**Project Number 282910**

**ÉCLAIRE**

**Effects of Climate Change on Air Pollution Impacts and Response Strategies for European Ecosystems**

**Seventh Framework Programme**

**Theme: Environment**

# D14.6 - Comparison of regional-scale models with validation data of test sites

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| **Dissemination Level** | | |
| **PU** | Public | x |
| **PP** | Restricted to other programme participants (including the Commission | ☐ |
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## 1. Executive Summary

In Eclaire work package 14, several land surface and dynamic global vegetation models are used to simulate the impacts on ecosystems of various scenarios of climate change, air quality (exposure to $O_3$ and $CO_2$) and deposition of nutrients on plant productivity and nutrient cycling. The specific objective of deliverable 14.6 was to make comparison of validation data on test sites in C3 with: (i) detailed applications of the regional-scale models and (ii) the outputs of large-scale model runs for the same regions and ecosystem types. It was found out that the validation data at Eclaire C3 sites is limited (just one site, i.e. Alp Flix that has relevant data) and consequently, it was decided to change this deliverable to a description of the validation status of involved dynamic global vegetation models (i.e. LPJ, Jules and OCN) and the regional model MADOC. The deliverable describes the status of model development as well as how the contributing partners have confronted the models with observations to assess the model performance at different scales.

## 2. Objectives

The original objective of Deliverable 14.6 entitled “comparison of regional-scale models applied on test sites in C3 with large-scale model runs” was a comparison of validation data on test sites in C3 with: (i) detailed applications of the regional-scale models and (ii) the outputs of large-scale model runs for the same regions and ecosystem types. Formally the task was limited to NERC-BAN and ULUND, thus implying the models Jules and LPJ-GUESS.

It was found, however, that the validation data at Eclaire C3 sites is limited (just one site, i.e. Alp Flix that has relevant data) and consequently, it was decided to change this deliverable to a description of the validation status of dynamic global vegetation models (i.e. LPJ, Jules and OCN) and the regional model MADOC. Since all participating groups are frequently engaged in confronting their models against observations we could thus draw from a larger range of model-data comparisons, which provide a more comprehensive picture on the present state-of-the-art.

## 3. Results:

## JULES and MADOC

### Modelling approach

The Joint UK Land Environment Simulator JULES is the land component of the Met Office Hadley Centre climate model (Best et al., 2012, Clark et al., 2012, Collins et al., 2011). It represents the fluxes of heat, moisture and momentum at a half-hourly timestep and depicts the terrestrial carbon cycle and vegetation dynamics, including plant phenology and vegetation competition (Clark et al., 2012). The model represents vegetation in terms of gridbox fractional coverage of five plant functional types (PFT): broad and needleleaf trees, C3 (temperate) and C4 (tropical grasses) and shrubs. Physiological processes at the leaf and canopy levels, e.g. plant photosynthesis, conductance and light interception, are key factors that determine vegetation competition and thus PFT fractional coverage at any given location and environment. JULES simulates plant photosynthesis using a multilayer canopy scheme for light interception, accounting for sunfleck penetration (Mercado et al 2009), a coupled scheme of leaf photosynthesis and stomatal conductance using a PFT-specific leaf nitrogen parameterization, which defines maximum photosynthetic capacity, representation of plant and soil respiration (Nitrogen and Temperature dependent), and representation of the effects of ozone on leaf physiology using a flux gradient approach (Sitch et al, 2007).

Sitch et al. (2007) modified JULES to include a simple empirical function to describe the effect of $O_3$ deposition on photosynthesis and to account for interactions between $O_3$ and $CO_2$ through stomatal closure. Specifically JULES assumes a suppression of net leaf photosynthesis by $O_3$ that varies proportionally to the $O_3$ flux through stomata above a specified critical $O_3$ deposition flux. This scheme includes an empirical relationship between stomatal conductance and photosynthesis, and through this mechanism the direct effect of $O_3$ deposition on photosynthesis also leads to a reduction in stomatal conductance. As the $O_3$ flux itself depends on the stomatal conductance, which in turn depends upon the net rate of photosynthesis, the model requires a consistent solution for the net photosynthesis, stomatal conductance and the ozone deposition flux. This model was calibrated based on $O_3$ dose response functions developed in temperate and boreal ecosystems. This scheme includes a 'high' and 'low' parameterization for each PFT to represent species more sensitive and less sensitive to $O_3$ effects. The model was calibrated with data from temperate and boreal vegetation. The model has been used to explore the extent to which $O_3$ increases will limit $CO_2$-fertilization of photosynthesis and thereby reduce the ability of ecosystems to mitigate global warming (Wittig et al., 2007, 2009, Collins et al., 2010, Ainsworth et al., 2012).

### Model improvement and validation within ECLAIRE

For ECLAIRE, an update of the parameterization of $O_3$ effects on photosynthesis from Sitch et al (2007) is included using new observed dose-response relationships (CLRTAP Mapping Manual (2004), Karlsson et al., (2007)) and also the existing empirical stomatal closure formulation in JULES has been replaced by the formulation from Medlyn et al (2011), which allows easy incorporation of leaf-level measurements used to derived stomatal conductance (Gs) model parameters. Gs model parameters were derived from leaf level data from European ecosystems.

Simulations from the large-scale model JULES were compared against site simulations from the regional scale model MADOC at five ECLAIRE C3 monitoring sites and one ECLAIRE treatment site (the only site with available observations at this stage). Model output from MADOC is provided by the NERC-BAN partner. JULES simulations were performed with ECLAIRE climate and $O_3$ forcing. We performed simulations with varying $CO_2$ and $O_3$ conditions (S2) and with preindustrial $O_3$ concentrations and varying $CO_2$ concentrations (S10), the difference between these two simulations (S10-S2) shows the ozone effect. Simulations with $O_3$ include a high and a low plant sensitivity parameterization to $O_3$ uptake.

### Comparison at monitoring sites

At the two high-latitude maritime sites (Clocaenog, UK and Oldebroek, Netherlands), MADOC and JULES (S2) agree remarkably well, and simulate relatively high NPP around 350-425 gC m-2 yr-1. Both models agree on simulating lower NPP at continental (Kinkunsag, Hungary and Klausen, Austria) and high-altitude, Mediterranean (Montseny, Spain) sites, than at the maritime sites, however they diverge in absolute values. JULES tends to have lower NPP at Kiskunsag and Montseny, but higher at Klausen. The most notable difference in model simulated NPP is obtained at Kiskungsag, which is the driest of all the monitoring sites. This result agrees with earlier findings, as model simulated carbon fluxes have been shown previously to diverge markedly, due to differential representations of soil water balance and plant-soil water interactions (Morales et al 2005).

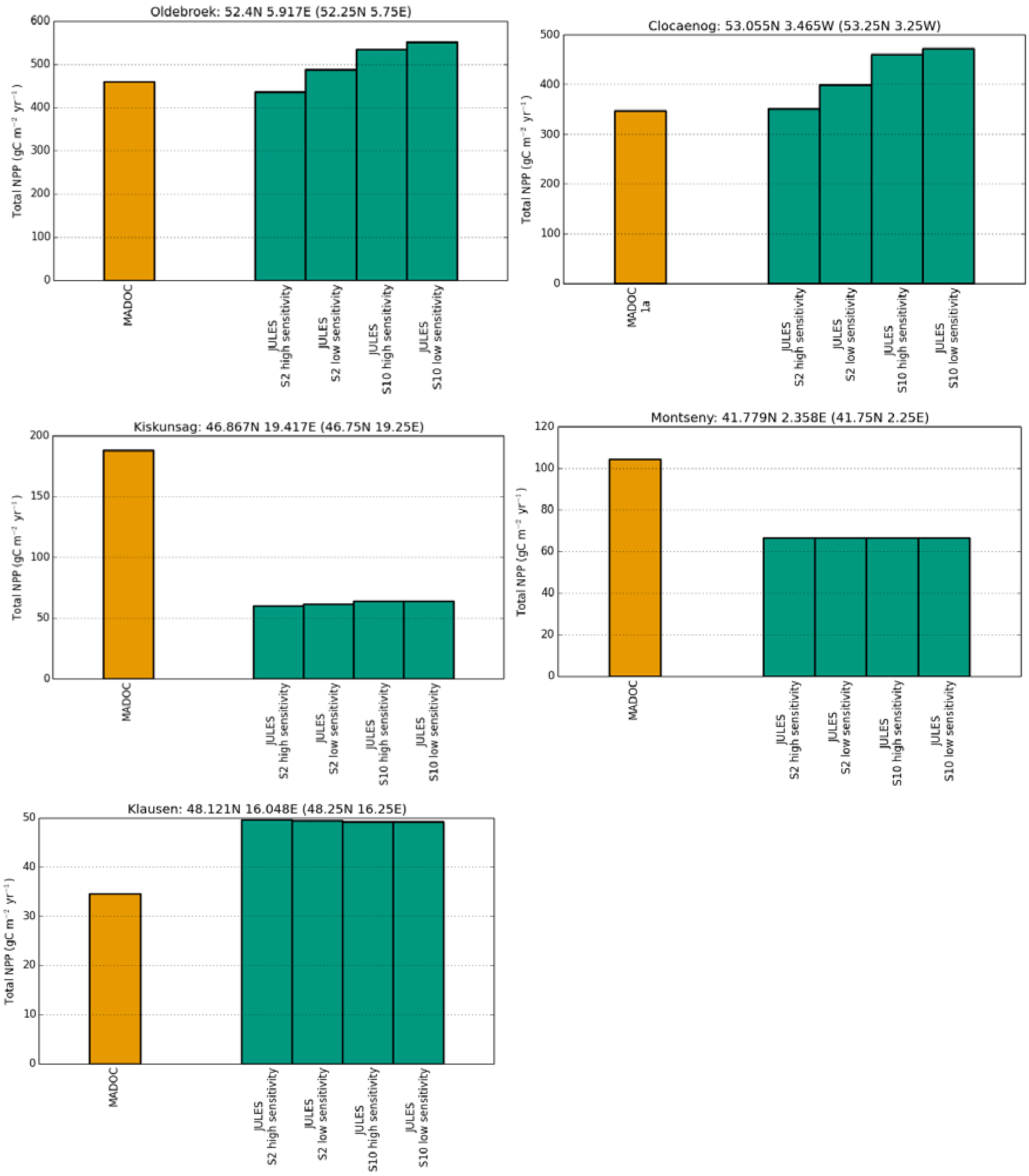


Figure 1: Comparison of JULES against MADOC simulations at five ECLAIRE C3 monitoring sites. S2 and S10 simulations include varying $CO_2$ and varying $O_3$ concentrations, and varying $CO_2$ with constant $O_3$ set at preindustrial levels, respectively.

At the high elevation alpine site in Switzerland, the observed control treatments are in reasonable agreement with the JULES S2 simulation (Figure 2). JULES simulates higher NPP than observation, and MADOC lower. At this site differential model response is likely due to their response to low annual mean, and seasonally varying temperatures, whereas the site receives the largest annual precipitation. As expected JULES simulates a reduction in NPP with ozone (S2 versus S10), with largest reductions simulated for the high sensitivity plant $O_3$ parameterization, of -13.9%, compared to a -8.6% reduction in NPP for the low sensitivity parameterization. This compares with a -5.5% and 5% change for the N4 and N54 treatments, respectively.

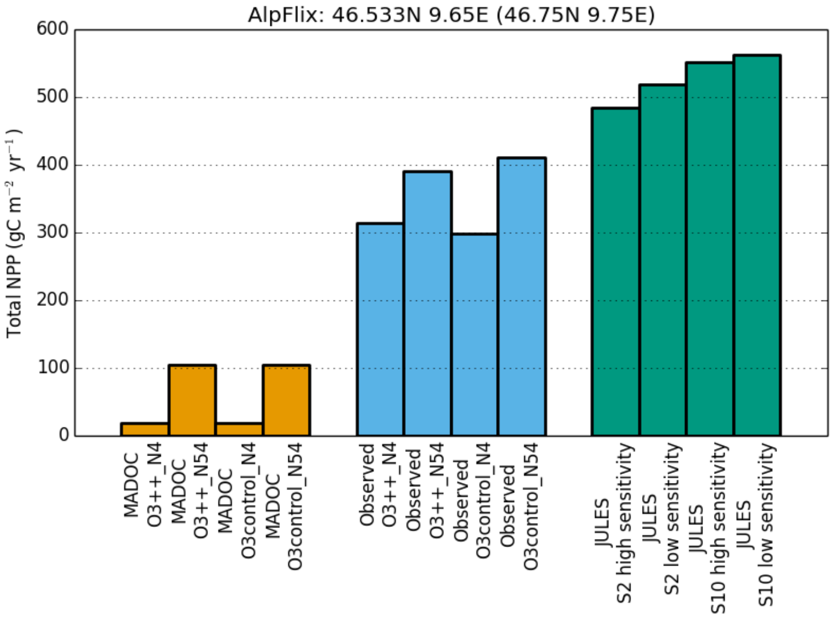


Figure 2: Comparison of JULES against MADOC simulations at one Eclaire C3 treatment site. JULES S2 and S10 simulations include varying $CO_2$ and varying $O_3$ concentrations and varying $CO_2$ with constant $O_3$ set at preindustrial levels.

## OCN

### Modelling approach

The O-CN model (Zaehle & Friend, 2010; Zaehle et al., 2011) describes the coupled terrestrial carbon and nitrogen cycles and their interactions with the terrestrial water and energy balance on a half-hourly timescale. It has been developed from the ORCHIDEE version-2 model (Krinner et al., 2005), with major modifications as the representation of photosynthesis, vegetation growth and phenology, as well as the addition of a complete nitrogen cycle representation. O-CN describes the carbon and nitrogen flows through plants, litter and soil organic matter for 13 plant functional types, accounting for N additions from biological N fixation and atmospheric Nr deposition, and N losses to leaching and emission resulting from nitrification and denitrification processes. The model is intended for studies of the global biogeochemical cycles and their interactions with the climate system and generally applied at a spatial resolution of 0.5°x0.5° or larger.

### Modelling improvement and validation within ECLAIRE

For the purpose of ECLAIRE, the boundary layer scheme was extended by the ozone deposition scheme of EMEP (Simpson et al., 2006; 2012) to simulate total surface and vegetation ozone uptake given ozone concentrations in the free, lower atmosphere, taken from a CTM (in the case of ECLAIRE, they are from EMEP), as well as the O-CN based aerodynamic and canopy conductances (Franz et al., in prep). Cumulated foliar ozone uptake is then related to the photosynthetic efficiency of the leaves, providing a feedback to leaf-level and plant gross primary and leaf-level/canopy conductance (Franz et al., in prep). We investigated several ways to translate ozone uptake into plant damage, using different meta-analyses for the reduction of growth following ozone exposure (e.g., Lombardozzi et al., 2012), as well as assessing the degree of stomatal sluggishness following ozone exposure.

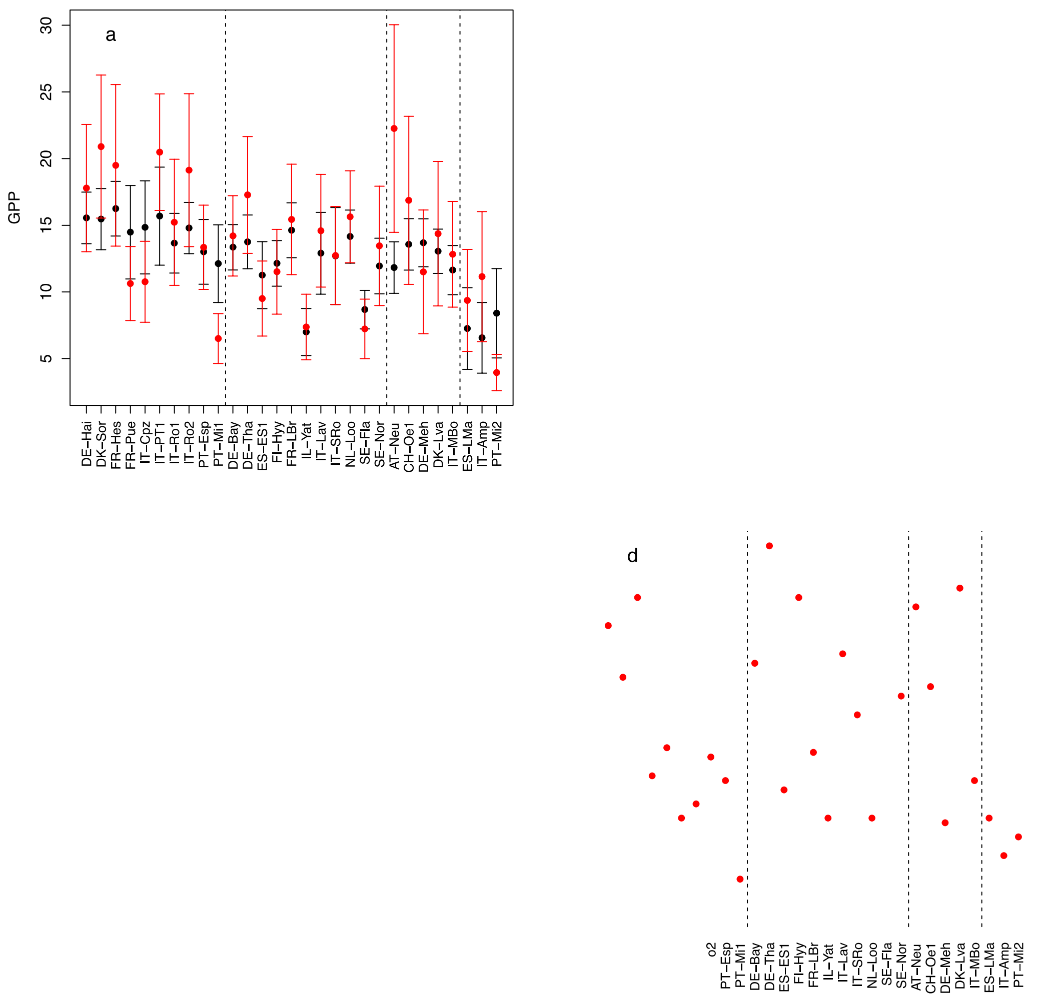


Figure 3: GPP, $G_C$, latent heat fluxes and LAI measured at 29 European FLUXNET sites (red) are compared to simulation output of OCN (black). Displayed are means and standard deviation of daily means of the measuring/simulation period for GPP, $G_C$ and latent heat fluxes. The displayed OCN LAI was calculated as the other 3 variables, the FLUXNET LAI is derived from the FLUXNET database and constitutes point measurements. The modelled values in general match the observed values well whereas the closeness of both varies from site to site.

Due to limited data being available from ECLAIRE by the time model development was complete, we assessed the performance of the model using estimates of canopy resistance as well as gross primary production for a range of European, long-term eddy-covariance based observations from the La-Thuille data base (open-access sites with sufficient quality and number of records). We found that OCN generally, but not always, captured the dynamics at these sites (Fig. 3), where some of the model-data disagreement may stem from the fact that the model was not parameterised specifically for each site.

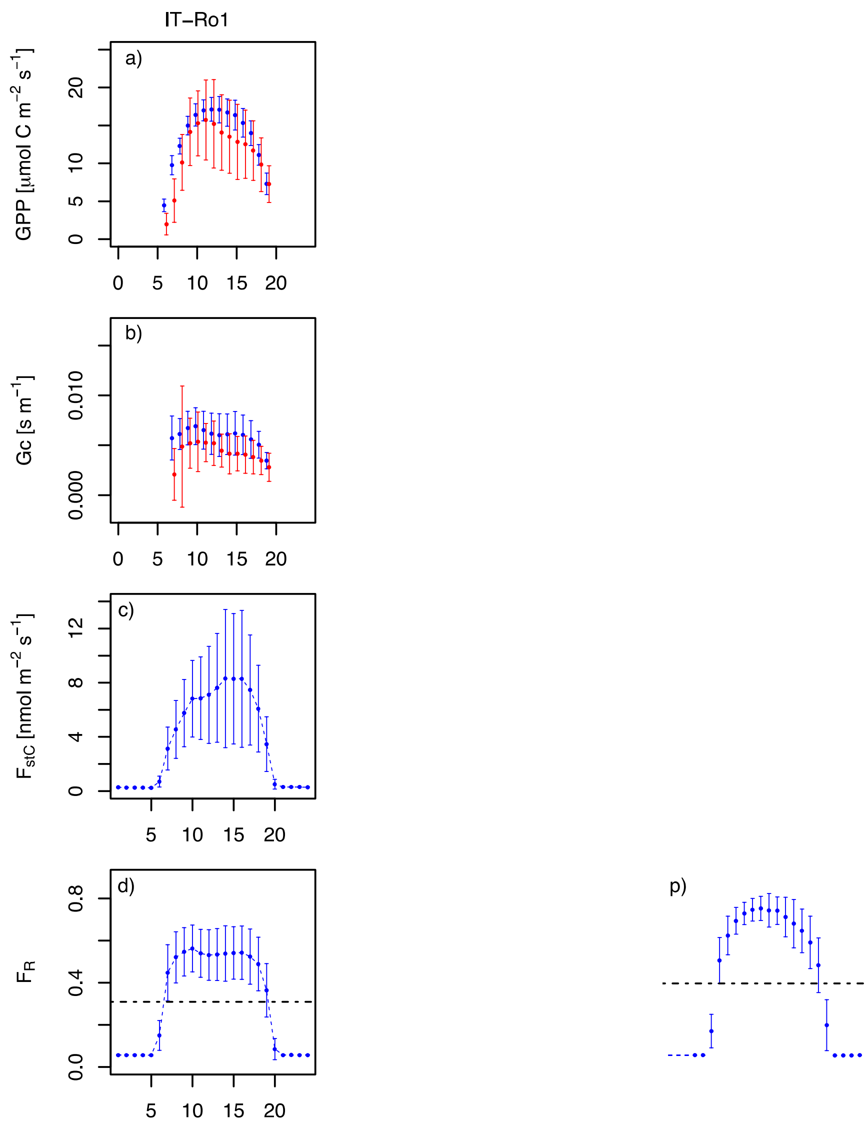


Figure 4: Simulated hourly means of July's within the simulation period of the respective sites. Simulated mean hourly values of a,g,m) GPP (blue: OCN, red: FLUXNET), b,h,n) canopy conductance ($G_C$) (blue: OCN, red: FLUXNET), c,i,o) ozone uptake ($F_{stC}$), d,j,p) the flux ratio $F_R$, e,k,q) ozone deposition velocity ($V_g$) and f,l,r) ozone surface resistance ($R_C$) for a temperate broad-leaved summergreen forest at the FLUXNET site 'IT-Ro1', a boreal needleleafed evergreen forest at the site 'FI-Hyy' and a C3 grassland 'CH-Oe1' are shown. The error bars indicate the standard deviation from the hourly mean. The dotted line in d,j,p) indicates the daily mean value.

The diurnal course of GPP and stomatal conductance were in acceptable agreement with the eddy-covariance derived measurements (see Fig. 4 for examples of a deciduous forest, evergreen forest and a grassland), lending some confidence to the simulated rates of ozone uptake, which appear in the order of magnitude reported from other studies (Franz et al., in prep). We assessed the model uncertainty in the simulated canopy-level ozone flux, and found that most of the, comparatively small uncertainty (see Fig. 5) resulted from uncertainty in the stomatal as well as non-stomatal leaf-level resistance to ozone uptake.

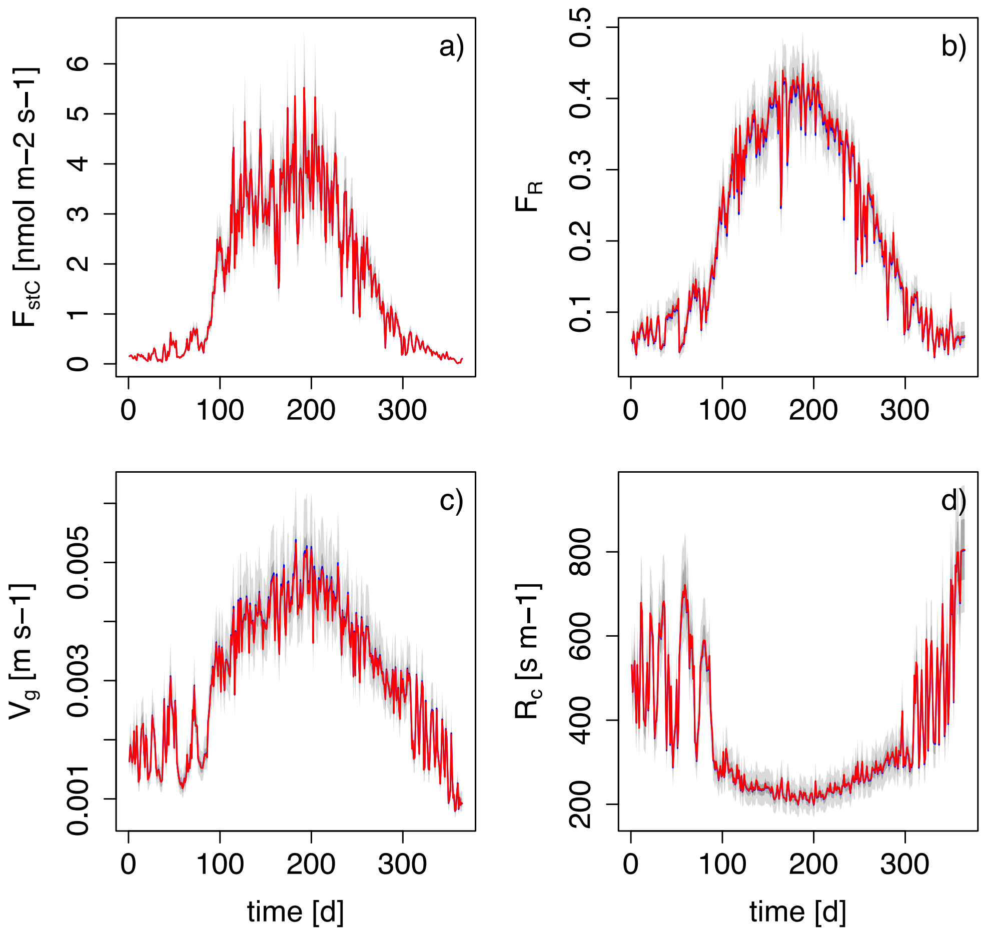


Figure 5: Ensemble range of key ozone uptake/ deposition variables. Simulated daily mean values of a) ozone uptake ($F_{stC}$), b) the ozone flux ratio ($F_R$), c) ozone deposition velocity ($v_g$) and d) ozone surface resistance ($R_c$) for a boreal needle-leafed evergreen tree species are shown. The plotted days constitute the growing season of the year 2001 at the finish FLUXNET site 'FI-Hyy'. Red: unperturbed model, blue: median of all sensitivity runs, dark grey area: interquartile-range and light grey area: min-max-range off all sensitivity runs

## LPJ-GUESS

### Modelling approach

LPJ-GUESS [Smith et al., 2014] is a dynamic global vegetation model (DGVM) that simulates dynamic vegetation response to climate, atmospheric $CO_2$ and N input through competition for light, N, and water on a daily time step. Vegetation is represented by plant functional types (PFTs) that differ in their temperature limits, phenology, shade tolerance and N requirements. Carbon uptake due to photosynthesis, autotrophic respiration and transpiration are represented in a process-based ways, and are coupled. Litter production is the basis for organic matter input to the soil, where the litter decomposes based on soil temperature, soil moisture and litter quality. Carbon and nitrogen are coupled, based on C:N ratios in different plant and soil compartments and a balance between nitrogen supply and demand. For potential natural vegetation, carbon allocation and stand dynamics (including effects of fire and stochastic mortality events such as storms) are modelled with a yearly time step. LPJ-GUESS applies forest-gap dynamic, a model feature which allows to simulate establishment, growth and mortality on an individual basis, representing age cohorts. While cohorts thus differ in age and size, individuals within a cohort are each similar. Replicate patches which are averaged account for stochastic ecosystem processes.

### Model improvement and validation within ECLAIRE

The main developments in LPJ-GUESS that were incorporated recently include (i) a coupled C-N cycle in natural ecosystems [Smith et al., 2014], representation of agricultural fields [Lindeskog et al., 2013], and a coupled CN-cycle in crop ecosystems [Olin et al., 2015b]. These improvements allow the assessment of important aspects of environmental change, for instance, how carbon and nitrogen limitation interacts under changing climate regarding development of the land carbon sink [Wårlind et al., 2014], or how climate change, nitrogen deposition and fertilisation and air quality (reg. $CO_2$) affect crops [Olin et al., 2015a].

In its current set-up, LPJ-GUESS can be configured to analyse various ecosystem services with respect to the combined impact of climate, and pollution (e.g., N-input). This aspect is currently under development and an example is shown in Fig 6, which compares different land management scenarios with their effect on crop yields, soil C balance, and N leaching. The analysis shows, that there is no real win: win situation, since in all cases a positive environmental aspect (e.g., less leaching, or higher yields, or higher C storage in soils) is confronted with a trade-off [Olin et al., 2015a]. Still, the model allows exploring these interactions under present-day and future conditions, and to ranging environments.

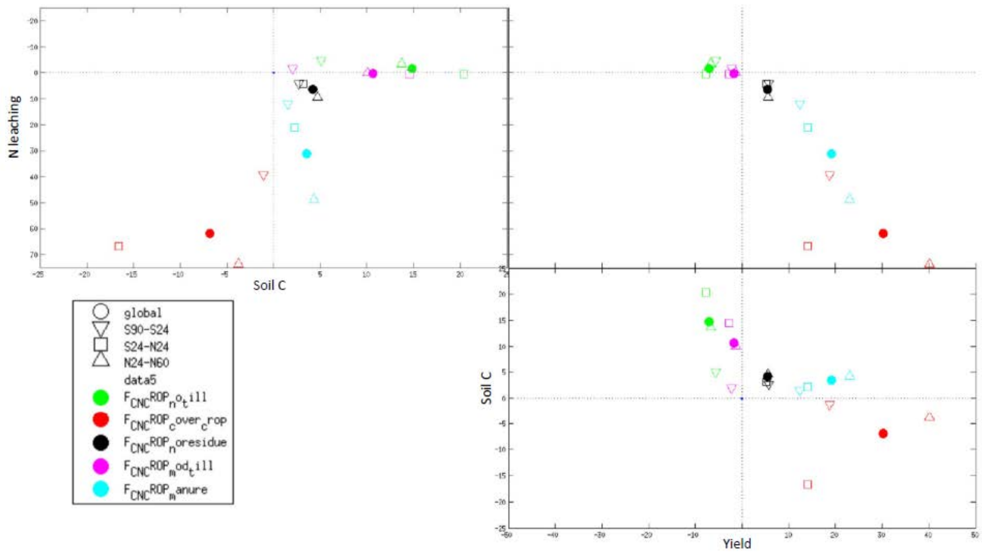


Figure 6: The simulated relative response (%) of soil carbon to management options compared to the standard setup, averaged for 1996-2005 and displayed as the global response and per climatic region. Note the reversed axes for N leaching (all axes display scales from reduced to enhanced ecosystem services).
CC: cover crops
MN: mineral fertiliser
NT: no tillage
MT: medium tillage
NT: no residue removal
Opt: optimised for C storage

Model evaluation has been performed at a number of spatial scales, and using a number of different observations. This is designed to provide a broad overview over the performance of the model with regard to interacting processes. Model evaluation includes the phenological status over the growing season, changes in C:N ratios under elevated $CO_2$ and growth and productivity, as discussed below:

Phenological status over the growing season

Phenology describes how biological stages, related to growth, change through a season in response to biotic (genetic) and abotic (weather) drivers. In the original crop version of LPJ-GUESS it had been shown that representing croplands, including sowing and harvesting, improved seasonal patterns of vegetation greenness at different locations across the African continent. Simulations of absorbed photosynthetically active radiation were compared with remotely sensed normalised differential vegetation index and the inclusion of the crop model improved the amplitude of increases and decreases of vegetation growth notably, as well as the timing of the onset of the growing season. The model did not manage to simulate localities that have two crops growing in one season (e.g. parts of Egypt), which was expected since multiple cropping has not yet been implemented [Lindeskog et al., 2013].

Recently, the crop module itself was updated with a refined phenology, and compared to a number of observations obtained at sites in The Netherlands [Olin et al., 2015b] (see Fig. 7).

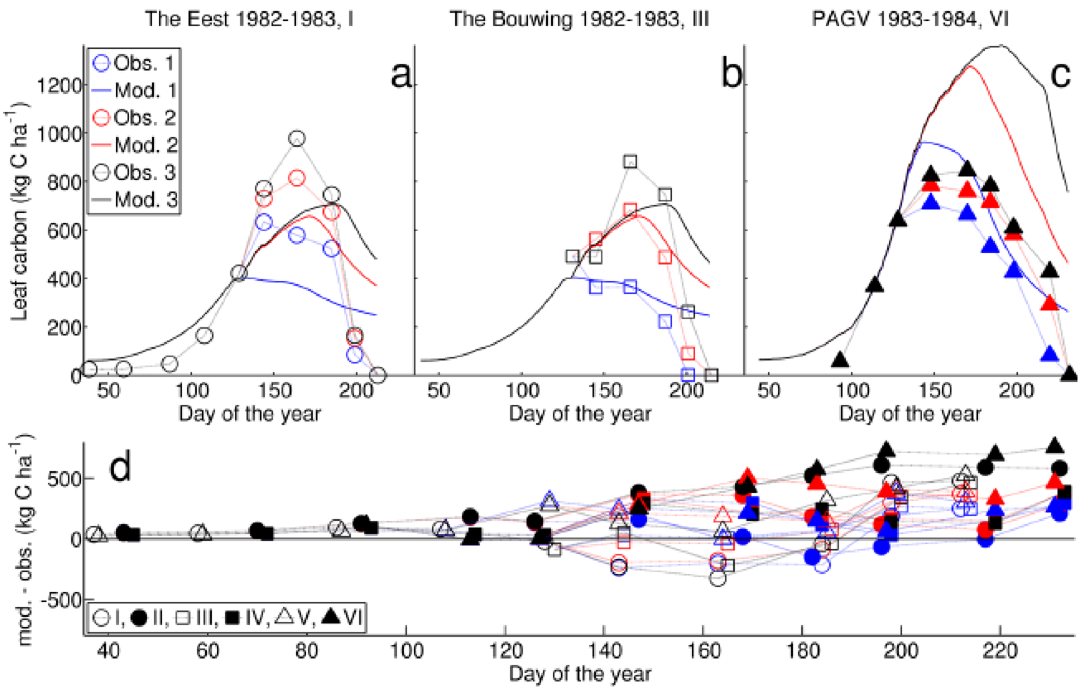


Figure 7: Observed (thin lines) and simulated (thick lines) leaf C for three crop sites for the season 1982–1983 and 1983–1984, for three example plots with different levels of N fertiliser input panels a-c). d). The difference between observed and simulated leaf C for three different levels of fertiliser application for these sites. Blue symbols indicate lowest levels of fertilisation; red represent medium and black symbols a high N fertiliser input. Open symbols are for the season 1982–83, and closed symbols are for the season 1983–84. For details see [Olin et al., 2015b].

During the growing-season, leaf C in the field trials increased until peaking around June, after which senescence commenced and leaf C decreased again (Fig. 7). Simulations with LPJ-GUESS at these sites and fertiliser schemes broadly captured these seasonal dynamics and the response to the different levels of N applications. Differences between simulated and observed leaf C values were largest towards the end of the growing-season (Fig. 7d), especially at the highest fertilised trial sites and in the second growing-season. As seen from the example time series, rates of senescence in the simulations were too slow, compared to measurements, which resulted also in underestimated dead-leaf C.

## Change in C:N ratios under elevated $CO_2$

A chief indicator for vegetation response to a changing climate or pollutant environment is how carbon and nutrient cycles interact. For natural vegetation, Smith et al. (2014) have shown that LPJ-GUESS responds realistically to constraints on C-N interactions imposed by stochiometric principles [Hungate et al., 2003; Smith et al., 2014]. Furthermore, the model applied to an experimental protocol such as the one of the Free Air Carbon Enrichment studies (FACE) showed the expected latitudinal gradient and a relatively low response in high latitudes. There, nitrogen is a limiting nutrient, and enhanced $CO_2$ alone has little to no effect on plant productivity. This is compared to tropical ecosystems where warm temperatures and relatively higher $CO_2$ concentration will foster the carboxylation-reaction of the chief photosynthetic enzyme, Rubisco [Hickler et al., 2008].

The evaluation against FACE sites was continued by Olin et al. [*Olin et al.*, 2015b] who showed that for the N-enabled version of LPJ-GUESS, under elevated [$CO_2$], increased C sequestration and yields were not balanced by grain N rising at the same rate as grain C, leading to enhanced grain C:N at elevated $CO_2$. In the observations, this increase was on average 16% for both N treatments, which was within 30% and 20% of simulated modelled increase of 24% (100%N) and 20% (50%N) (Table 1 below).

| | | Ambient $CO_2$ | | Elevated $CO_2$ | | $CO_2$ effect (%) | |
|---|---|---|---|---|---|---|---|
| | year | 100%N | 50%N | 100%N | 50%N | 100%N | 50%N |
| Modelled | 2000 | 21.7 | 16.1 | 27.9 | 20.8 | 28 | 29 |
| | 2002 | 21.0 | 17.9 | 24.1 | 21.1 | 15 | 18 |
| | 2003 | 16.1 | 13.5 | 21.5 | 15.1 | 33 | 12 |
| | 2005 | 20.3 | 15.9 | 24.6 | 19.1 | 22 | 21 |
| | mean | 19.8 | 15.9 | 24.5 | 19.0 | 24 | 20 |
| Observed | 2000 | 13.2 | 16.2 | 16.3 | 19.1 | 23 | 18 |
| | 2002 | 13.0 | 14.4 | 13.6 | 17.9 | 5 | 24 |
| | 2003 | 12.8 | 15.5 | 14.9 | 17.4 | 16 | 12 |
| | 2005 | 12.7 | 17.5 | 15.2 | 19.4 | 20 | 11 |
| | mean | 12.9 | 15.9 | 15.0 | 18.5 | 16 | 16 |
| | range | | | | | 7–26 | -3–40 |

Table 1: Comparison of modelled and observed C:N from a FACE experiment where wheat was grown in ambient $CO_2$ (_378 ppm)and elevated $CO_2$ (_548 ppm). The observed C:N where compiled, observed C values where derived from dry matter. See [Olin et al., 2015b] for details.

## Growth and productivity

An advantage of including forest-gap processes is to be able to compare model results against observations of growth and age-structure. This was done for a range of European sites, which included observations on a range of species of different plant functional type (see Fig. 8).

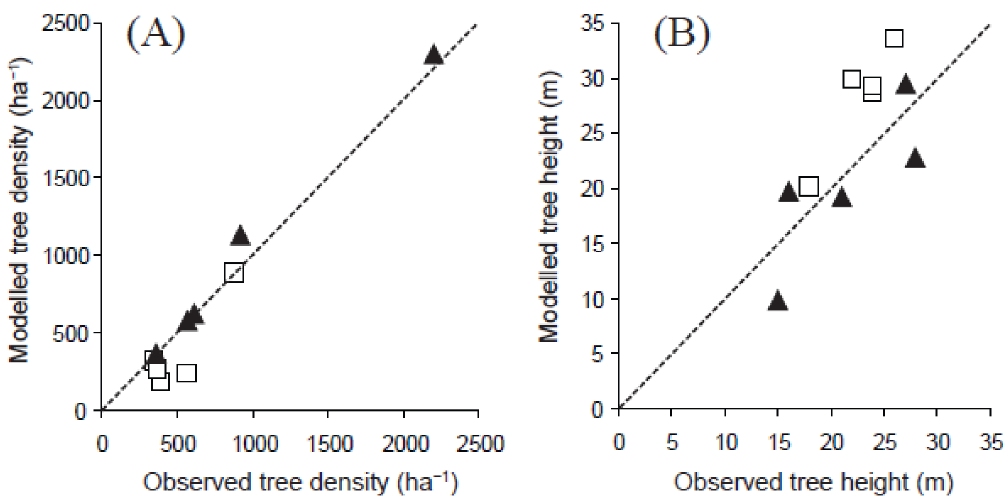


Figure 8: from [Smith et al., 2014]: Comparison of data on forest structure (A: tree density; B: height) for the CANIF European forest sites with simulation results from LPJ-GUESS. Model runs were adjusted to match the observed tree density at each site in (A). All other quantities are simulated without site-specific calibration. Open squares – broadleaf species; closed triangles – needleleaf species.

At the same time does the latest version of the model also allow assessment against other measures of productivity, such as crop yield? Figure 9 is again using the FACE experiments (see table 1) and contrast modelled and observed grain yields at different levels of N-input. The model was shown to slightly overestimate yields (by 10-20%) but the slope of yield increase at varying levels of N deposition and $CO_2$ was very close to the 1:1 line.

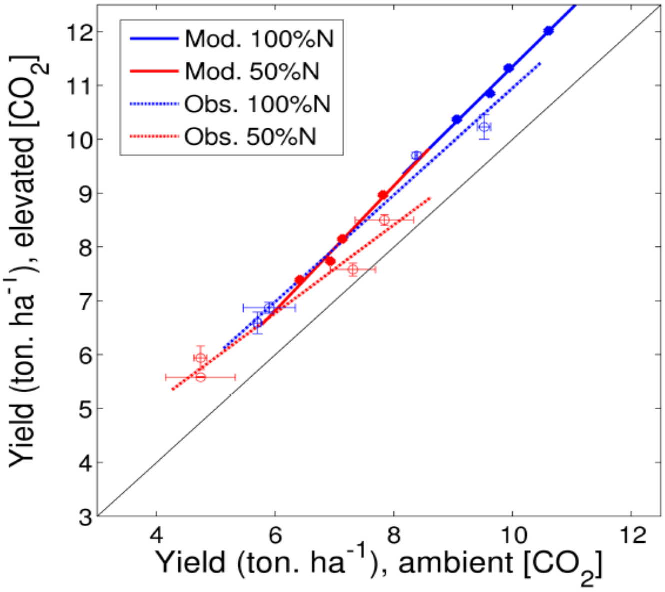


Figure 9: Effect of $CO_2$ fertilisation on observed and simulated grain yield, comparing wheat grain yields grown at elevated $CO_2$ (548 ppm) with those grown at ambient $CO_2$ (378 ppm). Simulated yields are depicted by solid lines and filled circles, observations are depicted by dashed lines and markers, shown for treatments with sufficient N fertiliser input (100%N, blue), and treatments that received half of that amount (50%N, red).

## 4. Milestones achieved:

No milestones were defined in relation to this deliverable

## 5. Deviations and reasons:

### Delay in D14.6

Deliverable 14.6 was completed with a delay of about five months. The main reason was a delay in the further development of the models including the combined interaction of both N and ozone deposition that appeared to be more demanding than originally foreseen.

## 6. Publications:

None

## 7. Meetings:

ECLAIRE plenary meetings.

## 8. List of Documents/Annexes:

None.

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