium, with their characteristics.

LULC	Resol	Freq	Extent	Period	Source
Baseline					
Ecoclimap v2	1 km	Fixed	Global	1992-2002	https://opensource.umr-cnrm.fr/projects/ecoclimap/wiki
Present Days					
Ecoclimap SG	300 m	Fixed	Global	(2008-2012)	https://opensource.umr-cnrm.fr/projects/ecoclimap-sg/wiki
WALOUS	1 m	Fixed	Wallonia	2018	http://www.geoportail.wallonie.be
BBK	1 m	Fixed	Flanders	2012, 2015	http://www.geopunt.be
GlobeLand30	30 m	Fixed	Global		http://www.globallandcover.com/
MODIS	250 m	1 yr	Global		https://lpdaac.usgs.gov/products/mcd12q1v006/
CGLOPS	100 m	1 yr	Europe	2017 - 2020	https://land.copernicus.eu/global/products/lc
WorldCover	10 m	Fixed	Global	2016-2020	https://esa-worldcover.org/en
Historical					
ESA-CCI C3S	300 m	1 yr	Global	1992-2019	http://www.esa-landcover-cci.org/
Corine CLC	100 m	Irreg	Europe	1990, 2000, -06, -12, -18	https://land.copernicus.eu/pan-european/corine-land-cover
HILDA-PLUS	1 km	1 yr	Global	1960 - 2019	https://doi.pangaea.de/10.1594/PANGAEA.921846
LANDMATE PFT	0.018°	Fixed	Europe	2015	https://doi.org/10.26050/WDCC/LM_PFT_LandCov_EUR2015_v1.0
Future projections					
LUCAS LUC	12 km	1 yr	Europe	2016-2100	https://doi.org/10.26050/WDCC/LUC_future_landCovChange_v1.0

A conversion matrix from several of the maps (eg WALOUS and BKK for Wallonia and Flanders) to the PFT classification of ECOCLIMAP SG has been proposed, and could serve later in refining the land surface representation over Belgium, if runs at higher resolution than 1 km are envisaged. As an example, a region around the Vielsalm site is inter-compared at 300m between ECOCLIMAP SG, Copernicus Global Land 2018 and WALOUS 2018, both classified according to ECOCLIMAP SG PFTs and rescaled to 300 m. Good spatial consistency can be noticed. CGL map shows more water compared to ECOCLIMAP SG, and WALOUS gives more space to grasslands.

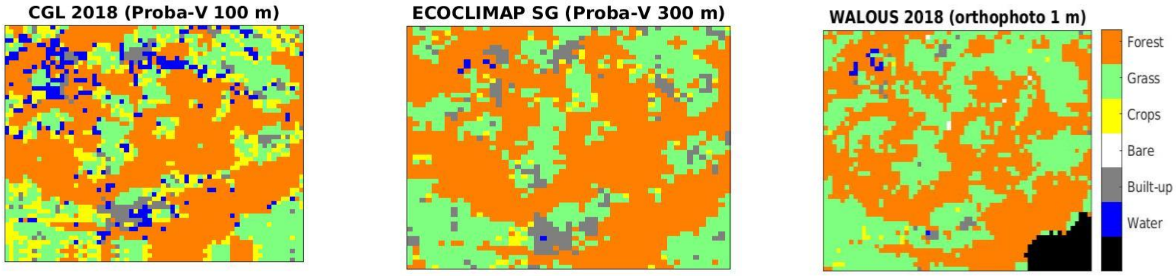

Figure 21: Comparison between ECOCLIMAP SG and transformed CGL and WALOUS, both upscaled to 300 m.

Land surface simulations: evaluation of SURFEXv8

An evaluation of SURFEXv8 over forest site at Braschaat has been carried out, to be sure to obtain similar results as in De Pue et al (2022). Soil surface moisture and gross primary production have been compared to in-situ and/or satellite datasets to evaluate the ability of the model to reproduce either the observed patterns and/or be within the range of contemporary retrievals from satellite imagery. The importance of evaluating those variables is to see to what extent the model can cope with coupling carbon and water cycle modelling, and how carbon fluxes modelling is potentially affecting the modelled water cycle. The performance of the model for surface soil moisture is shown in Figure 22 for the Brasschaat site, where SURFEXv8 correlates very well with the in-situ observations. Differences are however observed with the CGLOPS satellite product at 1 km based on Sentinel, especially when considering its high day-to-day variability, and also during the summer 2018 for which no large drying is seen in the product.

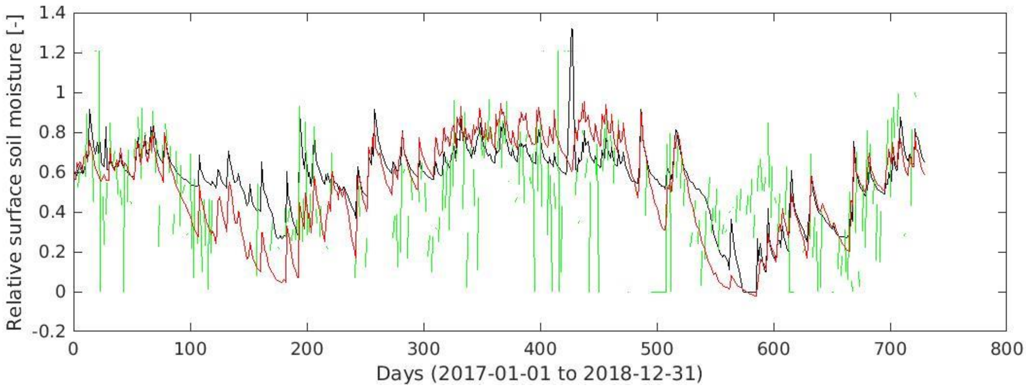

Figure 22: Comparison between SURFEXv8 soil moisture layer 1 (black), in-situ (red) and CGLOPS 1km SSM product (green) daily averaged and rescaled between minimum and maximum bounds for the years 2017 and 2018.

From the results, in agreement with De Pue et al (2022), GPP is relatively well modelled for Brasschaat, with a slight under-estimation and a delay in the annual signal (see Figure 23). The comparison with other datasets from satellite products (eg Copernicus Global Land, MOD17, LSASAF GPP) should be continued, especially to validate the spatial patterns. Point-wise, the weekly temporal course tended to vary from one dataset to another, partly due to the differences in the spatial resolution and only FLUXSAT could be exploited correctly. The good variability obtained for GPP is encouraging when considering impact studies on the role of forest in regulating the stock of atmospheric CO2. However, Leaf Area Index index prognosed by the model does not provide satisfactory results: the signal is even more delayed, the annual variability is underestimated, and absolute value as well.

As pointed by De Pue et al (2022), diagnostic models seem capable to reproduce the observed variability of LAI, which gives some perspective in the correction of this variable within the model itself or by post-processing. Correction of LAI should then be considered for further simulation experiments, such as to see whether it could correct the shift noticed in SURFEX GPP. In addition, such correction may be needed if SURFEXv8 is coupled online with ALARO-0, as it may impose an unrealistic roughness of the surface to the atmosphere.

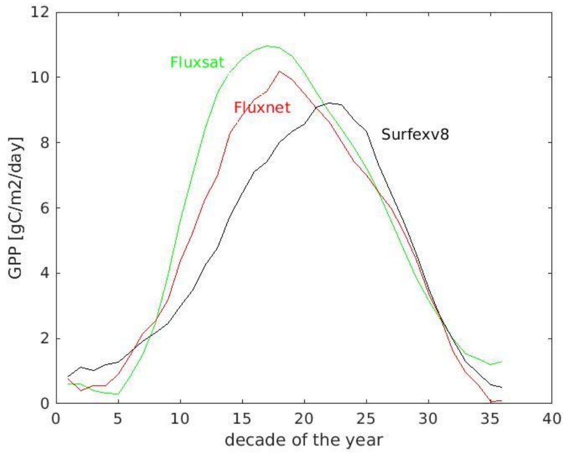

Figure 23: Comparison of the yearly cycle (averaged) of GPP over Brasschaat at 10 days frequency between SURFEXv8 GPP (black), in-situ (red) and Fluxsat daily product (green).

Abdulkareem, J., Abdulkadir, A. & Abdu, N. 2015. A Review of Different Types of Lysimeter Used in Solute Transport Studies. International Journal of Plant & Soil Science, 8, 1–14.

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Kaiser, K. & Kalbitz, K. 2012. Cycling downwards – dissolved organic matter in soils. Soil Biology and Biochemistry, 52, 29–32.

Moriasi, D.N., Arnold, J.G., Van Liew, M.W., Bingner, R.L., Harmel, R.D. and Veith, T.L. (2007) Model Evaluation Guidelines for Systematic Quantification of Accuracy in Watershed Simulations. Transactions of the ASABE, 50, 885-900.https://doi.org/10.13031/2013.23153

Sanderman, J., Baldock, J.A. & Amundson, R. 2008. Dissolved organic carbon chemistry and dynamics in contrasting forest and grassland soils. Biogeochemistry, 89, 181–198.

Sowerby, A., Emmett, B.A., Williams, D., Beier, C. & Evans, C.D. 2010. The response of dissolved organic carbon (DOC) and the ecosystem carbon balance to experimental drought in a temperate shrubland. European Journal of Soil Science, 61, 697–709.

5. DISSEMINATION AND VALORISATION

We put strong value on the dissemination and valorization in our project. In the overview below, we refer to the original proposal, and indicate where we proceeded as originally planned in the dissemination, and where we eventually decided for another dissemination/valorization activity. Overall, COVID-19 struck society exactly during the period that our main dissemination events were planned. This means not all originally planned objectives were obtained, especially since COVID-19 also interfered with collaborative research and progress in interaction. The prolonged period was mainly used to harmonize scientific results and finalize project cooperation.

Dissemination

-Thematic meetings: Through our direct link with the ICOS infrastructure, we foresee two thematic meetings on the current state-of-the-art in DOC flux quantification in forest ecosystems. One is foreseen in the first 6 months of the project. Here we will bring together experts on this topic, who can present current efforts to identify soil carbon dynamics in forests. The first meeting will include a one day discussion on optimization of our sampling and modelling design.

- ➔ *We organized several thematic discussions with the Belgian ICOS team, where Caroline Vincke, Bert Gielen and Ivan Janssens are prominent members. The meetings included representatives from the partners, the ICOS network and Iflux. Among others, we discussed the potential for the installation of the sampler, the sampling design and the planned analyses.*

The second meeting is planned near the end of the project. Here we will present how our project has moved forward technical ability to quantify DOC-fluxes in the ICOS infrastructure, providing a potential implementation plan through the ICOS infrastructure. Both meetings can be embedded in annual ICOS meetings.

- ➔ *This thematic meeting was not organized yet, due to the 3 year absence of ICOS meetings due to COVID-19. However, dissemination of the results to the ICOS partners, both national and international, is planned to be performed in an upcoming ICOS event.*

-Popularisation of the results: The results of the proposed research are relevant and of interest to both expert and non-expert audiences, in particular as people are more and more experiencing the potential impact of climate change, including extreme rain and drought events. Apart from peer reviewed articles, we thus aim to write and explain the main results and implications of this research proposal in a popular science magazine, as well as to participate in national and international conferences and workshops regarding climate change and carbon cycling. Co-partnership of our research groups in many projects, including ICOS, related to interactions between carbon and other element cycles will aid broadcasting of the results to non-experts, policy makers or stakeholders. We will engage to present our project on public initiatives such as the "open science days" and the "children's university", and will use social media channels of the University for broad audience communication.

We have engaged in several public and scientific dissemination activities, which are summarized below:

-Popularizing blogposts. The ForestFlow teams regularly post popularizing blogposts on the well-visited blog www.globalchangeecology.blog, to bring the climate/ecosystem interactions to the broader public. Examples:

- *https://globalchangeecology.blog/2018/05/09/bossen-zijn-nog-koeler-dan-gedacht/*
- *https://globalchangeecology.blog/2019/11/04/natuurlijke-ecosystemen-op-het-land-als-buffer-tegen-klimaatverandering/*
- *https://globalchangeecology.blog/2022/03/16/longread-klimaatoplossingen/*

-Participation in public science events: the coordinator team participated in the public science events 'Sound of Science', 'KinderUniversiteit' and 'Dag van de Wetenschap' with climate related workshops in 2017, 2018 and 2019.

-Climate workshops in secondary schools, and last years of primary school, together with WWF. The coordinator brings climate science to school children through a dedicated experimental workshop, which also focuses specifically on tree phenology and soil processes.

-Regular posts on social media via https://twitter.com/gce_uantwerp

Scientific dissemination

-Databases: embedding of our project into the ICOS-project, and direct involvement of the ICOS Thematic Centre, ensures inclusion of all data into ICOS databases.

- ➔ We ensured for a direct interconnection between project data and the ICOS databases.

-ForestFlow Poster on ICOS Belgium Consortium Study Day - Louvain-La-Neuve, June 1st 2018

-Forestflow Poster on ICOS International Science Conference Prague (International), September 2018

-Forestflow Poster on EGU 2018: A design of a 3D printed Zero Tension Lysimeter for tracing percolating water and Dissolved Organic Carbon in soil forests in Belgium.

- Collaboration with Lancaster and Linköping Universities for the installation of the ZTL3D in the Amazon rain forest. The samplers were installed in four sites that get flooded at different times during the year. For these sites the samplers were installed at 2, 30 and 75 cm depth as the installation in Belgium but also at 1, 2 and 3 meters depth. The installation was based on ForestFlow experience.

- Abstract “Coupling of Hydrological and Carbon Fluxes Models for Simulating Dissolved Organic Carbon Fluxes in Forests under Different Rainfall Regimes” will be submitted to “BIOGEOMON 2022 10th International Symposium on Ecosystem Behavior”, University of Tartu, Estonia, by the Forestflow Team

Valorisation

-Our project will provide a unique stage to show the advantages of the iFlux® sampler, a state-of-the-art environmental sampler developed in Belgium, to a broad scientific community worldwide. This provides strong valorisation potential to the project, and also will provide crucial data to optimise its design. It has a large application potential in specifically the ICOS infrastructure, but also other individual experiments regarding ecosystem carbon balances. We will engage to organize a thematic stand on the iFlux® sampler and its advantages, on ICOS meetings during the last 2 years of the project.

- ➔ In the end, we were unable to use the targeted IFlux sampler in the project, and together with IFlux, designed a novel 3D printed sampler. The challenges we were confronted with in the project, have been a stimulus for IFlux to further develop sampler. As a result, a digital sampler was developed for tracking both horizontal and vertical soil water fluxes permanently, and emphasis was put on optimizing the IFlux samplers for DOC sampling.
  This led to new cooperations between IFlux and the partners, i.e. Curieuzeneuzen in de Tuin, a citizen science project on soil moisture in Flemish gardens using an optimized soil moisture sampler, which was made IOT ready in cooperation between UAntwerpen, IFlux and Orange. In addition, we have engaged with the city of Mechelen and Telenet, to install a large scale water flux monitoring network in the West of Mechelen, based on the novel IFlux technology. The strong involvement of IFlux and the project partners has thus ensured further joint academic-commercial cooperation.

-We engage to organize a stakeholder meeting, including policy-makers, experts and environmental consultants at the end of the project. During this project, we will clearly emphasize how our results improve state-of-the-art knowledge on the stability and biogeochemistry of soil carbon stocks, and potential future alterations in future carbon balances of forests due to climate change. This stakeholder engagement can be embedded in ICOS stakeholder activities, which guarantees a strong policy and public valorisation. The ICOS target audiences include global organisations such as UNFCCC and IPCC, SME's and NGO's developing solutions for climate mitigation and adaptation, COP negotiators and national and European Commission stakeholders. The newly granted RINGO project (H2020-Infradev 2016-2017), strongly linked to ICOS implementation, puts special emphasis on science communication to multiple stakeholders.

➔ This meeting was not organized yet, for reasons mentioned above, with no general ICOS meetings planned during the COVID-19 period. However, this activity is planned in an upcoming ICOS event.

6. PUBLICATIONS

“Transpiration at leaf and tree level in a poplar short-rotation coppice culture: seasonal and genotypic differences”. Navarro, A., Portillo-Estrada, M., Vanbeveren, S.P.P., Ariza-Carricondo, C. and Ceulemans, R. (2018). Acta Hortic. 1222, 93-102. DOI: 10.17660/ActaHortic.2018.1222.13.

"A comparison of different methods for assessing leaf area index in four canopy types". Ariza-Carricondo, C., Di Mauro, F., de Beeck, M., Roland, M., Gielen, B., Vitale, D., Ceulemans, R. and Papale, D. (2019) Central European Forestry Journal, 65, 2, 67-80. https://doi.org/10.2478/forj-2019-0011.

“Outburst of senescence-related VOC emissions from a bioenergy poplar plantation”. Portillo-Estrada, M., Ariza-Carricondo, C., and Ceulemans, R. (2020) Plant Physiology and Biochemistry 148, 324-332. https://doi.org/10.1016/j.plaphy.2020.01.024.

“Two types of installation of 3D-printed Zero Tension Lysimeter for soil leaching and Water Bucket Model validation”. Ariza-Carricondo, C., Stryuf, E., Roland, M., Gielen, B., Vincke, C., and Janssens, I.A. Accepted at the European Journal of Soil Science.

“Effect of extreme rainfall on DOC leaching from a temperate pine forest I. The importance of rainfall intensity and antecedent soil conditions.”. Ariza-Carricondo, C., Fransen, E., Neirynck, J., Verstraeten, A., Cools, N., Roland, M., Gielen, B., Vincke, C., and Janssens, I.A. In preparation.

“Effect of extreme rainfall on DOC leaching from a temperate pine forest. II. Importance of rainfall distribution”. Ariza-Carricondo, C., Fransen, E., Neirynck, J., Verstraeten, A., Cools, N.,Roland, M., Gielen, B., Vincke, C., and Janssens, I.A. In preparation.

“Coupling of Hydrological and Carbon Fluxes Models for Simulating Dissolved Organic Carbon Fluxes in Forests under Different Rainfall Regimes”. Mena S., Willems, P. In Preparation