Project Number 282910

ÉCLAIRE

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

Seventh Framework Programme

Theme: Environment

D13.4 Scenario assessments of ecosystem responses to air pollution and climate change at experimental sites

Due date of deliverable: **31/09/2014 (Month 36)** Actual submission date: **04/08/2015**

Start Date of Project: **01/10/2011** Duration: **48 months**

Organisation name of lead contractor for this deliverable :
NERC (Natural Environment Research Council – Centre for Ecology and Hydrology)

Project co-funded by the European Commission within the Seventh Framework Programme		
Dissemination Level		
PU	Public	X
PP	Restricted to other programme participants (including the Commission Services)	☐
RE	Restricted to a group specified by the consortium (including the Commission Services)	☐
CO	Confidential, only for members of the consortium (including the Commission Services)	☐

Rowe EC, Hayes F, Sawicka K, Mills G & Evans CD (2015) ECLAIRE Deliverable 13.4: Scenario assessments of ecosystem responses to air pollution and climate change at experimental sites.

1. Executive Summary

A modelling study was carried out to assess the interacting effects of ozone and nitrogen (N) pollution and climate change. The MADOC model, originally developed to simulate effects of acid and N pollution, was extended early on in the ECLAIRE project by incorporating effects of ozone on plant productivity and on the translocation of N out of leaves before senescence. These effects were included as functions derived from empirical observations. Testing of the ozone-sensitive version of MADOC was described in a previous report (Deliverable 13.4). In the current report, the model was used to explore the effects of air pollution and climate change at two sites, Gårdsjön (Sweden) and Whim (UK). The model was first calibrated to key observations at the sites, such as mineral N flux, dissolved organic carbon flux, and soil total C/N ratio. Simple scenarios were then imposed from 2020, increasing mean annual temperature by +2 ºC or +4 ºC, and increasing and/or decreasing N and ozone pollution by +/- 20%.

The main effects of ozone and N pollution are broadly opposite. Nitrogen stimulates productivity in N-limited semi-natural ecosystems, whereas the major effect of ozone is to decrease productivity. These effects were well-illustrated by the model: for example, a 20% increase in N at Gårdsjön for ten years increased NPP by 5%, whereas a 20% increase in ozone at Gårdsjön for ten years decreased NPP by 2%. It is important to recognise that productivity is correlated with several ecosystem services (agricultural and forest production, and carbon sequestration) but is often inversely correlated with biodiversity, for example because species typical of infertile environments tend to be more scarce. Productivity changes are therefore likely to be valued differently by different societal actors.

Increased productivity is clearly not of universal benefit, and the effects of ozone beyond those on NPP also need to be considered. Although decreasing productivity is ostensibly beneficial for biodiversity, and ozone could be seen as mitigating the damage to biodiversity caused by N, this mitigation is likely to be partial. Sensitive plant and animal species may be affected directly by ozone as well as by N, and an environment chronically polluted by both of these atmospheric pollutants is likely to be impoverished. Effects of climate change (increase in mean annual temperate) were similar to the effects of N pollution, with direct impacts on NPP, and also through increased N mineralisation and availability. As with the other pollutants, broad effects simulated via impacts on NPP are unlikely to represent all likely changes, since many species will be unable to adapt to the changed climate at a particular site. Despite these limitations and subtleties, the modelling approach taken proved useful in illustrating the major effects of air pollution and climate change on ecosystems.

2. Objectives:

The main aim of Work Package 13 was to develop existing dynamic vegetation models to better simulate the impacts of different air pollutants on plant growth and competition, and feedbacks on ecosystem carbon cycling. This was achieved via:

- Reviewing models that could be applied or adapted to simulate air pollution impacts, in particular combined impacts of ozone and N;
- Assessing data requirements for these models and determining which could realistically be applied;
- Adapting and improving the selected models;
- Collating data for setting up and testing the models;
- Assessing model performance against empirical data;

- Exploring effects of ozone and N pollution on key ecosystem processes and functions using the models.

Most of these objectives were attained earlier in the project and reported in Rowe et al. (2015). The current report focuses particularly on the last of these objectives, i.e. exploring the sensitivity of key ecosystem processes and functions to ozone and N pollution scenarios.

3. Activities:

3.1 Model identification and development

An extensive set of models was initially proposed for use within WP13. Following an assessment of data requirements and availability, this set was reduced to three models: DO3SE, MADOC and VSD+/CSR, as described in ECLAIRE Deliverable report 13.3. The DO3SE model is not suitable for ecosystem modelling since it is focused on leaf-scale processes (see Deliverable report 13.3). Development of the VSD+/CSR model has also focused on leaf-level processes (Kramer et al., in prep) and runs have not been attempted for the ECLAIRE experimental sites. The current report therefore uses the MADOC model (Rowe et al., 2014) to explore ecosystem responses to pollution scenarios.

The MADOC model was modified to incorporate two effects of increased ozone concentrations: a reduction in Net Primary Productivity (NPP); and early leaf senescence, resulting in reduced resorption of N and therefore a greater concentration of N in leaf litter. Response functions were obtained by relating empirical observations of the relative strength of these effects to measured ozone concentrations (Equations 1 and 2).

$$NPP_{red} = 1 - \beta cO_3 \quad [1]$$

$$Ret_{red} = 1 - 0.0077cO_3 \quad [2]$$

where NPP_{red} is the relative reduction in net primary production, which is applied in the MADOC model following calculation of the effects of temperature, water and nutrient availability; β has the value of 0.0022 for trees and heathland vegetation, 0.0019 for wet grassland and bog, or 0.0063 for dry grassland; cO_3 is the daytime growing-season ozone concentration in nL L^{-1}, and Ret_{red} is the relative reduction in N retention in leaves before senescence.

The revised MADOC model was tested against data from a set of 15 experimental and long-term monitoring sites (Table 1, Figure 1). This testing was described in Rowe et al. (2015) and will not be repeated here. The current report focuses on two particularly data-rich sites:

a) The set of catchments at Gårdsjön, Sweden, which were subjected to N addition and removal (via catchment roofing and substitution of artificial 'clean' rain) treatments;
b) The N addition experiment at Whim, Scotland, UK, which has been subjected to N addition in wet oxidised, wet reduced, and dry reduced forms.

Table 1. Summary of sites used for testing the MADOC model. Long. = Longitude, degrees; Lat. = Latitude, degrees; Alt. = altitude, m above sea level; Precip. = mean annual precipitation, mm yr^{-1}; Temp. = mean annual temperature, ºC; Factors = N and/or ozone factors used in the current study; "Monitoring" refers to sites without treatments, or where only control treatment data were used. Coordinates are presented approximately for sites where the landowner may be sensitive about revealing the site location.

Site	Country	Long.	Lat.	Alt.	Precip.	Temp.	Vegetation	Factors (N or O_3)
AlpFlix	Switzerland	9.650	46.533	2000	1300	1.1	Grassland	N, O3
Clocaenog	UK	-3.465	53.055	492	995	7.5	Heathland	Monitoring
Gårdsjön	Sweden	12.500	58.050	130	685	9.1	Conifer Forest	N
Glensaugh	UK	-2.6	56.9	300	1530	7.8	Grassland (Moorland)	Monitoring
Grizedale	UK	-3.0	54.3	115	1920	9.6	Broadleaf Forest	Monitoring
Kiskunsag	Hungary	19.417	46.867	108	572	10.5	Steppe / Broadleaf Forest	Monitoring
Klausen	Austria	16.048	48.121	515	768	7.6	Broadleaf Forest	Monitoring
Ladybower	UK	-1.8	53.4	265	1265	10.5	Coniferous forest	Monitoring
Llyn Brianne	UK	-3.7	52.1	450	2020	10.1	Coniferous forest	Monitoring
Montseny	Spain	2.358	41.779	720	870	9.5	Heathland / Broadleaf Forest	Monitoring
Moor House	UK	-2.4	54.7	540	1930	6.1	Grassland (Moorland)	Monitoring
Oldebroek	Netherlands	5.917	52.400	25	940	10.8	Heathland	Monitoring
Solling	Germany	9.500	51.667	508	1100	7.3	Coniferous forest	Monitoring
Sourhope	UK	-2.2	55.5	495	1280	7.7	Grassland	Monitoring
Whim	UK	-3.272	55.766	288	1090	7.7	Bog	N

Figure 1. Locations of monitoring and experimental sites used for testing the MADOC model.

3.2 Air pollution and climate change scenarios

Detailed scenarios for the spatial distribution of ozone and N under different socioeconomic scenarios were not available for use in preparing the current report. Scenarios were instead based on the central EMEP scenario (Current Legislated Emissions, CLE). The impacts of two combinations of drivers were assessed.

Firstly, combinations were made of total N deposition rate and ozone concentration, in both cases either maintained at the CLE level, increased by 20% or decreased by 20%, resulting in nine scenarios. In reality it is unlikely that exposure to one of these pollutants will increase while exposure to the other decreases (since nitrogen oxides contribute to the formation of tropospheric ozone), but these scenarios are useful to illustrate the distinct effects of the two pollutants.

Secondly, combinations were made of mean annual temperature and ozone concentration. Mean annual temperature was assumed to increase by 0 ºC, 2 ºC or 4 ºC. Ozone concentration was either maintained at the CLE level, increased by 20% or decreased by 20%, resulting in nine further scenarios.

4. Results:

4.1 Comparison of predictions with observations

Detailed and long-term measurements related to stream chemistry and C and N cycling at the Gårdsjön experimental catchments are shown in Figure 2, along with MADOC model predictions. The model was well able to reproduce changes in solution chemistry due to the decline in acid deposition at the site since the 1990s.

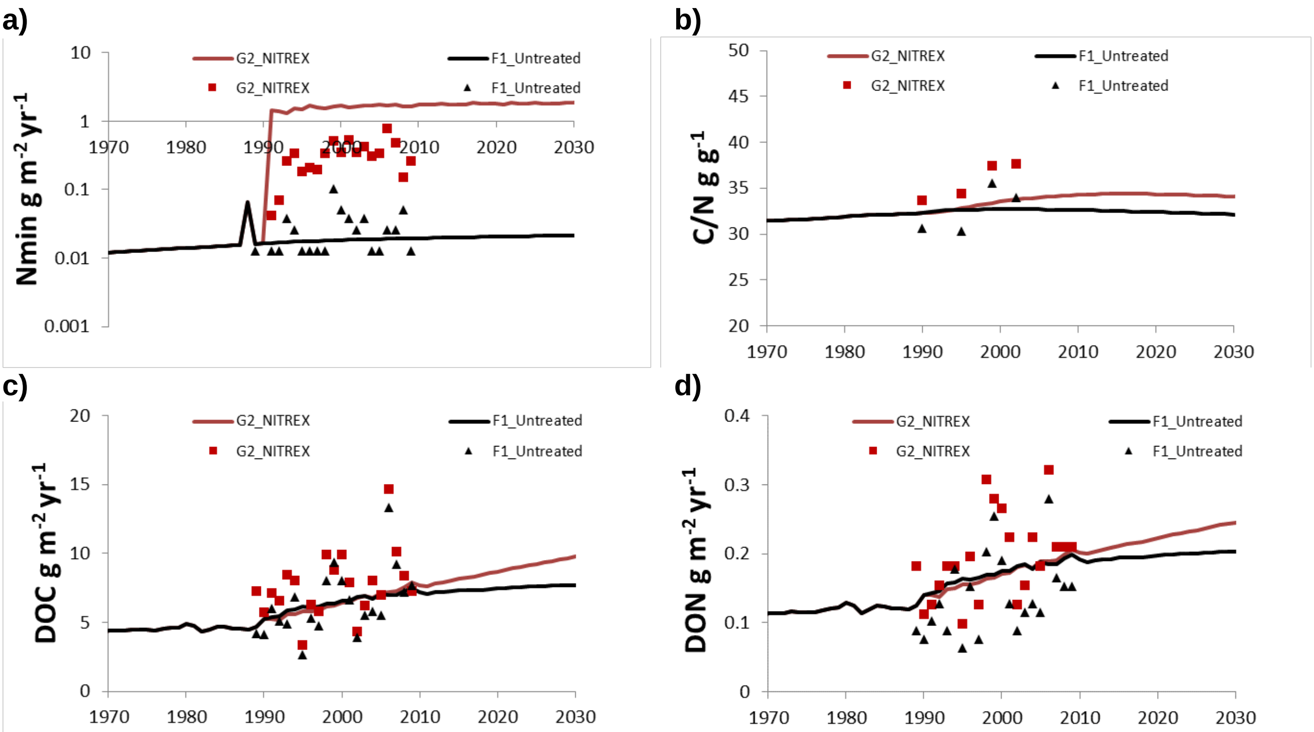

Figure 2. Observed effects (symbols) of two rain chemistry treatments at the Gårdsjön site: G2 Nitrex (nitrogen addition; red) and F1 Untreated (untreated; black), and equivalent results simulated by the MADOC model (lines): a) mineral N leaching flux; b) soil total carbon / nitrogen ratio; c) dissolved organic carbon (DOC) leaching flux; and d) dissolved organic nitrogen (DON) leaching flux.

Fewer measurements suitable for model testing were available from the Whim experimental site. The model was not quite able to attain the very large observed dissolved organic carbon (DOC) flux and consequent extremely low measured pH value measured at the site, but was able to reproduce the soil C/ N ratio (Figure 3).

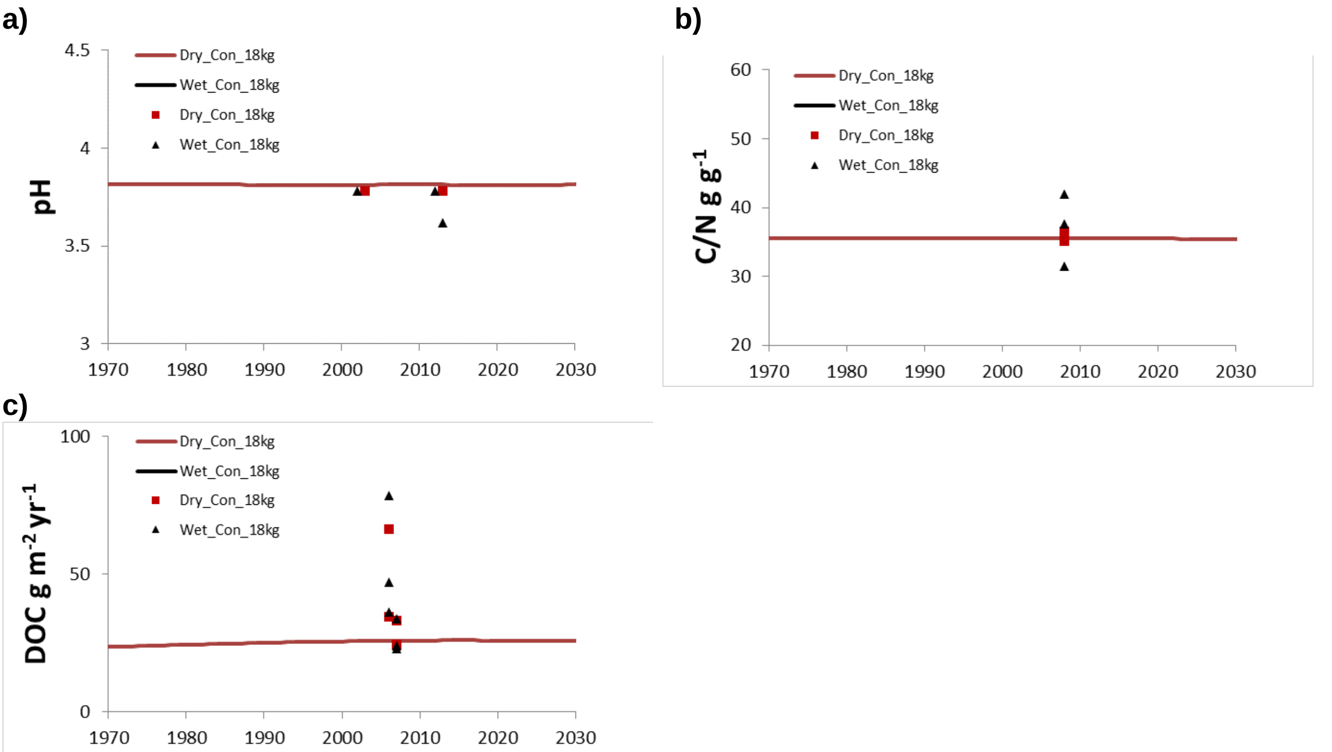

Figure 3. Measurements (symbols) from the two treatments at the Whim site that did not receive experimental N applications (these were control treatments in the 'wet' and 'dry' experiments), and equivalent results simulated by the MADOC model (lines; the line for 'Dry control' is identical to, and behind, the line for 'Wet control'): a) soil solution pH; b) soil total carbon / nitrogen ratio; and c) dissolved organic carbon (DOC) leaching flux.

The MADOC model has not been tested extensively against data from ozone addition and ozone-nitrogen interaction experiments, due to the scarcity of such data. However, the responses to ozone were derived from empirical data, and the simulated responses and interactions are the best basis currently available for assessing and predicting interactive responses to ozone and nitrogen.

4.2 Scenario analyses

The modelled responses of key ecosystem properties and processes to air pollution and climate change scenarios are shown in Figure 4 to Figure 6. The addition of N had a large effect on the flux of plant-available N at Gårdsjön, showing the importance of N limitation in this modelled system (Figure 4). Less effect of N addition on N leaching was observed, since plants took up most of the extra N. However, the increased plant N uptake led to substantial increases in plant productivity (NPP) and carbon storage. Ozone had a comparatively small effect, although this was not insignificant, particularly for processes that are directly mediated by plants such as NPP and C storage.

The simulated effects of interacting pollutants at Whim were less dominated by N (Figure 5), suggesting that the system was less N-limited. Although N addition had clear effects on plant-mediated processes, the effects of productivity limitation by ozone were also apparent. This limitation of productivity had knock-on effects on C storage and on DOC production.

The effects of climate change, simply imposed as +2 ^{o}C or +4 ^{o}C scenarios, were substantial (Figure 6), although in the model these were not so much due to direct effects on plant growth as to effects on N mineralisation. Increased temperatures led to decomposition and release of N from the more labile soil pools. These resulted in boosts to growth, but these were mainly short-lived, and NPP responses had largely ceased after 10 years. Effects on soil C decomposition were more substantial, leading to a sustained loss of C storage with increased temperature.

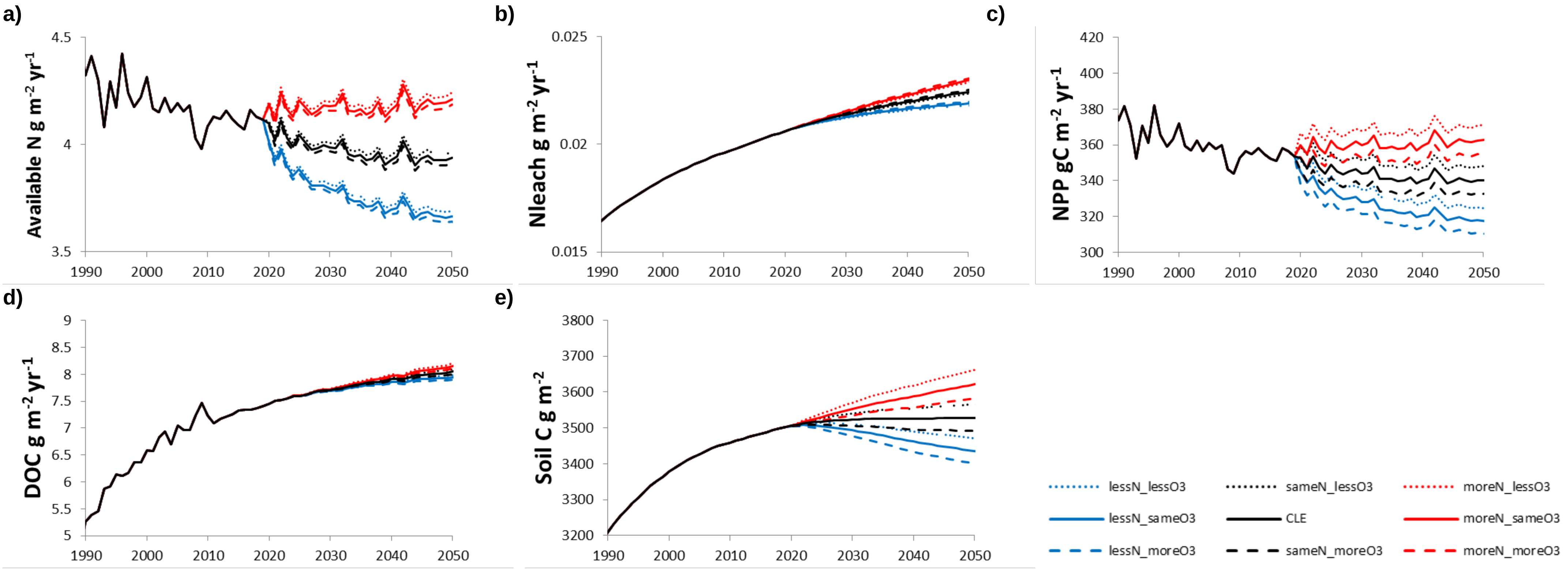

Figure 4. Effects of different ozone and nitrogen (N) pollution scenarios imposed from 2020 on key ecosystem properties and processes at the Gårdsjön experimental site, Sweden, as simulated using the MADOC model. The solid black line represents ozone and N exposure with Current Legislated Emissions (CLE), as simulated using the CBED model. Different rates of N deposition are represented by colour (blue = decreased 20%, red = increased 20 %), and different ozone concentrations by line type (dotted = decreased 20%; dashed = increased 20%). Effects are shown of these scenarios on a) plant-available N; b) N leaching; c) Total (above- and below-ground) net primary plant production (NPP); d) dissolved organic carbon (DOC) leaching flux; e) soil total carbon stock.

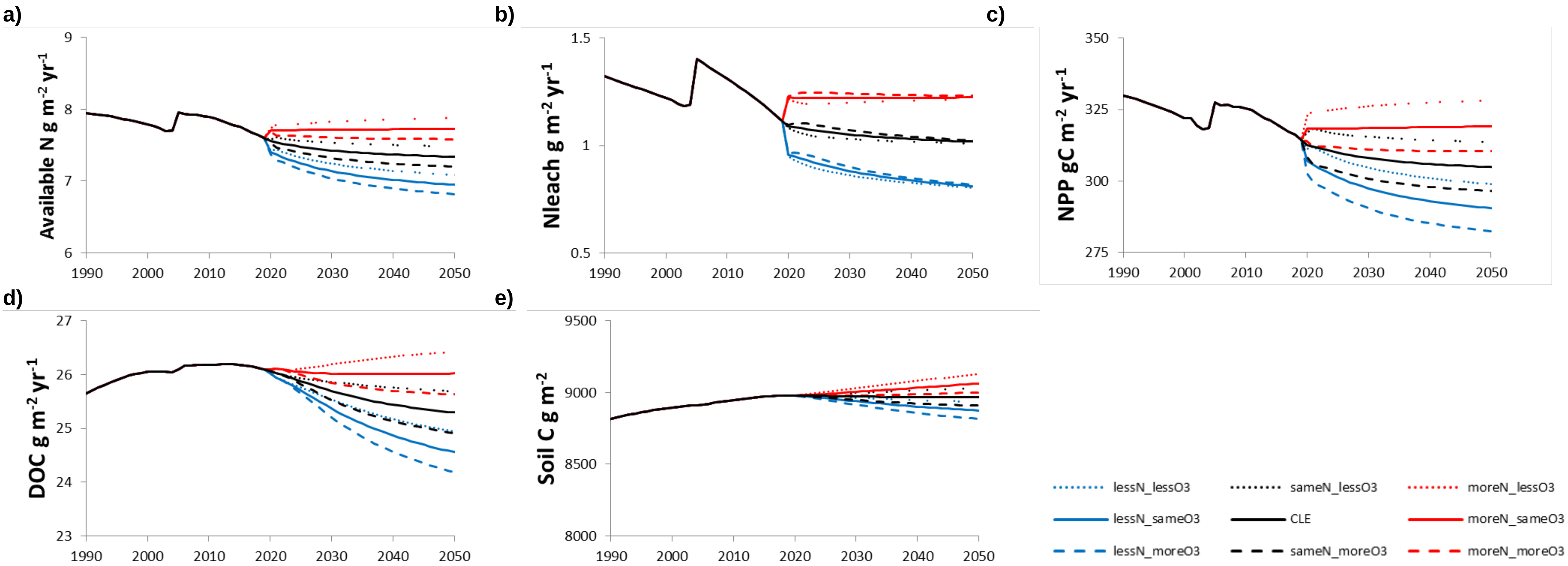

Figure 5. Effects of different ozone and nitrogen (N) pollution scenarios imposed from 2020 on key ecosystem properties and processes at the Whim experimental site, UK, as simulated using the MADOC model. The solid black line represents ozone and N exposure with Current Legislated Emissions (CLE), as simulated using the CBED model. Different rates of N deposition are represented by colour (blue = decreased 20%, red = increased 20 %), and different ozone concentrations by line type (dotted = decreased 20%; dashed = increased 20%). Effects are shown of these scenarios on a) plant-available N; b) N leaching; c) Total (above- and below-ground) net primary plant production (NPP); d) dissolved organic carbon (DOC) leaching flux; e) soil total carbon stock.

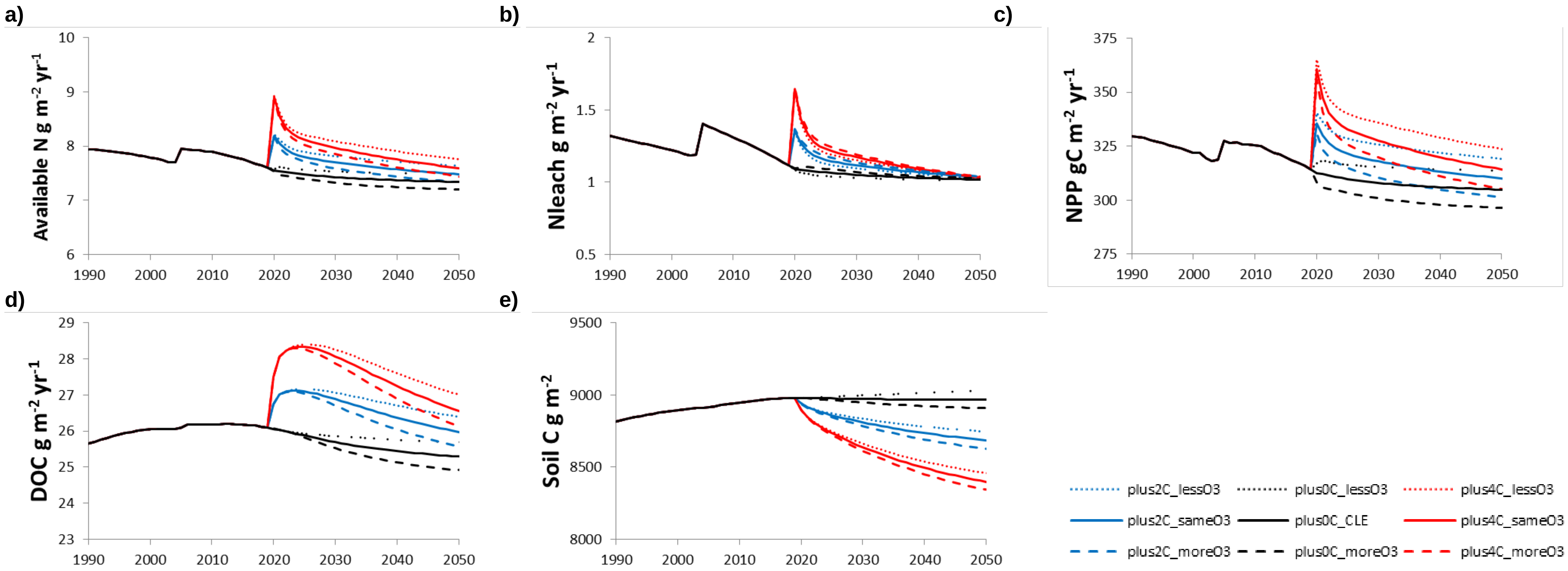

Figure 6. Effects of different ozone pollution and temperature scenarios imposed from 2020 on key ecosystem properties and processes at the Whim experimental site, UK, as simulated using the MADOC model. The solid black line represents ozone and N exposure with Current Legislated Emissions (CLE), as simulated using the CBED model. Different rates of N deposition are represented by colour (blue = decreased 20%, red = increased 20 %), and different ozone concentrations by line type (dotted = decreased 20%; dashed = increased 20%). Effects are shown of these scenarios on a) plant-available N; b) N leaching; c) Total (above- and below-ground) net primary plant production (NPP); d) dissolved organic carbon (DOC) leaching flux; e) soil total carbon stock.

4.3 Discussion

Empirical evidence for the effects of ozone on semi-natural ecosystems is sparse. Modelling studies can be useful in that they provide a focus for developing quantified theory; improve understanding of effects and interactions and highlight key areas of current ignorance; and illustrate effects on a variety of ecosystem properties and processes. The MADOC model had difficulty attaining the extremely low pH values observed at Whim, but otherwise proved capable of simulating a wide variety of ecosystems.

The ecosystem properties that are illustrated in the plots and scenarios presented here are important to people in several ways. Carbon stored within soils may be cycled back into the atmosphere over decade to century timescales, so soil C stock should not be seen as equivalent to geosphere carbon, but the storage of C within soil may provide some temporary mitigation for human fossil fuel use. Losses of DOC are increasingly recognised as important to the overall soil C budget. The flux of DOC is also an important disbenefit, increasing water treatment costs. This is in part for cosmetic reasons (consumers tend to find brown water unpalatable) but DOC can also contribute to the mobilisation and transport of toxic pollutants such as heavy metals, so needs to be removed. Leaching of mineral N, especially nitrate, is also an important factor governing water quality and treatment costs. However, nitrate leaching is not commonly observed in semi-natural systems and remains mainly a problem of improved agriculture.

The simulated interactions of nitrogen, ozone and climate change can be simplified as mainly related to changes in plant productivity (NPP). Many semi-natural ecosystems are N-limited, so NPP will be increased by N pollution. Ozone will have a generally opposite effect. Although the productivity of an ozone-tolerant species may increase at greater ozone concentrations if it is released from competition with a more sensitive species, in general ozone is a toxic pollutant which interferes with the photosynthetic mechanism and so decreases NPP. Temperature increases have a small positive effect on simulated NPP, but this is outweighed and obscured by the substantial effects of increased temperature on soil organic matter mineralisation. In an N-limited system, the resultant release of mineral N will have a substantially greater effect on NPP than temperature rise *per se*.

Viewing N, ozone and climate change impacts through the lens of NPP does not however obviate the need for careful consideration of messages. Increased productivity is associated in many people's minds with ecosystem benefits. Extra forest and agricultural production are undoubtedly beneficial, and extra C storage is arguably beneficial. However, there is a critical tradeoff in that increased productivity in semi-natural systems is strongly associated with species loss. Extra plant growth results in faster closure of vegetation gaps and less light availability at ground level. This is a major reason for widespread biodiversity loss (Hautier et al., 2009; Hodgson et al., 2014).

Effects of climate change on species and biodiversity are difficult to predict, involving not only changes to the local environment, but rates of species extinction and dispersal. Broadly, species richness is greater in warmer environments, but increased temperatures in northern latitudes and at high altitudes are likely to lead to the loss of specialised species.

Even if the tradeoff between productivity and biodiversity is fully recognised, it would be simplistic to say that since ozone and N pollution have broadly opposite effects on productivity, one mitigates the impact of the other. The mechanism whereby extra growth and litterfall causes species loss is important, but it is not the only one whereby ozone and N pollution cause damage. The direct impacts of even extremely low N concentrations on sensitive species are now well-understood (Cape et al., 2009). Impacts of ozone on sensitive species have been observed less often, but this may be due to the difficulties with attributing causation to ozone, which is inherently more variable in space and time than nitrogen pollution. It is clear that some ecosystem functions could be maintained in a highly N-polluted and ozone-polluted environment, with tolerant species responding to the N and not being affected too greatly by the ozone. However, it is also clear that many species are not tolerant of such conditions, and a more N- and ozone polluted environment would be a more impoverished one.

5. Milestones achieved:

M56 (due Month 6, 31/03/2012) Identification of priorities for model development. Completed on time.
M57 (due Month 12, 30/09/2012) Collation of preliminary data from experimental sites for initial model application. Completed on time.
M58 (due Month 18, 31/03/2013) Initial application and testing of integrated models. Completed 05/04/2013, as described in Deliverable 13.2 report.
M59 (due Month 24, 30/09/2013) Update of experimental datasets, completed testing of site-based and regional-scale models. Completed 31/03/2015, as described in Deliverable 13.3 report.
M60 (due Month 36, 31/09/2014) Scenario assessments of ecosystem responses to air pollution and climate change at experimental sites. Completed 04/08/2015, as described in the current report.

6. Deviations and reasons:

Initial deviations were minor, but later reports have been considerably delayed. Completing the collation of data was delayed due to the identification of additional sites, and of new data that had not yet been included in the NITROEUROPE or ECLAIRE databases. The finalisation of an ozone-responsive version of the MADOC model was delayed due to the need to incorporate response functions derived from the data-mining exercise. These functions did not become available until June 2014. The process of setting up and testing the models was more time-consuming than anticipated, and the VSD-CSR model was not completed in time for application to ecosystem surveys and experiments. However, the development of an ozone-sensitive version of MADOC was successful. The original MADOC model was published in a peer-reviewed journal early in the ECLAIRE project, and the results of the testing of the ozone-sensitive version are currently being finalised for a journal manuscript.

7. Publications:

Rowe EC, Sawicka K & Evans (2013) MADOC – update on progress. Presentation at ECLAIRE conference, Zagreb, Croatia, 22-24 October 2013.
Rowe EC, Sawicka K & Evans (2013) MADOC – ozone response functions and sensitivity analyses. Presentation at ECLAIRE conference, Zagreb, Croatia, 22-24 October 2013.
Rowe EC (2013) Biodiversity endpoints. Presentation at ECLAIRE conference, Zagreb, Croatia, 22-24 October 2013.
Emberson LD, Bueker P, Briolat A. (2013) DO_3SE – update on progress. Presentation at ECLAIRE conference, Zagreb, Croatia, 22-24 October 2013.
Emberson LD, Bueker P, Briolat A. (2013) DO_3SE – Using DO_3SE as an analytical tool for experimental studies. Presentation at ECLAIRE conference, Zagreb, Croatia, 22-24 October 2013.
Rowe EC, E Tipping, Davies J, Monteith DT & Evans CD (2014) Towards an understanding of feedbacks between plant productivity, acidity and dissolved organic matter. Oral presentation, European Geosciences Union conference, Vienna, Austria, 28 April - 2 May 2014.
Rowe EC, Tipping E, Posch M, Oulehle F, Cooper DM, Jones TG, Burden A, Hall J & Evans CD (2014) Predicting nitrogen and acidity effects on long-term dynamics of dissolved organic matter. *Environmental Pollution* 184: 271-282.
Emberson LD, Bueker P, Briolat A. (2014) The use of DO_3SE in seasonal crop forecasting. Meeting at JRC, ISPRA. Italy. Nov 2014.
Evans C, Hayes F, Sawicka K, Mills G & Rowe E (2014) Ecosystem responses to nitrogen and ozone simulated by MADOC. Presentation at ECLAIRE conference, Budapest, Hungary, 29 Sept - 2 Oct 2014.
Rowe E, Sawicka K, Hayes F & Evans C (2014) MADOC. Presentation at ECLAIRE conference, Budapest, Hungary, 29 Sept - 2 Oct 2014.

Rowe E, Hayes F, Sawicka K, Mills G & Evans C (2014) Modelling ozone impacts in the UK and elsewhere. Oral presentation, Joint Expert Group on Dynamic Modelling (15th Meeting), Sitges, Spain, 28-30 October 2014.

Rowe EC (2015) Humus and humility in ecosystem model design. Abstract for European Geosciences Union conference, Vienna, Austria, 13-16 April 2015.

Rowe EC, Hayes F, Sawicka K, Mills G, Jones L, Moldan F, Sereina B, van Dijk N & Evans C (2015) Ecosystem-scale trade-offs between impacts of ozone and reactive nitrogen. Abstract for European Geosciences Union conference, Vienna, Austria, 13-16 April 2015.

Emberson LD, Bueker P, Briolat A. (*in prep*.). The incorporation of multiple stresses (O3 and N) on plant growth using process based methods within the DO_3SE model. *Global Change Biology*.

Rowe EC, Sawicka K, Hayes F, Mills G, Albert KR, Bassin S, Sheppard LJ & Evans CD (*in prep.*) Predicting integrated effects of nitrogen and ozone on plant productivity and carbon storage. *Environmental Pollution*.

Sawicka K, Rowe EC, Monteith DT, Vanguelova E, Wade AJ & Clark JM (*in prep.*) Modelling past, current and future trends in soil water dissolved organic carbon. *Science of the Total Environment*.

Kramer K, Bijlsma RJ, Bonten LTC, Reinds GJ, de Winter W & de Vries W (*in prep*.) Sensitivity analyses of the interactions between climate change, nitrogen deposition and atmospheric ozone on plant growth. *Environmental Pollution*.

8. Meetings:

- ECLAIRE conference, Zagreb, Croatia, 22-24 October 2013. Development of MADOC presented.
- European Geosciences Union conference, Vienna, Austria, 28 April - 2 May 2014. Development of MADOC presented.
- ECLAIRE conference, Budapest, Hungary, 29 Sept - 2 Oct 2014. Development of and results from ozone-sensitive version of MADOC presented.
- 15th Meeting of the Joint Expert Group on Dynamic Modelling under the Working Group on Effects, Sitges, Spain, 28-30 October 2014. Development of and results from ozone-sensitive version of MADOC presented.

9. List of Documents/Annexes:

None.

References

Cape, J.N., van der Eerden, L.J., Sheppard, L.J., Leith, I.D., Sutton, M.A., 2009. Evidence for changing the critical level for ammonia. Environmental Pollution 157, 1033-1037.

Hautier, Y., Niklaus, P.A., Hector, A., 2009. Competition for light causes plant biodiversity loss after eutrophication. Science 324, 636-638.

Hodgson, J.G., Tallowin, J., Dennis, R.L.H., Thompson, K., Poschlod, P., Dhanoa, M.S., Charles, M., Jones, G., Wilson, P., Band, S.R., Bogaard, A., Palmer, C., Carter, G., Hynd, A., 2014. Leaf nitrogen and canopy height identify processes leading to plant and butterfly diversity loss in agricultural landscapes . Functional Ecology 28, 1284-1291.

Kramer, K., Bijlsma, R.J., Bonten, L.T.C., Reinds, G.J., de Winter, W., de Vries, W., in prep. Sensitivity analyses of the interactions between climate change, nitrogen deposition and atmospheric ozone on plant growth. Environmental Pollution.

Rowe, E.C., Hayes, F., Sawicka, K., Evans, C.D., Mills, G., Emberson, L., Briolat, A., Büker, P., 2015. ECLAIRE Deliverable 13.3: Report on performance of site-based and regional-scale models. . Unpublished report on ECLAIRE project. Centre for Ecology and Hydrology, Bangor, UK., p. 20.

Rowe, E.C., Tipping, E., Posch, M., Oulehle, F., Cooper, D.M., Jones, T.G., Burden, A., Monteith, D.T., Hall, J., Evans, C.D., 2014. Predicting nitrogen and acidity effects on long-term dynamics of dissolved organic matter. Environmental Pollution 184, 271-282.