Project Number 282910

ÉCLAIRE

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

Seventh Framework Programme

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D20.7: Final cost optimization scenarios for 2050 and beyond

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Dissemination Level		
PU	Public	☒
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)	☐

1. Executive Summary

An ECLAIRE optimization scenario has been developed, which is based on incremental improvements over an optimization scenario focusing on human health (the “Commission proposal”). Optimization is based on the new ECLAIRE indicator for biodiversity protection, the Habitat Suitability Index (HSI). It is able to provide the least cost measure associated with a given HSI, expressed as exceeding deposition of N and S compounds above a certain threshold. The parameter seems rather robust with respect to its exact formulation, even while levels of exceedance obviously depend on such a formulation, abatement measures derived from an optimization approach do not change. A large positive effect towards biodiversity protection is achieved already by health-related measures that are part of a current Commission proposal, such that about 1% extra cost cover 75% of the emission reductions available.

While the above implies considerable positive interaction between different air-pollution related measures, much less interaction becomes visible in terms of ozone. The effect of measures recommended under biodiversity protection allows only a modest decrease of ozone-related parameters, both in terms of ecosystem protection (Phytotoxic Ozone Dose, POD) and health protection (Sum of Ozone Over 35 ppb, SOMO35) only about a quarter of the totally achievable abatement as captured by measures to optimize biodiversity. This reduction is equivalent to roughly 1 ppb decrease in ozone background concentration, implying to focus on the factors responsible for hemispheric pollution levels.

Model results indicate that climate change will also affect the sensitivity of plant ecosystems with regard to biodiversity. With vegetation being more sensitive, considerable cost will result in any attempts just to maintain vegetation effects. This adaptation measure is needed, first of all, due to the plant sensitivities, but (to a lesser extent) also to expected increases in ammonia emissions due to effects of higher temperature. For 2050, costs amount to be somewhat lower, but in the same order of magnitude as a recent commission proposal for health protection (~1500 M€ annually for EU28).

The instruments developed in ECLAIRE also allow addressing situations in the longer term, towards the end of the century. Deposition maps have been developed, but emission data of S and oxidized N are not available at a quality level that can be recommended for further use. Existing long-term inventories focus on an optimistic pathway that implements available technology. For NH_3 emissions, it can be shown that indeed management, the way pollution is being dealt with, will have a larger effect than natural changes, autonomous technological improvements or the economic developments.

2. Objectives:

In order to support cost-benefit analyses, a cost minimizing scenario to achieve biodiversity protection in protected zones (Nature 2000) was to be devised. This included coverage of the new Habitat Suitability Index in the GAINS model. Effects expected till 2050 were to be covered as part of GAINS, but the concept was to be developed beyond 2050 towards an “indicative 2100” target year, which only could be dealt with outside of GAINS.

3. Activities:

Adjusting the GAINS optimization module also required numerous test runs with the new setup, before the algorithm was properly in place. The ECLAIRE optimized scenario was adjusted to an optimization run for the Commission proposal on health, its sensitivities in terms of detailed input parameters were tested, and it was extended into the year 2050. Outside the model the impacts for a tentative “indicative 2100” year were implemented and evaluated, for discussion at a dedicated meeting in Laxenburg, Austria (C5 final workshop) and at the final ECLAIRE general assembly in Edinburgh.

4. Results:

See the documents attached for details. A cost-optimized ECLAIRE scenario was developed based on a new indicator for biodiversity (habitat suitability index). The scenario was compared with its relation to health (strong positive interaction) and with ozone (small interaction, still positive – i.e. measures taken will be no-regret solutions). An extension beyond 2050 lacks of robust data on S and oxidized N emissions, which, if available, can be easily appended. Emissions and thus deposition of NH_3 are more strongly affected by management than by any other uncertainty due to future developments.

5. Milestones achieved:

MS98: Results finalized for evaluation and dissemination (Component 5 workshop)

6. Deviations and reasons:

Following the late availability of an operative Habitat Suitability Index, a slight delay also occurred into this deliverable. With intense exchange of information between partners throughout the project period, there should be little impact on the further project outcomes.

7. Publications:

Wilfried Winiwarter, Nico Vellinga, Wolfgang Schöpp, Max Posch, Chris Heyes, Markus Amann. ECLAIRE policy scenarios of cost-optimized options for vegetation protection. Presented at the 25th CCE Workshop and 31th Task Force Meeting of the ICP Modelling and Mapping, 20-23rd April 2015, Zagreb, Croatia

8. Meetings:

- 25th CCE Workshop and 31th Task Force Meeting of the ICP Modelling and Mapping, Zagreb, 20-23 April 2015.
- Task Force on Reactive Nitrogen, Lisbon, April 27-30, 2015
- ÉCLAIRE Component 5 final workshop, IIASA, Laxenburg (Austria), June 29-30, 2015
- ÉCLAIRE 5th General Assembly, Edinburgh, September 1-4, 2015

9. List of Documents/Annexes:

- ECLAIRE optimization scenario based on the Habitat Suitability concept
- Ozone impacts of ECLAIRE scenarios
- Climate sensitivity and climate effects on ECLAIRE scenarios
- Annex: Consensus paper on forest N impacts

ECLAIRE optimization scenario based on the Habitat Suitability concept

1. Introduction

The GAINS model has been used successfully in the past to provide cost-effective pollution abatement scenarios towards given “endpoints” like human health or ecosystem damage. In an attempt to characterize the value of ecosystems (Maas and Holland, 2014), the challenges of providing an adequate measure of ecosystems functioning to be used as an endpoint have been discussed. Among the targets proposed, it was the concept of “no net loss of biodiversity”, formulated under the Aichi targets of the CBD as well as in the EU’s habitat directive (Council Directive 92/43/EEC of 21 May 1992 on the conservation of natural habitats and of wild fauna and flora) that provided a robust legal framework to protect biodiversity in protected areas, the “Natura 2000” areas.

The Coordination Centre for Effects (CCE) has been developing an indicator to guide impacts on biodiversity based on the extent to which a certain habitat is suitable for a given EUNIS vegetation unit (consisting of a number of species). This “Habitat Suitability index” (HSI, Posch et al., 2014) describes the suitability to maintain full biodiversity under a given range of sulphur and nitrogen deposition. It is based on the results of the PROPS model which estimates by species the potential effects of excess exposure to these compounds. This concept is sufficiently similar to previous vegetation-related endpoints (notably, the soils acidification targets) to be employed in GAINS.

This paper describes the implementation of the HSI in GAINS, and the sensitivity analyses performed in order to understand the importance in choosing specific parameters, for which no pre-determined values have been set (yet).

2. Methods

The concept of the HSI has been described in detail by Posch et al. (2014). In short, it allows defining an area in the N-deposition / S-deposition space that is characterized by the probability of appearance for certain species / species groups to exceed a given value. Starting from the probability isolines, a simplified function is defined to establish a zone in the diagram for which biodiversity is considered to be safeguarded. The size of the zone depends on the exact parameters chosen (Fig. 1). For a given set of parameters (e.g., 80%, 67% or 50% of maximum suitability), and for given country emissions (based on a source-receptor matrix derived from the EMEP model), the Natura-2000 areas of Europe can be tested for exceedance, and if exceeded the accumulated exceedance levels can be derived as the protected area affected multiplied with the area-rated exceedance.

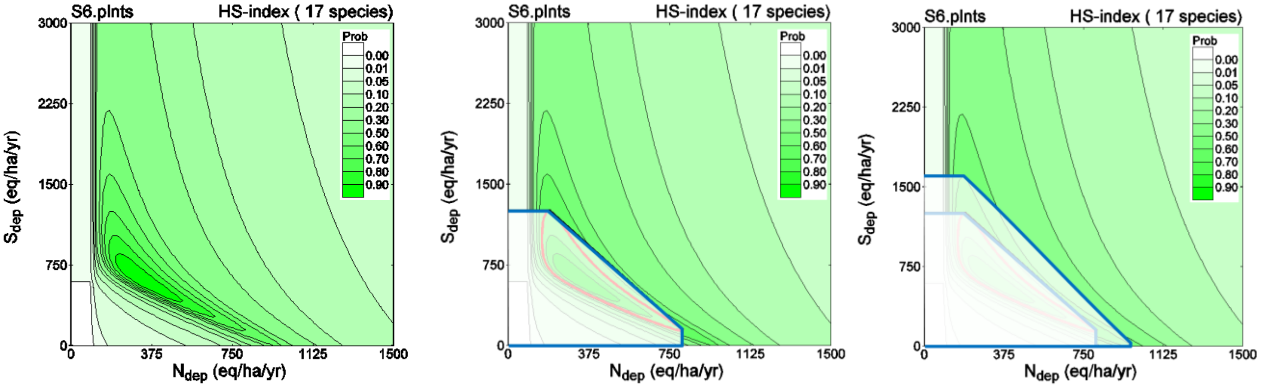

Fig. 1: Habitat suitability in the Sulphur-Nitrogen deposition space, and two levels of suitability

In the following, we will use a level of 80% of the optimum as the parameter for which biodiversity is considered to be safeguarded as the central case, and 67% (or 50%) as sensitivity case. In accordance with guidance provided in ECLAIRE generally (see deliverable D21.2), we employ emission projections based on the results of the ECLIPSE project (Klimont et al., 2012) for 2030 and for 2050. By default, results for 2030 are shown. This set of emissions is slightly different, but in general consistent with those used by the EU Commission in their current Clean Air Proposal (Amann et al., 2014). Also abatement measures as discussed for the Commission proposal are basically identical. Finally, the relationship between emissions and impacts, as mentioned above, is based on results of the EMEP model at 28x28km² grid (source-receptor relationship data version 1210).

3. Cost curve and positive interaction with health-related measures

In order to understand the impact of measures on the costs, we employ the “gap closure” concept. The GAINS model uses, for optimization, the range between a “current legislation” (CLE) scenario, and a “maximum feasible reduction” (MFR) scenario. The CLE case reflects a situation when only measures that are implemented now or in legal documents affecting a future emission technology are being applied in the target year. For MFR, all abatement measures implemented in GAINS are being applied. For both cases, the “endpoint” is being calculated – in this case, the exceedance (in equivalents = moles of charge) above.

In a “cost curve”, abatement measures are subsequently applied on top of those measures already covered under CLE. Measures are sorted by cost-effectiveness, i.e. those measures are first selected that arrive at the largest change in the effect parameter (here: excess equivalents deposited to protected area) at least costs. The total spacing between CLE and MFR is called “gap”, and the extent to which it is filled (in equal spacing expressed as percent) is called gap closure.

Fig. 2 presents the cost curve derived for the given set of European emissions. At low levels of gap closure, considerable achievements are demonstrated at fairly small costs. As mentioned above, The sort order of abatement measures (or: the model’s recommendation of selecting measures) is set to take the most cost-effective measures first, until at high gap closure levels only the very expensive ones remain, leading to a steep slope on the right-hand side of the cost curve. Costs presented at the vertical axis are on top of the costs needed for CLE, which are estimated to amount to 87000 M€/yr for 2030 in the EU28, much larger than all of the additional measures available.

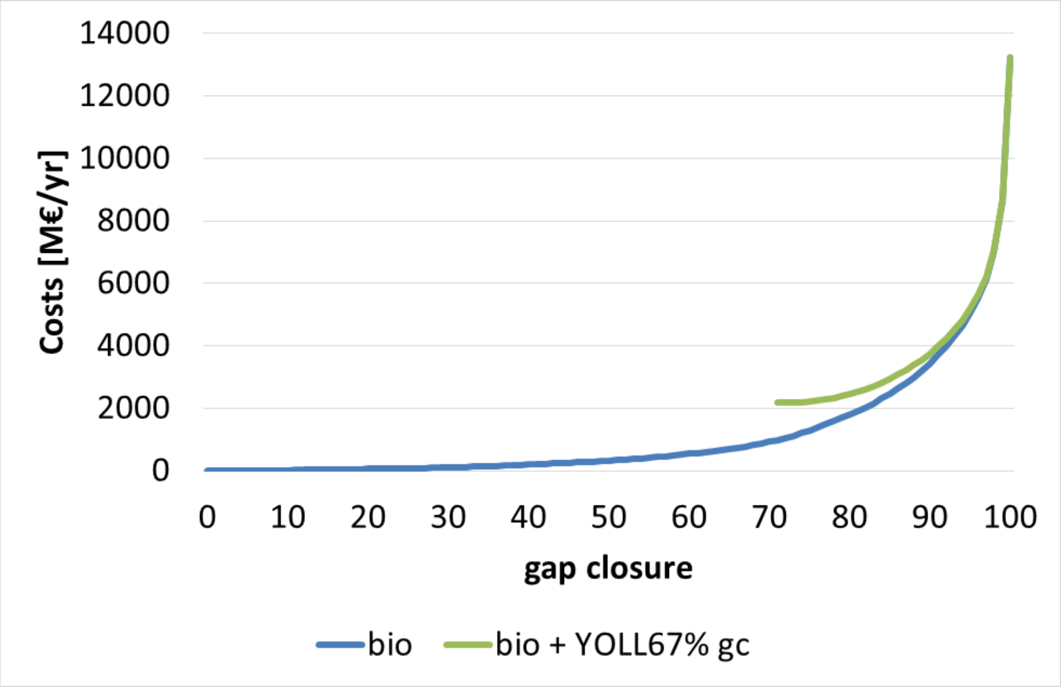

Figure 2: Cost curve for the “biodiversity indicator” (blue line) vs. cost curve of the additional measures when starting from the Commission proposal towards protecting human health only (projected for 2030).

In a recent modelling exercise for the European Commission (Amann et al., 2015), similar concepts have been used to improve air quality related to human health. In that study, the target parameter was “years of life lost” (YOLL’s), and the gap closure of the “Commission proposal” was 67%. It is interesting to observe that, when using the commission proposal as a starting point, A large share of biodiversity-related abatement measures will have been taken already (gap closure of 71.2%). While costs are higher than needed to achieve that level of gap closure for biodiversity, these costs (2200 M€/yr) may be attributed to human health preservation.

Clearly there exists a positive interaction between measures towards preserving human health, and towards protecting biodiversity. This also becomes visible when following a cost curve to be applied “on top” of the health-related emission reductions. Again, a number of rather cost-efficient options are available in the very first part of the curve, partly due to exchanging measures that are relevant for health only, by others that affect both health and biodiversity in a positive manner. Thus we propose to use a value of 75% gap closure for the biodiversity indicator, which is available at very low marginal costs (23.1 M€, or 1.1% of the additional costs of the health related commission proposal) but nevertheless rather effective in protecting biodiversity.

We may establish an analysis of costs per country and by source sector (Figure 3) to provide a “fingerprint” of the measures selected in the cost optimization routine. As long as the difference between two scenarios is small, it may be concluded that also the individual measures chosen by the optimization are largely identical. In principle, this signal is rather sensitive as small variations in the ambition of measures may lead to major discrepancies in the optimized way to respond to the challenges, often even between countries. Thus a “fingerprint” helps to identify such issues. E.g., it allows to differentiate measures needed for health impact alone, and those required for simultaneously achieving the ecosystem protection target. While overall costs (see above) are hardly affected, it turns out that some countries (Bulgaria, Portugal) would need to bear higher costs of emission reductions if also protecting ecosystems, and also some sectors (agriculture) while other sectors (domestic) would be spared. This reflects the area-based focus of ecosystem protection, as opposed to the population-density orientation of a purely health oriented parameter.

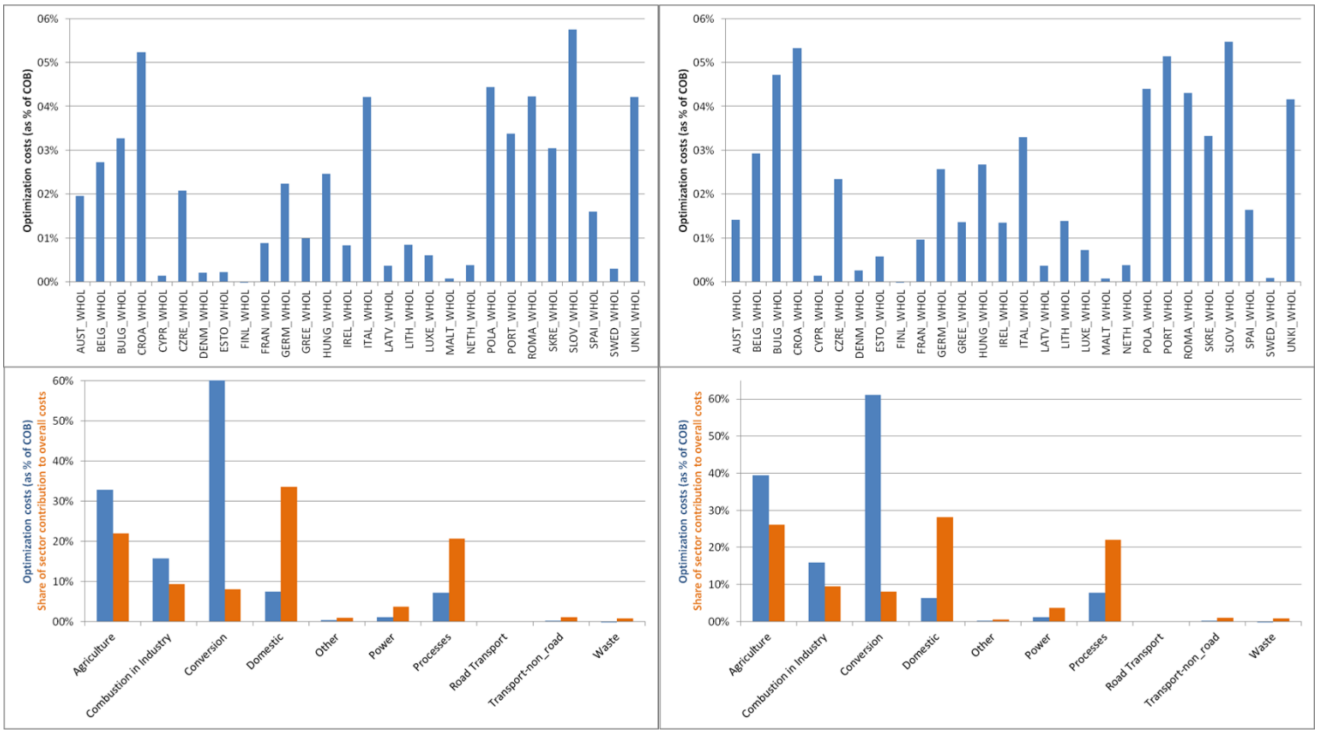

Figure 3: Additional costs of measures (in relation to the “cost optimized baseline”, COB costs, which reflect the current legislation measures) split by country and by sector (“fingerprints”). Panels on the left side represent the “Commission proposal”, those on the right side reflect the ECLAIRE optimization scenario comprising 67% gap closure for human health and 75% gap closure for biodiversity (projected data for 2030).

The same fingerprint analysis may also be used to assess the sensitivity of the results depending on the choice of certain inputs. Specifically, it is of interest here to assess the impact a different choice of “habitat suitability” may have. The central or “stringent” case, as also used above, operated at a level of 80% of optimum habitat suitability. For the sensitivity (“less stringent”) case, in Fig. 4 we use the 67% level of the optimum. It can be demonstrated that the change of this parameter, while strongly affecting the exceedance parameters (equivalents excess deposition are only about half at these relaxed conditions), recommended measures leading towards the desired gap closure would hardly be impacted – the fingerprint shows very little differences. This indicates that, at least from the type of abatement measures identified by the algorithm, the choice of parameters for determining habitat suitability may not be so important.

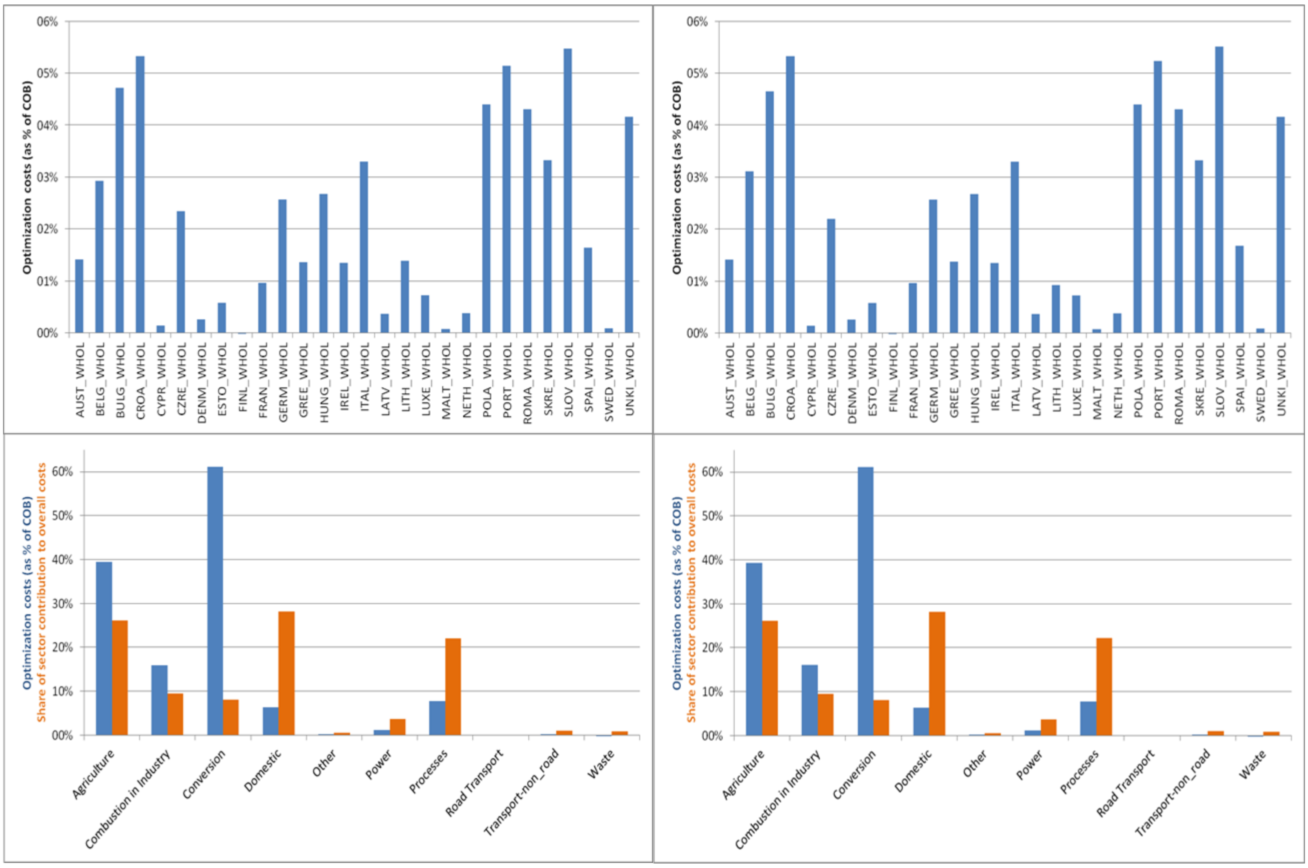

Figure 4: Impact of choosing different sets of "habitat suitability" to the distribution of mitigation costs by country as well as by sector. Left panel shows the central case, 80% of habitat optimum accepted, right panel the sensitivity case of 67% of the optimum (projected data for 2030).

4. Results

In order to better understand the impacts of the "ECLAIRE scenario", Table 1 compares the impacts towards biodiversity, of the "Current legislation", the health-optimized "Commission proposal" and the ECLAIRE scenario also explicitly aiming for reducing impacts on biodiversity. No agreed metrics exists to adequately quantify such impacts. In line with the "critical load" concept, we may use the average accumulated exceedance of the threshold developed for the "habitat suitability" concept. This threshold obviously depends on the level ("stringency") of habitat optimum considered tolerable (80% or 67%) – for comparison the table provides a value as an average over the total protected area. Another aspect of interest is the area in which threshold exceedance occurs – again a function of tolerable level of habitat optimum, and quantified in protected area still exceeded. Both parameters are being compared to the "gap closure" as the fraction of difference between abatement options chosen in the baseline and the maximum available in GAINS. Still they only substitute for the key topic of interest for biodiversity, the number of species endangered. While development of species number as an additional metric seems possible based on the modelling chain employed, further work will be needed to arrive at any conclusive results here.

Table 1: Impact of different metrics on measuring the success of abatement policies

	Scenario	gap closure	average exceedance (eq/ha)	impact reduction exceedance	exceeded area (km^2)	share of protected area affected	costs above CLE [M€]
stringent habitat suitability index	CLE	0.0%	26.0		60980	15.8%	
	COM proposal	71.2%	14.6	44%	47536	12.3%	2189
	ECLAIRE optimized scenario	75.0%	14.0	46%	46958	12.2%	2212
	MFR	100.0%	10.2	61%	43183	11.2%	40006
less stringent habitat suitability index	CLE	0.0%	13.7		34901	9.1%	
	COM proposal	71.2%	6.7	51%	24500	6.4%	2189
	ECLAIRE optimized scenario	75.0%	6.3	54%	23807	6.2%	2212
	MFR	100.0%	4.0	71%	20802	5.4%	40006

The results presented in Table 1 show, first of all, that the “less stringent” setting of biodiversity targets is more sensitive, but also allows further reductions. This is as it is possible, if the parameters chosen reflect impacts adequately, to come closer to a value of attainment using the abatement measures available. On a more qualitative level, however, conclusions drawn do not differ between the choice of the tolerable difference from the optimum level.

Even with all measures employed, exceedance will remain. Depending on metrics chosen, between one and two thirds of the impact exerted under CLE will remain, indicating improvement is possible. The major part of this improvement occurs already with the commission proposal targeting on health only. Clearly, with current technology as implemented in GAINS not much more can be achieved in addition. At the same time that shows a considerable level of interaction with health-related targets, which biodiversity protection can take advantage of. Combining health and biodiversity, as suggested in the ECLAIRE optimization scenario, will lead to only incremental improvements – but the costs involved of 23 M€ reflect only one percent in addition to the costs of the commission proposal. So there is a notable incremental effect based on little effort. Again depending on the metric, the effect ranges between 4.3% and 6.7% for 1% of costs (all quoted as additional achievements in excess of the health target). ECLAIRE optimization indicates that a modest, but potentially useful improvement still is available.

5. References

Amann M, Bertok I, Borken-Kleefeld J, Cofala J, Heyes C, Hoeglund-Isaksson L, Kiesewetter G, Klimont Z, Schoepp W, Vellinga N, Winiwarter W (2015). Adjusted historic emission data, projections, and optimized emission reduction targets for 2030 - a comparison with COM data 2013. Part A: Results for EU-28. TSAP Report #16A, V1.1, International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria.

Posch M, Hettelingh J-P, Slootweg J, Reinds GJ (2014). Deriving critical loads based on plant diversity targets. In: Slootweg J, Posch M, Hettelingh J-P, Mathijssen L (eds), 2014. Modelling and mapping the impacts of atmospheric deposition on plant species diversity in Europe: CCE Status Report 2014. RIVM Report 2014-0075, Coordination Centre for Effects, Bilthoven, Netherlands, pp. 41-46; www.wge-cce.org

Klimont Z., Kupiainen K., Heyes Ch., Schöpp W., Höglund-Isaksson L. (2012). Updated GAINS database including reference emission scenario. Deliverable: D1.1, ECLIPSE (Evaluating the Climate and Air Quality Impacts of Short-Lived Pollutants) Collaborative Project, Project no. 282688 , Laxenburg, July 2012 (report restricted).

Holland, Mike, Rob Maas (2014). Quantification of economic damage to biodiversity. ECLAIRE Project, Work package 18. Ecometrics Research and Consulting (EMRC), Reading, UK, May 2014.

Ozone impacts of ECLAIRE scenarios

1. Introduction

The ECLAIRE project aims to comprehensively assess the vegetation response to air pollution both in relation to nitrogen and to ozone. Interference exists in both directions, with additional nitrogen deposition from air pollution being considered as damaging as well as fertilizing vegetation (Emberson et al., 2015; see also "Annex: Consensus paper on forest N impacts"). This section reports on the expected impact of a biodiversity-oriented policy on the expected ozone impacts on vegetation.

We use the ECLAIRE optimization scenario, based on the habitat suitability index (Posch et al., 2014), in order to understand the ozone-related impacts of policies restricting nitrogen. Potential ozone impacts are quantified as the "phytotoxic ozone dose", POD, which is defined as accumulated stomatal flux above a given threshold of 1 or 3 nmol m^{-2} s^{-1} , respectively, where POD1 (threshold of 1 nmol m^{-2} s^{-1}) stands for the protection of deciduous forests, and POD3 (threshold of 3 nmol m^{-2} s^{-1}) for crop protection. In both cases, we employ the "IAM" variant of the parameter, which is characterized by a different quantification period (90 days in the IAM case).

2. ECLAIRE optimization scenario

The "ECLAIRE optimization scenario based on the Habitat Suitability concept" is described in more detail in the respective section of this report. Basically, a given "acceptable" level of adverse impact of air pollution on biodiversity has been chosen, and a cost-effective solution to apply abatement measures derived using the GAINS model. Sensitivities of this approach also have been described.

Using a source-receptor matrix based on a photochemical transport model (the EMEP model) run over several years on past meteorological data, the resulting emission reductions are translated into POD1IAM and POD3IAM values. Emissions refer to the projections for the year 2030 and represent the database prepared for the ECLIPSE project (version 5), which for Europe is largely in line with emission projections used for the updated Commission Proposal for the Clean Air Policy Package (Amann et al., 2015). In addition to the optimized scenario, a "current legislation" (CLE) and a "maximum feasible reduction" (MFR) scenario have been provided. The latter two reflect the future developments as implanted in the GAINS model without cost optimization.

3. Results

As an average over European forest ecosystems, accumulated ozone fluxes over a threshold of 1 nmol m^{-2} s^{-1} are presented in Fig. 1 (accumulation period of 90 days for IAM calculations). When comparing results of the different scenarios, the small difference even between current legislation and the most advanced technical possibilities, the MFR scenario, becomes apparent. The value of POD1 decreases by merely 4.4%. Only about a quarter of this decrease is achieved in the ECLAIRE optimization scenario already. Note that the updated Commission Proposal (not shown) on health protection will practically not differ from the ECLAIRE optimization scenario.

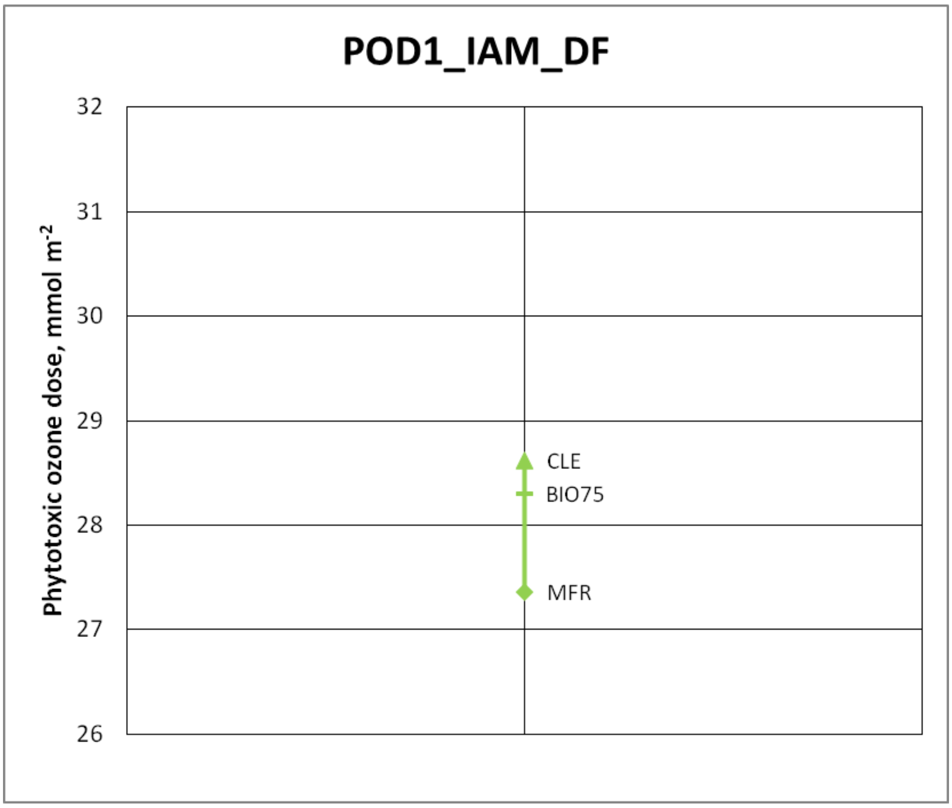

Figure 1: Average POD values in EU28 (for forest protection: DF for “deciduous forest”)

This result will not change when considering other ozone-related metrics. Fig. 2 displays POD1 as well as POD3, the metrics used to attribute crop damage, as well as SOMO35 (Sum of Ozone Means Over 35 ppb, taken as the maximum daily 8-hour averages over 365 days), a health-related parameter. They all show very similar behavior, except that SOMO35 is much more sensitive to changes. It is interesting to compare to another parameter affecting ozone-related endpoints: the hemispheric background concentrations. These derive from a separate study for the year 2020, thus differing also from the CLE (Schulz et al., 2014). For all parameters considered, 1 ppb change in background concentration will provide a similar effect as the optimization scenario.

The past and future developments become even more transparent when extending the available data according to Fig. 3, which only displays values relative to 2010. Here POD1 and POD3 cannot be distinguished anymore. Considerable decrease POD’s of about 20% can be seen between 1990 and 2010 (despite of starting at a lower hemispheric background) due to air pollution abatement measures. The “hypothetical” trend reflects a business-as-usual emission increase that never materialized. Further POD reductions can be expected under current legislation by 2030 (about 7%) and another 5% reduction is available as a “maximum feasible” scenario. While sensitivity is stronger, the basically same trends appear with SOMO35 also.

The ECLAIRE optimization scenario shows reductions of POD and SOMO values, even if optimization does not aim towards minimizing ozone. Thus the scenario provides a no-regret solution. In comparison to what has been achieved in the past, and what is expected for 2030 anyway (under current legislation) little further improvements can be expected, not even under a maximum feasible reduction scenario. Here the hemispheric background concentrations of ozone seem to be the key to further curb ozone exposure of humans as well as of plants.

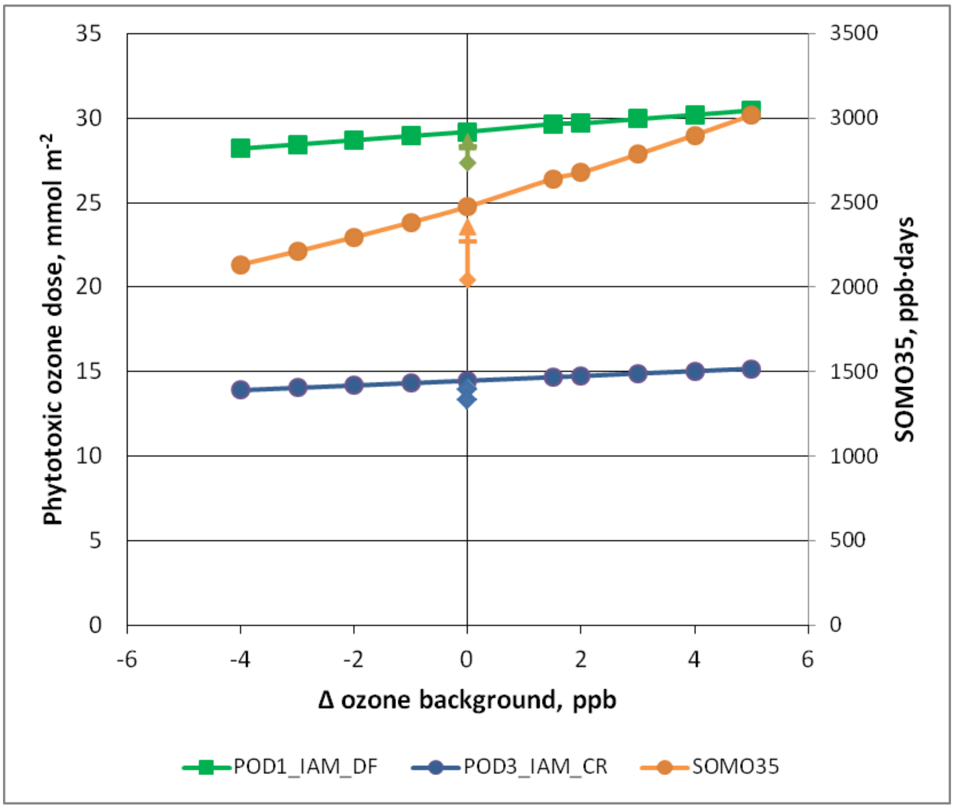

Figure 2: Average POD1 and POD3 values as well as population-weighted country averages of SOMO35 for EU28. Scenarios (based on 2030 projections) are current legislation (triangle, upper value), ECLAIRE optimization scenario (horizontal bar) and maximum feasible reduction (diamond). Also shown (but based on different emission scenarios for 2020 under current legislation) is the dependency of parameters on hemispheric background ozone.

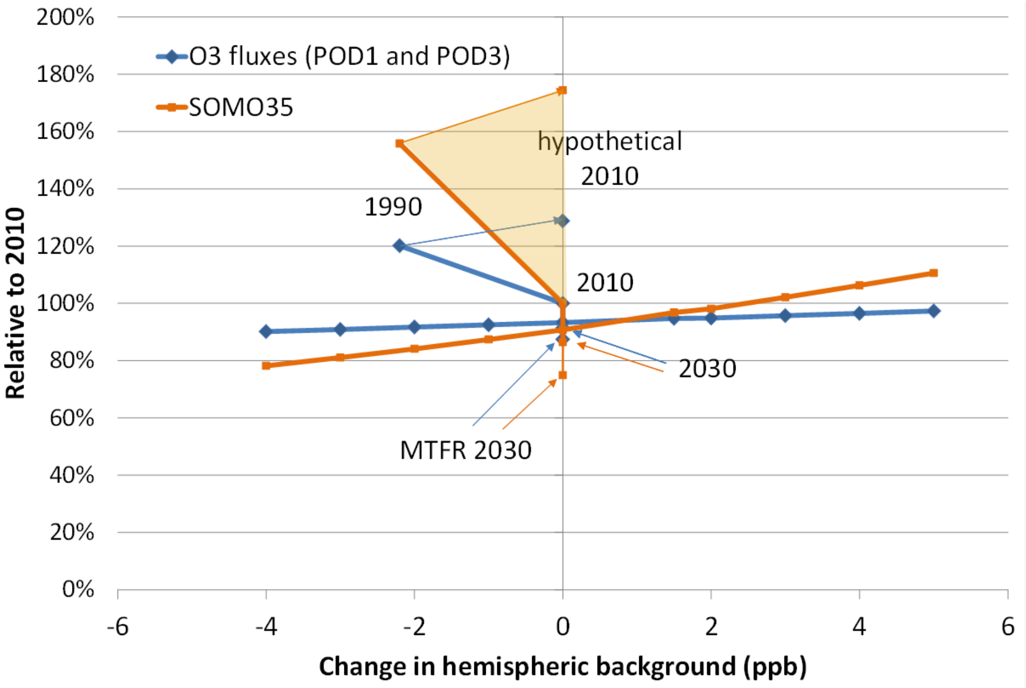

Figure 3: Developments of relative POD and SOMO35 changes in the past (starting from a lower hemispheric background) and expectations under current legislation as well as potential for the year 2030.

4. References

Amann M, Bertok I, Borken-Kleefeld J, Cofala J, Heyes C, Hoeglund-Isaksson L, Kiesewetter G, Klimont Z, Schoepp W, Vellinga N, Winiwarter W (2015). Adjusted historic emission data, projections, and optimized emission reduction targets for 2030 - a comparison with COM data 2013. Part A: Results for EU-28. TSAP Report #16A, V1.1, International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria.

Emberson L et al. (2015). ECLAIRE deliverable D12.3 – Delivery of novel thresholds for key dose-response relationships. Stockholm Environment Institute and University of York, York, UK.

Posch M, Hettelingh J-P, Slootweg J, Reinds GJ (2014). Deriving critical loads based on plant diversity targets. In: Slootweg J, Posch M, Hettelingh J-P, Mathijssen L (eds), 2014. Modelling and mapping the impacts of atmospheric deposition on plant species diversity in Europe: CCE Status Report 2014. RIVM Report 2014-0075, Coordination Centre for Effects, Bilthoven, Netherlands, pp. 41-46; www.wge-cce.org

Schulz M, Jonson JE, Fagerli H, Valiyaveetil S, Klimont Z, Amann M, Heyes C, Schöpp W (2014). Assessment of hemispheric air pollution on EU air policy. ANNEX VI, Impact analysis of Air Pollution Control Options. Final report to contract no. 07.0307/2011/605671/SER/C3. MetNo, Oslo.

Climate sensitivity and climate effects on ECLAIRE scenarios

1. Introduction

There are many elements of global change that may have an impact on the flourishing of vegetation and of ecosystems. ECLAIRE only investigates impacts of air pollution. Some of the air-pollution related factors concern altered anthropogenic activities, others are a direct consequence of climate (more specifically: temperature) to the release of potentially noxious trace compounds into the atmosphere, and again others are caused by an altered plant response to air pollutants.

Each of these factors can be investigated separately: projections of anthropogenic activities and economic developments, even over a time period to the end of this century, have been a topic of the latest IPCC reports. These scenarios also cover the potential of technology improvements that may limit the release of trace compounds. Other emission sources may be directly impacted by temperature increases – especially those that are consequences of biological processes, like agricultural ammonia emissions. Also here, information has been provided previously (see below for detailed references). Little information, however, is available on potentially changing meteorological patterns that might influence atmospheric transport and transformation of trace compounds, and on the altered response ecosystems may have on air pollution, if impacted by climate change. Especially the latter element is considered relevant, and investigated here.

This report thus focuses on two elements, (i) how may future impacts on ecosystems may look like, considering global change, and (ii) which additional measure are needed to limit ecosystem impacts to a level that would occur without climate change. Thus the evaluation presents both climate mitigation and climate adaptation measures.

2. Available scenario data

Much of the material used to establish scenarios has been described in detail as part of ECLAIRE deliverables, which can be referred to for more details. The “ECLAIRE scenario reference” (Winiwarter et al., 2015a) constitutes the central document here. Reference is also given here to the most important scientific background literature, as appropriate interpretation may be relevant for the results presented.

ECLAIRE scenarios as well as the ECLAIRE optimization scenario are based on the closely related ECLIPSE project (Klimont et al., 2011) which provided key input data on anthropogenic activities and on emission abatement technology available as “current legislation” for the GAINS model. The GAINS model (Amann et al., 2011) covers a time scale until 2050; extended scenarios rely on additional data as outlined in Tab. 1. Following IPCC (2013), we adopt the two extreme of their four “RCP” scenarios as to indicate possible future directions: RCP2.6 stands for a world that successfully meets the challenges of global change and converges within the “Two-degree-target” of global temperature increase, while RCP8.5 allows developments to proceed largely irrespective of climate impacts (see van Vuuren et al., 2011, and references therein for an extensive discussion of the RCP scenarios).

In addition, downscaled global circulation models have been made available for ECLAIRE (again see Winiwarter et al., 2015, for details). Due to long processing times, model data reflect an earlier set of IPCC scenarios rather than the RCP’s, they are based on the IPCC’s Second Report on Emission Scenarios (SRES: Nakicenovic and Swart, 2000), specifically employing an “A1B” scenario. In comparison with RCP, that scenario reflects a non-mitigated case, in a way related to RCP8.5. With IPCC (2014) projecting global mean temperature increases beyond current of 1° in RCP2.6 by 2100, and 3.7° in RCP8.5 (at an average global temperature increase of 1° beyond a pre-industrial situation already achieved, this is 2° and 4.7°, respectively, above pre-industrial), and 1° change also expected for 2050, we simply assume that under RCP2.6 no further changes will occur beyond 2050, while for 2100 a 3.7-fold change is to be expected. The combination of inconsistent datasets as outlined here obviously is less than ideal, but the approach anyway can only serve as indicative to the factors that characterize future situations.

3. Climate change impacts on biodiversity sensitivity

The "habitat suitability index" (Posch et al., 2014, see also section "ECLAIRE optimization scenario based on the Habitat Suitability concept") has been selected within ECLAIRE as the metric to represent biodiversity. Using meteorological information as one of the input parameters, the PROPS model (Reinds et al., 2015) assesses, for a given EUNIS vegetation class, the optimum biodiversity situation in a N and S deposition landscape, and connects points of equal probability to maintain biodiversity. Thus by using altered climate data (from downscaled global circulation models instead of real data) PROPS also allows assessing expected impacts in a 2050 (or 2100) climate.

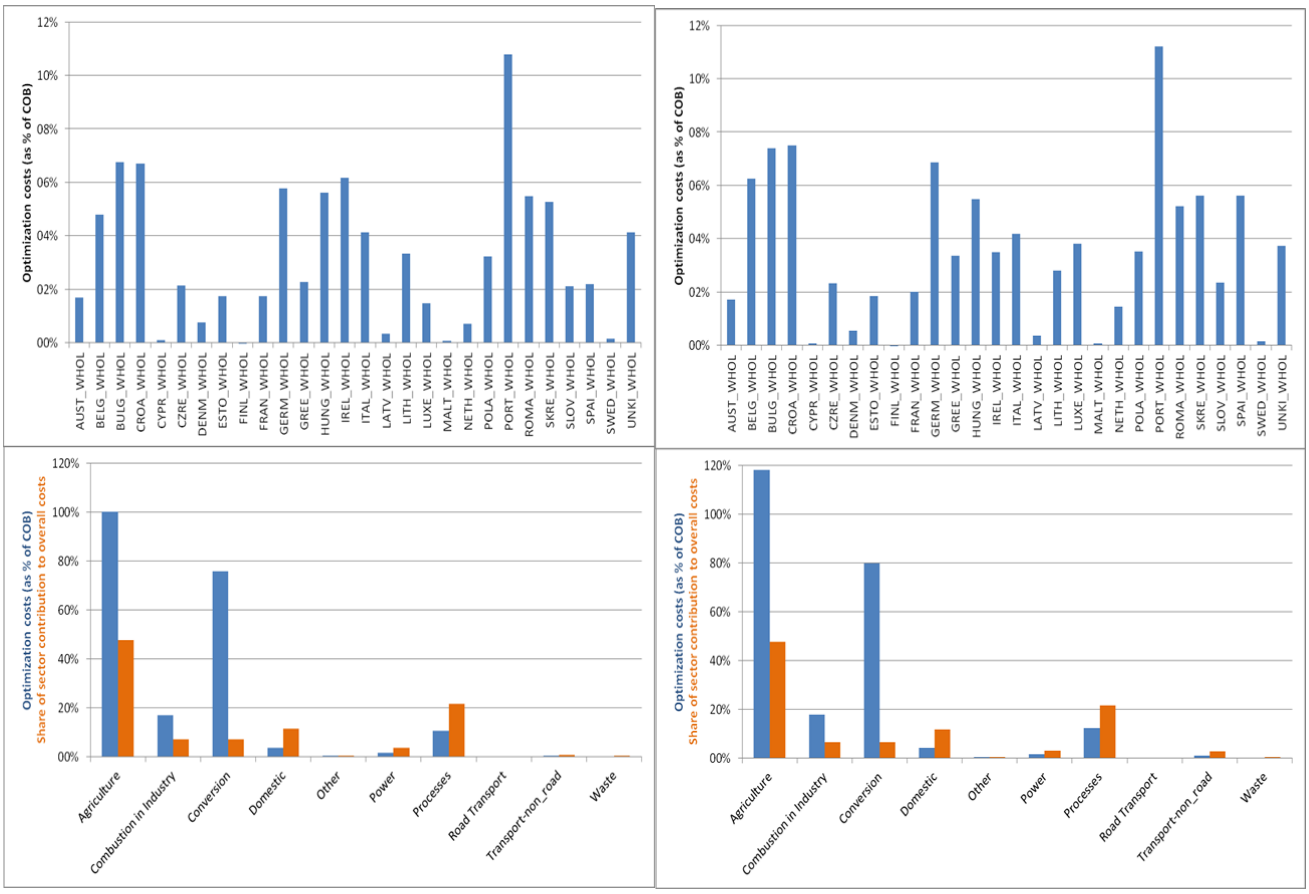

Figure 1: Impact of choosing different sets of "habitat suitability" to the distribution of mitigation costs by country as well as by sector. Left panel shows the central case, 80% of habitat optimum accepted, right panel the sensitivity case of 67% of the optimum (projected data for 2030, climate sensitivity reflects the situation of 2050).

In translating PROPS results to acceptable loads of N and S in protected (Natura 2000) areas, different acceptable levels of habitat suitability have been chosen – 80% for the central "stringent" case, and 67% for the "less stringent" sensitivity case. Optimizing measures to attain the pre-defined ECLAIRE optimization scenario (an extension to the "commission proposal" to tackle human health threats of air pollution) identifies certain sets of abatement measures as the most cost-effective. Fig 1 combines costs per source sector and per country for both the "stringent" and the "less stringent" case. Despite of the notable differences in exceedance, there is remarkable agreement in the "fingerprints" of identified measures. This indicates that the resulting optimization is robust with respect of the exact parametrization of indicators chosen. In order to avoid entering too many differences at once, this analysis did not extend emission projections to 2050. But in defining the optimization requirements we maintained the absolute levels of exceedance (and thus also the average exceedance) at least at the level achieved with current climate sensitivity of vegetation. Thus we assume that climate change would not reduce the permissible impacts but rather lead to acceptance of additional costs. (For the health-related "COM-proposal", parameters set compare the biodiversity-related excess deposition, so that comparison is not set on health.)

Resulting abatement costs (for the "central case" of acceptable habitat suitability only) are presented in Tab. 1, where they are contrasted to optimization results based on habitat suitability indices derived without such a climate effect. First of all, it becomes evident that average exceedance increases under consideration of the climate effect: vegetation is indeed more sensitive. Just in order to achieve the same level of exceedance as in the CLE case, about 23.2% gap closure (the possible range of effect decrease between "current legislation" and "maximum feasible reduction" scenario) need to be applied. In consequence, also the gap closure – and hence the costs – needed to attain the level of exceedance are higher. Moreover, even with "maximum feasible" technology, the final level of exceedance remains higher than without considering climate effects.

Table 1: Impact of climate-affected different metrics on measuring the success of abatement policies (using 2030 emission projections)

Scenario		gap closure	average exceedance (eq/ha)	impact reduction exceedance	costs above CLE [M€]
Optimization scenario based on 2050 HSI	CLE	0.0%	30.9		
	COM proposal-related	83.9%	14.6	53%	3078
	ECLAIRE optimized scenario	87.0%	14.0	55%	3544
	MFR	100.0%	11.6	63%	40006
Optimization scenario based on current HSI	CLE	0.0%	26.0		
	COM proposal	71.2%	14.6	44%	2189
	ECLAIRE optimized scenario	75.0%	14.0	46%	2212
	MFR	100.0%	10.2	61%	40006

4. Adaptation: compensating climate-related effects

The analysis presented in Tab. 1 shows already that costs increase when climate related impacts on vegetation sensitivity also have to be captured by measures taken. In Tab. 2 we compare the central case under current climate conditions with this case considering climate-affected biodiversity indicators, and separately reduction needs under increased NH3 emission as a result of increased temperatures.

The increase of NH_3 emissions has been postulated by Sutton et al. (2013). We use here a modified version according to Winiwarter et al. (2014), in which we understand that a general temperature increase (of 1° by 2050 above current conditions) will not only affect conversion and evaporation rate, but also agricultural management as fertilization times etc., such that there are different levels of increase depending on the specific process. The results shown in Tab. 2 assume a 4% temperature induced increase in ammonia emissions which needs to be covered by adequate abatement.

Table 2: Costs to compensate increased biodiversity impacts caused by climate change

	Central case, Current climate 2030		With biodiversity indicators under climate change**)			With higher NH3 emissions due to climate change ***)		
	HS indicator (eq/ha)	Costs *)	HS indicator (eq/ha)	Additional costs to return to central case *)		HS indicator (eq/ha)	Additional costs to return to central case *)	
CLE	26.0	0	30.9	+95	0.11%	26.7	+26	0.03%
COM proposal	14.6	2189	17.7	+889	1.03%	14.9	+236	0.27%
ECLAIRE scenario	14.0	2212	16.3	+1333	1.54%	14.4	+386	0.33%

*) costs in M€/yr, on top of current legislation /% of CLE costs
**) for 2050 climate scenario (~1° higher temperature)
***) 4% increased total NH$_3$ emissions in EU-28

These results establish that both elements of change, the increased sensitivity of vegetation as well as the increased ammonia emissions will require additional abatement measures to be taken in order to arrive at the same level of ecosystem protection. It is interesting to note that the effect of biodiversity sensitivity is considered about four times as important (in terms of costs accrued) as that of increased ammonia emissions. Further investigation will be needed in order to confirm this analysis. Possibly more important is the magnitude of additional efforts required: just because of the climate effects, the additional efforts spent amount to almost the same as the health-related “commission proposal” (see Amann et al., 2015), if we simply add NH$_3$-emission and biodiversity related cost. With respect to costs of current legislation, which alone is much more costly than the additional efforts under discussion, this still remains in the very low percent range (<2%) but indicate that adaptation will be needed also in this area.

5. Developing “indicative 2100” scenarios

Projections that extend beyond 2100 necessarily rely on many different assumptions that lack of adequate full confirmations. While scenarios are merely a side issue in ECLAIRE, dealing with climate change impacts necessarily also involves to consider developments that become relevant only at the end of the century. Tab. 3 provides guidance on data used and approach taken to develop such scenarios.

Due to the considerable uncertainty involved, there was some hesitation to explicitly name a target year of such projections. In fact, for some developments it originally seemed more logical to focus on a given climate change (“ΔT= 2°”) instead of a fixed timeline. On the other hand, economic developments and technological improvements can better be captured on a timeline. Integrating this only seemed useful by returning to the given calendar. In order to underline the uncertainty involved, this report remains consistently with the term of “indicative 2100”.

Table 3: Concept to extend results beyond 2050.

Element	Source	Approach
SO_2 emissions, NO_x emissions	RCP database* (see van Vuuren et al., 2012)	Change factor (by emission sector and by world region: OECD, REF are relevant for Europe) 2050→2100 trends are applied to ECLAIRE scenario
Vegetation sensitivity	CCE/Alterra (Reinds et al., 2015)	Based on results of the PROPS model, applied using downscaled GCM data from 2050 to reflect a 1°C change, and from 2100 to reflect a 3.7° change
Atmospheric transport pattern	EMEP / SMHI	No different source-receptor relationship available yet – for HIS, the principle of mass conservation prevails, i.e. deposition necessarily equates the emissions
N in agriculture (activity indicator)	RCP and global agricultural models	2050→2100 trends from global estimates (Bouwman et al., Winiwarter et al., 2013; Bodirsky et al.) are applied to ECLAIRE scenario
NH_3 emission factors	Sutton et al (2013); technological improvements	See previous ECLAIRE deliverables (D20.4-5 and especially D20.6): Winiwarter et al., 2014

*) http://tntcat.iiasa.ac.at/RcpDb/dsd?Action=htmlpage&page=about

In an attempt to follow the IPCC (2013) approach, RCP2.6 and RCP8.5 have been selected as underlying scenarios for ECLAIRE. Indeed, the emissions derived allow developing deposition patterns (Fig. 2) as a result of emissions and transfer matrices. As shown in the figures, we may expect the problem of S deposition to be mostly resolved by 2100, while N deposition will stay with us even under climate change conditions. However, more detailed analysis (also on the RCP emission data) demonstrates that there are two different effects separating oxidized and reduced N – while oxidized N shows trends very similar to those of S, only emissions of reduced N remain. While here we do not employ RCP data to project reduced N emissions, the message indeed is confirmed by RCP.

Still, the result can not be deemed fully reliable. RCP’s have been developed without underlying storylines. Originally, they focus on different levels of climate mitigation in place, with RCP8.5 having little or no dedicated regulation. Trace gases were not the primary focus, and the range of possible future conditions is not reflected in the RCP projections. Instead, emission estimates for S and oxidized N characterize a technological optimum – in short, emission estimates tend to be too low. Again supporting IPCC, activities are under way that intend to resolve the situation. Based on consistent storylines, the “shared socioeconomic pathways” (SSPs) are under construction which will also provide situations of emissions that remain high into the future. Before these results become available, there is little reason to fully trust the results of the deposition maps.

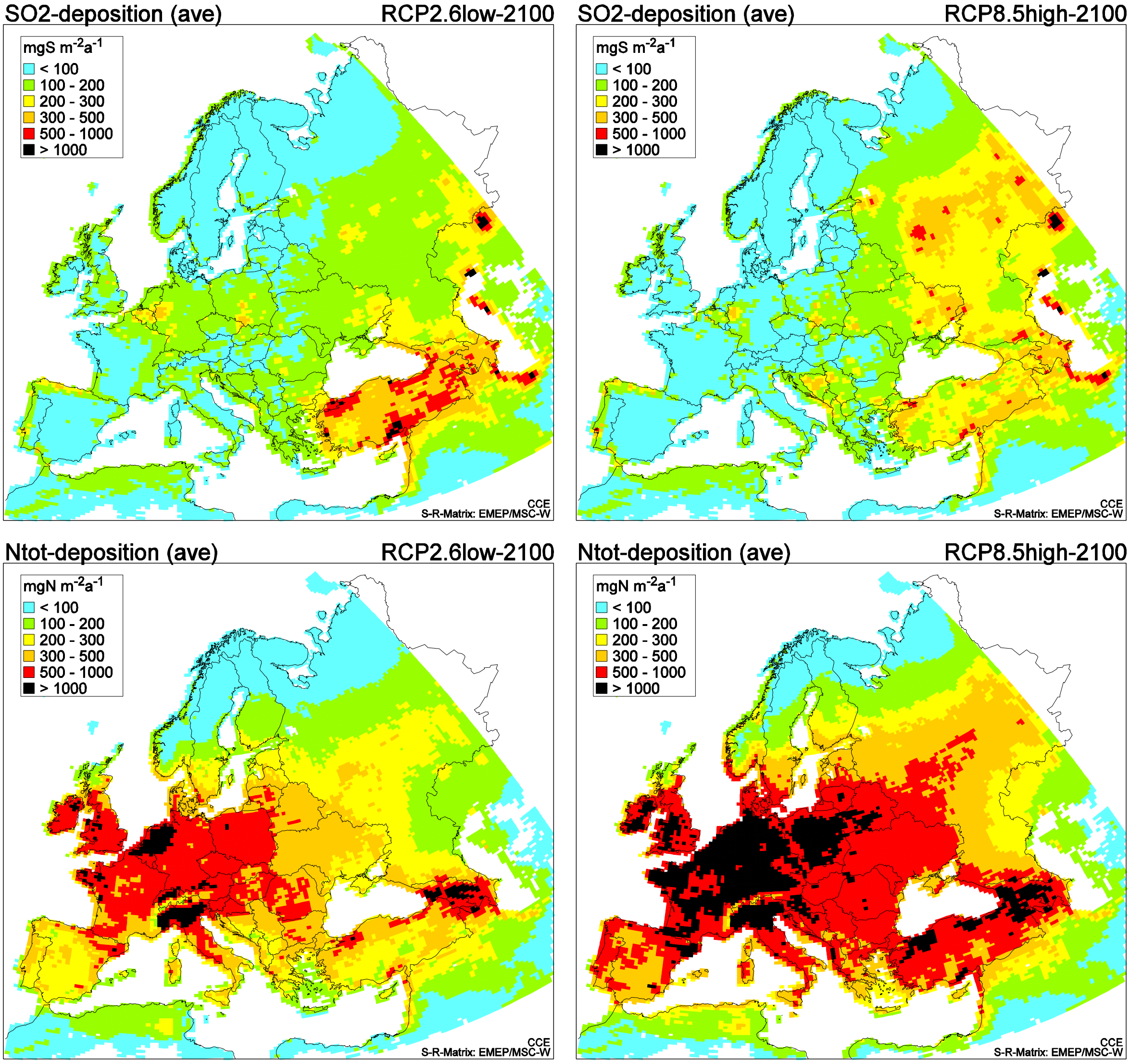

Figure 2: Depositions from ECLAIRE emission scenarios (100 mg/m^2 = 1 kg/ha). Total S depositions (Units: mgS/m^2/yr) [top panels] & total N depositions (mgN/m^2/yr) [bottom panels]

Lack of proper underlying data merely is one aspect of uncertainty. In a previous ECLAIRE deliverable (Winiwarter et al., 2014), an attempt was offered to quantify each of the projection elements for a 2100 scenario of NH3 emissions (40 European countries) – the details of that analysis fully covered in that report. In Fig. 3 we extend this analysis, pointing out that the difference between the "current legislation" emissions and those of the "maximum feasible reductions" need to be seen as the possible range of management changes. Indeed, a rather large operating space exists that supersedes all of the other uncertainty elements – in the end, future emissions of NH_3 into the atmosphere need to be seen as the consequence of human decision ("management") rather than any incidental effect that cannot be controlled.

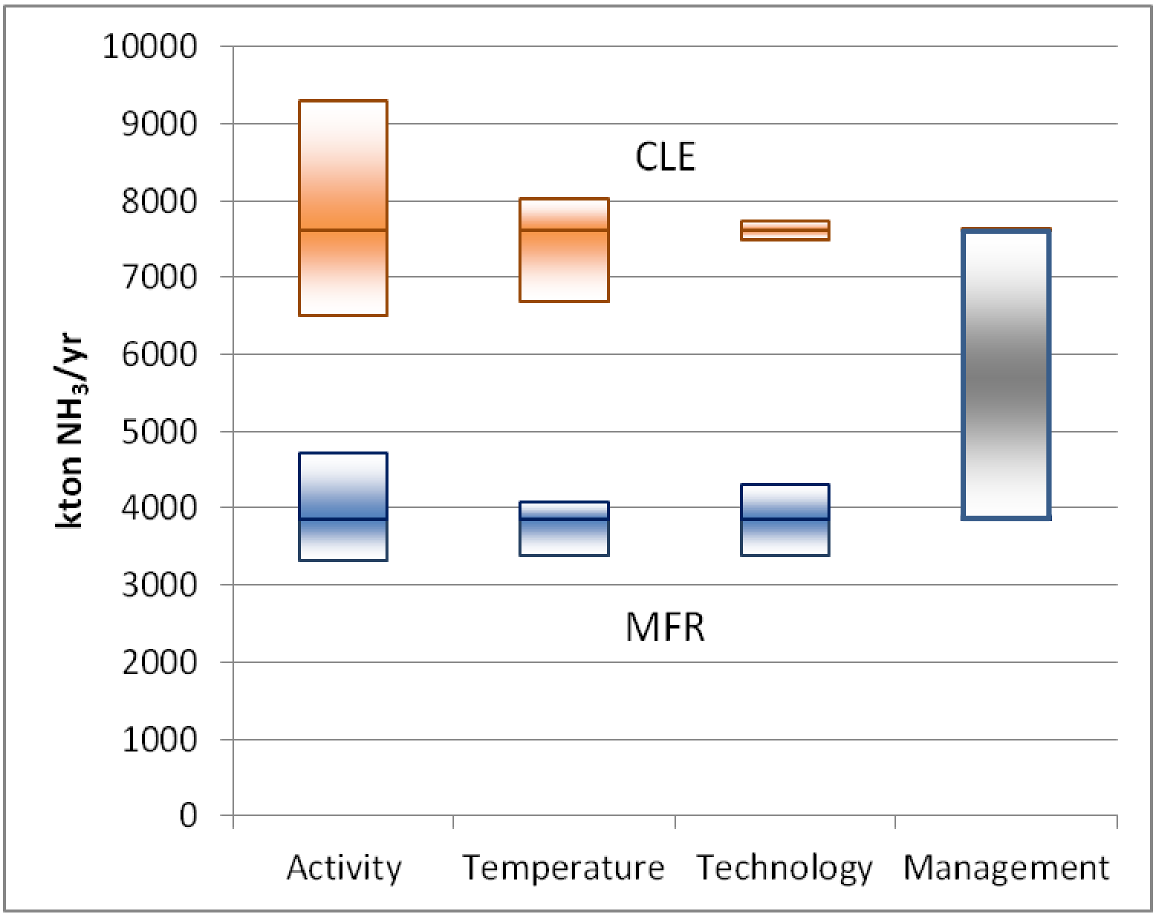

Figure 3: Emissions of NH_3 and ranges of uncertainty of future emissions (“nominal 2100”) as the total of 40 European countries

6. References

Amann M, Bertok I, Borken-Kleefeld J, Cofala J, Heyes C, Höglund-Isaksson L, Klimont Z, Nguyen B, Posch M, Rafaj P, Sandler R, Schöpp W, Wagner F, Winiwarter W (2011). Cost-effective control of air quality and greenhouse gases in Europe: modeling and policy applications. Environmental Modelling and Software 26, 1489-1501.

Amann M, Bertok I, Borken-Kleefeld J, Cofala J, Heyes C, Höglund-Isaksson L, Kiesewetter G, Klimont Z, Schoepp W, Vellinga N, Winiwarter W (2015). Adjusted historic emission data, projections, and optimized emission reduction targets for 2030 - a comparison with COM data 2013. Part A: Results for EU-28. TSAP Report #16A, V1.1, International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria.

Posch M, Hettelingh J-P, Slootweg J, Reinds GJ (2014). Deriving critical loads based on plant diversity targets. In: Slootweg J, Posch M, Hettelingh J-P, Mathijssen L (eds), 2014. Modelling and mapping the impacts of atmospheric deposition on plant species diversity in Europe: CCE Status Report 2014. RIVM Report 2014-0075, Coordination Centre for Effects, Bilthoven, Netherlands, pp. 41-46; www.wge-cce.org

IPCC (2013). Climate Change 2013: The Physical Science Basis. Cambridge University Press, Cambridge, UK.

Klimont Z, K Kupiainen, Ch Heyes, W Schöpp, L Höglund-Isaksson (2012). Updated GAINS database including reference emission scenario. Deliverable: D1.1, ECLIPSE (Evaluating the Climate and Air Quality Impacts of Short-Lived Pollutants) Collaborative Project, Project no. 282688 , Laxenburg, July 2012 (report restricted).

Nakicenovic N, R Swart (2000). Special Report on Emissions Scenarios (SRES). Cambridge University Press, Cambridge, UK.

Reinds GJ, et al. (2015) Deliverable D15.4 Assessments of the effects of combined air pollution and climate change scenarios on plant species diversity and soil quality. ECLAIRE project.

Reinds GJ, J Mol, L Bonten, W Wamelink, J-C Voogd (2015). The PROPS Vegetation model: New Developments. Presented at the 25th CCE Workshop and 31st meeting of the ICP TF on Modelling and Mapping, 20-23 April 2015, Zagreb, Croatia.

van Vuuren D P, Edmonds J, Kainuma M, Riahi K, Thomson A, Hibbard K, Hurtt G C, Kram T, Krey V, Lamarque J-F, Masui T, Meinshausen M, Nakicenovic N, Smith S J, Rose S K (2011). The representative concentration pathways: an overview. Climatic Change 109, 5–31.

Winiwarter W, JW Erisman, J N Galloway, Z Klimont and M A Sutton (2013). Estimating environmentally relevant fixed nitrogen demand in the 21st century. Climatic Change 120, 889-901.

Winiwarter W, W Schöpp, G Kiesewetter, M Amann, M Posch, J-P Hettelingh, D Simpson (2014). ECLAIRE deliverable D20.6 – Assessment of sensitivities and uncertainties of the scenarios, considering the effects of management changes. International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria.

Winiwarter W, M Engardt, A Cescatti, C Howard (2015) ECLAIRE deliverable D21.2 – ÉCLAIRE scenario reference. International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria.

Annex:
Consensus paper on forest N impacts

Compiled by: W. Winiwarter

Contributors, Panelists and Discussants at the Budapest workshop and beyond:
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This paper has been compiled as an outcome after the ECLAIRE Panel discussion at the occasion of the ECLAIRE Open Science Conference in Budapest, Sept. 29, 2014.

An ÉCLAIRE consensus on nitrogen impacts to ecosystems

Introduction

At the occasion of the ÉCLAIRE general assembly in Budapest, September 2014, a panel discussion was organized to better understand and evaluate the impact of nitrogen on forest ecosystems. Focus of the discussion was the impact of nitrogen to forest growth. Nitrogen impacts on biodiversity, within ÉCLAIRE, will be dealt with in a separate parameterization, taking advantage of the “habitat suitability index” developed by the Coordination Centre for Effects (CCE) of the ICP Modelling & Mapping (see Hettelingh et al., 2014). It has been observed in both experimental and large scale field studies that forest growth is stimulated by i.a. nitrogen impacts (e.g. Magnani et al., 2007), but studies on a European level came to the conclusion that this stimulation may be reversed at elevated N deposition levels (Nellemann and Thomsen, 2001, Kint et al., 2012). The discussion was set up in order to evaluate whether this fertilization aspect of nitrogen pollution would go in opposing directions for biodiversity issues (limiting N application) on the one hand and forest growth consideration (requiring additional input) on the other hand and thus evade optimization algorithms. The key question posed to the panel (consisting of Markus Amann (chair), Sabine Braun, Lisa Emberson, Mike Holland and Wim de Vries) was to what extent and up to which N deposition level the impact of nitrogen on European ecosystems may be considered beneficial or represents a threat.

Looking at the full picture

The impact of nitrogen on vegetation and vegetation growth comes in many facets, and interactions with other nutrients, with other compounds need to be considered as well as different considerations are needed when looking at individual species or whole ecosystems. Finally, ways of addressing the problems may vary, depending on the priorities set: the “ecosystems service” allows considering nature as one element of overall economy, while a perspective of planetary (or regional) boundaries would in principle prioritize ecological integrity above economic needs.

In a nutshell, adding nitrogen can stimulate growth of forests up to a certain N deposition level and possibly over a limited time period due to other limitations, such as deficiencies in phosphate and base cations. Also when considering interactions with ozone, the statement holds – biomass growth increases with higher N, but at higher ozone this increase will be diminished (in other words: nitrogen use efficiency will be hampered at presence of ozone). While the relationship is not considered linear, there are linear aspects, and clearly no tipping points visible.

In a long-term view, problems and damage due to (accumulated) nitrogen input become apparent. De Vries et al. (2014) provide a review of the existing literature, in which several phases of nitrogen inputs are differentiated (Fig. 1). At rates below a change point of N_1, the amount of N retained in the system is not affected – basically any additional N can be used. Net primary production (NPP) increases with increased nitrogen. At higher inputs ($<N_2$), the system starts to become leaky, losing nitrogen. Still NPP increases, albeit at a smaller rate. With nitrogen inputs exceeding the change point N_2, leakage further increases while also NPP starts to become smaller, thus causing also economic damage. But only above N_3 will NPP be as small as or even lower than without external nitrogen input.

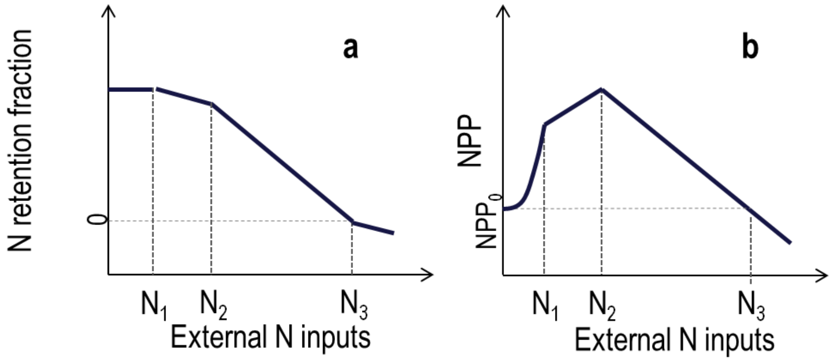

Fig. 1: Schematized nonlinear responses of (a) N retention efficiency and (b) net primary production (NPP) to external of N inputs to forests (de Vries et al., 2014). N1 indicates a change point at which N retention efficiency starts to decrease and the NPP increase levels off. N2 indicates a change point at which forest ecosystem start to become N saturated and NPP declines with further N addition. N3 indicates a change point at which forest ecosystems are completely N saturated and NPP is below the value at no addition.

Quantifying nitrogen levels impairing forest growth

De Vries et al. (2014) attempt to quantify these change points, based on available literature. Quantifications based on long-term field data, implicitly accounting for historic accumulation of N, are presented in Table 1. One prominent example taken from the literature data is based on Kint et al. (2012), who quantified growth impacts with respect to nitrogen inputs for the case of Belgian forests, using the decrease of the basal area increment (BAI) as a parameter. The result, presented in Fig. 2, is consistent with the change point N_2illustrated in Table 1near 20 kg N ha^{-1} yr^{-1}.

Table1: long-term change points of external nitrogen inputs to forests (according to de Vries et al., 2014, all values in kg N ha^{-1} yr^{-1})

	N_1	N_2	N_3
Long-term field data	10 – 15	15 – 35	25 – 65

The ranges presented indicate that change points may vary depending on local conditions such as the buffer capacity of the soil and the related availability of base cations and phosphate, interactions with climate and parasite infestation.

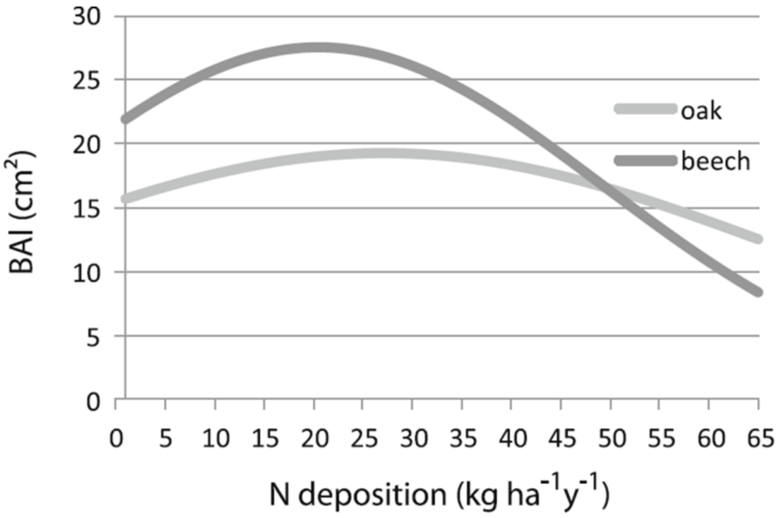

Fig. 2: Effect of N deposition on Basal Area Increment (BAI) in Flemish forests (Kint et al., 2012)

As the combination of Fig. 2 and Table 1 indicates, there may already be no further growth increase on the longer term, at a deposition of around 15 kg N (the lower range of change point N_2). Considering a precautionary principle, the lower end value for N_2, 15 kg N ha^{-1} yr^{-1}, is suggested as a threshold to describe growth impacts.

A number of underlying causes are due to a decline in growth (NPP) response to N deposition, including a limiting availability of phosphate and base cations. The latter is induced by both enhanced base cation demand and acidification induced enhanced base cation leaching. Especially decreased soil quality due to acidification may play a role, when soil cations are mobilized by the addition of nitrogen compounds (ammonia and nitrogen oxides) over long time periods. In this context sulphur deposition also plays a role. Whether N deposition leads to a depletion of base cations depends on the rate of N leaching causing related base cation leaching and the rate of base cation uptake versus the input by deposition and weathering. Braun et al. (2010) demonstrated that nitrogen input around 15-20 kg N/ha/yr is no longer stimulating growth in Swiss forest observation plots. The reason for this is probably phosphorus limitation, as a result of impaired phosphorus uptake due to N effects on mycorrhiza.

The change point N_1 of 15 kg N ha^{-1} yr^{-1} , being a threshold to describe growth impacts is not meant to supersede thresholds of other endpoints for ecosystem impacts, such as biodiversity or acidification. in this context, Critical Loads for nitrogen have been set at 5-15 kg N ha^{-1} yr^{-1} for coniferous woodland and 10-20 kg N ha^{-1} yr^{-1} for deciduous woodland to avoid overall negative impacts on soil processes (e.g. ammonium accumulation), nutrient balances, mycorrhiza composition and ground vegetation. (Bobbink and Hettelingh, 2011) These ranges are lower than the range for N1, but near the lower value of 15 kg N ha^{-1} yr^{-1} .

Conclusions

Experimental and field evidence clearly shows that forest growth is elevated at relatively low N inputs and impaired by high nitrogen inputs, especially over long time periods. The deposition level at which the growth response declines depends on time and on the impact of other limiting factors which include nutrients and interactions with climate and parasite infestation. Work to better understand these relationships is in progress but results will not be finalized in time for use in ECLAIRE. Progress during ECLAIRE may include tentative revisions of findings described in this document. According to a literature evaluation (de Vries et al., 2014), on the long term, N depositions above 15 kg N ha^{-1} yr^{-1} may already have negative impacts on growth. This is in the range of Critical Loads set for coniferous forests of 5-15 kg N ha^{-1} yr^{-1} and for deciduous forests of 10-20 kg N ha^{-1} yr^{-1} (Bobbink and Hettelingh, 2011) based on negative impacts on soil processes (e.g. ammonium accumulation), nutrient balances, mycorrhiza composition and ground vegetation. Therefore, and from a precautionary principle point of view, an indicative deposition value of 15 kg N ha^{-1} yr^{-1} is proposed as a threshold related to forest growth impairment while acknowledging that other (even lower) change points may exist when other endpoints are incorporated.

In summary, long term growth responses are to be expected up to 15 kg N $ha^{-1}yr^{-1}$. At this value, there may still be adverse impacts on other ecosystem compartments, such as changes in ground vegetation and in mycorrhiza, and an increased occurrence of free-living algae. Below an N input of 5-10 kgN ha^{-1} yr^{-1} these effects hardly occur.

References

Bobbink, R., Hettelingh, J.-P., 2011. Review and revision of empirical critical loads and dose-response relationships. Proceedings of an expert workshop, Noordwijkerhout, 23-25 June 2010. RIVM report 680359002 Coordination Centre for Effects, National Institute for Public Health and the Environment (RIVM),

Braun, S., Thomas, V.F.D., Quiring, R., Flückiger, W., 2010. Does nitrogen deposition increase forest production? The role of phosphorus. Environmental Pollution 158, 2043–2052. doi:10.1016/j.envpol.2009.11.030

De Vries, W., Du, E., Butterbach-Bahl, K., 2014. Short and long-term impacts of nitrogen deposition on carbon sequestration by forest ecosystems. Current Opinion in Environmental Sustainability 9-10, 90–104. doi:10.1016/j.cosust.2014.09.001

Hettelingh, J-P, Posch, M, Slootweg, J, 2014. Critical Loads: Call for Data. 33rd session of the Working Group on Effects. Geneva, 17-19 Sep 2014.

Kint, V., Aertsen, W., Campioli, M., Vansteenkiste, D., Delcloo, A., Muys, B., 2012. Radial growth change of temperate tree species in response to altered regional climate and air quality in the period 1901-2008. Climatic Change 115, 343-363.

Nellemann, C., Thomsen, M. G., 2001. Long-term changes in forest growth: Potential effects of nitrogen deposition and acidification. Water, Air and Soil Pollution 128, 197-205.

Magnani, F., Mencuccini, M., Borghetti, M., Berbigier, P., Berninger, F., Delzon, S., Grelle, A., Hari, P., Jarvis, P.G., Kolari, P., Kowalski, A.S., Lankreijer, H., Law, B.E., Lindroth, A., Loustau, D., Manca, G., Moncrieff, J.B., Rayment, M., Tedeschi, V., Valentini, R., Grace, J., 2007. The human footprint in the carbon cycle of temperate and boreal forests. Nature 447, 849–851. doi:10.1038/nature05847