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ACHIEVEMENTS REPORT ON OPEN INTERDISCIPLINARY CASE STUDIES HIGHLIGHTING THE COMMON OPERATION OF NETWORKS

WORK PACKAGE 4

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Abstract

It is widely recognized that Europe and the world is undergoing a period of profound ecosystem changes and that climate change and global change still remain the most difficult societal challenges to confront. Environmental Research infrastructure (ERIs) provides all necessary instruments and tools for scientists in their quest for understanding the underlying principles of the global change and its effects. However, the societal needs do not only require answers to the why, but also needs answers to how to solve these problems. New challenges require new perspectives to be taken, and hence adapting and adjusting the infrastructures related. This is especially the case in the field of environment and climate related aspects. The purpose of this white paper is to identify ERIs reforms and investments that will deliver these aspirations. In other words build bridges across networks of observatories and determine how emerging environmental research questions can benefit from these new interactions and synergies using concrete and representative showcases. The paper reveals the need for more improvement of ERIs linkages and coordination alongside scientific communities synergies to actively mitigate the risk of reactive nitrogen on ecosystem system services, monitoring stressors with the level of accuracy and temporal frequency (cf. O_3) and finaly enhance spatial coverage of current infrastructure to better assess and understand the state of methane sources in the Arctic regions and its influence on global warming.

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INTRODUCTION

Europe currently enjoys access to many world-class Environmental Research infrastructure (ERIs) services. Such infrastructures have strongly benefited research possibilities in Europe, and by this also the positive aspects of research on the competitiveness of the European society and on the daily life of citizens. The expectations towards such research networks change. First of all, the increasing complexity of society requiring more complex research infrastructure to become available. Moreover, new challenges require new perspectives to be taken, and hence adapting and adjusting the infrastructures related. This is especially the case in the field of environmental infrastructures and climate related aspects.

Europe and the world is undergoing a period of profound ecosystem changes (Ecosystems services are threatened by climate change, land-use change, pollution, soil degradation and loss of biodiversity…) and in 15 years' time or less Europe will be a very different continent from the one it is today. If ecosystem dynamics are not understood, Europe will not be able to assess the impacts, control the risks or adapt to the changes that will affect these ecosystems. In other words European society's growing number of complex issues related to ecosystem changes and degradation calls for an integrated research infrastructure to understand and support decision-making. In addition to a need to cut across academic boundaries, there is a need for "multi-stakeholder" projects gathering the public, academia, land managers, and policy makers. While the ideas of working with complex systems and inter/trans-disciplinary research have achieved a certain popularity, they have not reached their full potential.

Our ecosystem-related problems are still typically considered separately: soil and water quality, greenhouse gas emissions (GHG) (CO_2, N_2O, CH_4, O_3…), public health, loss of biodiversity, and more. Each has its own ERIs, databases, funding streams, and researchers assigned to it. With no agreement in place to restore climate stability and with few years left to ensure that there is sufficient ecosystem resilience in ecosystems before the hard effects of climate change commence, it is time to stop simply looking at the symptoms. It is time to pool our resources— funding, data, and human ingenuity — so that we can successfully address the root cause of systemic degradation of ecosystems, environmental pollution, this can only be done by connecting and upgrading environmental research infrastructures. Nearly all of our most pressing issues can be alleviated by ensuring connectivity of ERIs and integrated approaches to solving problems, along with open data access and ensuring cross-ERI interoperability.

Success stories in every region and ecosystem inform us — many of these success stories are based on use of indigenous knowledge. Simple principles, observable in natural systems everywhere, and already verified by extensive research infrastructure tools, can guide our actions. Our next step is to create the conditions for ecosystem to be comprehensively viewed — based on integrated ERIs — as a dynamic learning project, open to all, with natural ecologies as the leading authorities. Great progress have been achieved in the prior periods of ENVRI, but that is now over. The world is changing, new challenges are ahead and this applies equally to research infrastructures – which anyway suffer from an inherent time lag – they need to be adjusted, or where not existing, created quickly in order to provide meaningful results to society.

The complementarity and synergistic relationships among ERIs play a crucial role in solving complex environmental questions. As mentioned above we are facing new and emerging environmental challenges, with significant risks of losing ecosystem resilience if we don't act quickly, and consequently losing out on ecosystem services. Anthropogenic impacts are becoming more apparent and these compromise adaptation and call on us to rethink our strategic governance of ERIs to deliver services, ones which strengthen our role in preventing the risks of ecosystem failure and support a transition to a more sustainable and resilient economy.

The purpose of this white paper is to identify ERIs reforms and investments that will deliver these aspirations. In other words, we must build bridges and ensure we have networks of observatories in place and we must determine how emerging environmental research questions can benefit from the use of these new networked interactions and synergies. The white paper will focus on three showcase examples. Beyond their apparent simplicity, they demonstrate exactly what we have been missing to date in earlier ENVRI initiatives:

1. Nitrogen from the field to the coastal ocean
2. Simulating and monitoring O_3 and CO_2 deposition/coupling/interaction
3. Arctic observation, with a special focus on CH_4

1. NITROGEN, FROM AGRICULTURAL FIELDS TO COASTAL OCEAN: THE CONCEPT OF NITROGEN BUDGETS AND COROLLARY RESEARCH INFRASTRUCTURES CONTRIBUTIONS

Humankind's contribution to the amount of nitrogen available for plants on land is now five times higher than it was 60 years ago. The anthropogenic fixation of atmospheric, non-reactive molecular nitrogen to plant-available reactive nitrogen (Nr), globally, has surpassed the natural amount[1], including that of the global oceans, with significant effect on vegetation world-wide. Human activity creates reactive nitrogen through three mechanisms: (1) encouragement of biological nitrogen fixation associated with agriculture; (2) production of synthetic nitrogen fertilizer; and (3) inadvertent creation of reactive nitrogen through reaction with oxygen as fossil fuels are burned[2]. Paralleling the massive growth of atmospheric carbon, main culprit of climate change, the increasing availability of nitrogen could pose as much of a danger to Earth's environment[3]. Nitrogen-based fertilizers helped prompt the agricultural revolution to respond to food demand. But that revolution came at a cost: artificial fertilizers, often applied in amounts beyond crops need to grow, are carried in runoff from farmland into streams, lakes and costal areas. Excess nitrogen compounds in waterways and lakes cause toxic algal blooms, killing off aquatic species through widespread hypoxia and anoxia in addition to habitat degradation, alteration of food-web structure, loss of biodiversity [4,5]. Too much nitrogen in the soil benefits a limited number of species that can outcompete native species, again reducing biodiversity. Moreover, abundance of nitrogen compounds reduces retention against release into the atmosphere, where it contributes to air pollution as NH_3 or NO, or to climate change as N_2O[6].

Despite improvements in crop production and nitrogen fertilizer efficiency, large losses of Nr to the environment are still common from agricultural systems through transport of nitrate to groundwater or surface waters and through emissions of nitrogen gases to the air[7] Given public concern about environmental nitrogen losses and their strong relationship with nitrogen balance, coordinated ERIs networks to monitor nitrogen fluxes are required.

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[1] Fowler, D., Coyle, M., Skiba, U., Sutton, M.A., Cape, J.N., Reis, S., Sheppard, L.J., Jenkins, A., Grizzetti, B., Galloway, J.N., Vitousek, P., Leach, A., Bouwman, A.F., Butterbach-Bahl, K., Dentener, F., Stevenson, D., Amann, M., Voss, M., (2013). The global nitrogen cycle in the twenty-first century. Philosophical Transactions of the Royal Society B: Biological Sciences 368, 20130164–20130164. https://doi.org/10.1098/rstb.2013.0164

[2] Galloway, J.N., Dentener, F.J., Capone, D.G., Boyer, E.W., Howarth, R.W., Seitzinger, S.P., Asner, G.P., Cleveland, C.C., Green, P.A., Holland, E.A., Karl, D.M., Michaels, A.F., Porter, J.H., Townsend, A.R. and Vörösmarty, C.J. (2004). Nitrogen cycles: past, present and future. Biogeochemistry 70 (2), 153-226.

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[4] Howarth, R.W., Anderson, D., Cloern, J., Elfring, C., Hopkinson, C., Lapointe, B., Malone, T., Marcus, N., McGlathery, K., Sharpley, A., Walker, D., (2000). Nutrient pollution of coastal rivers, bays, and seas. Issues Ecol. 7, 1–15.

[5] Boesch, D.F., (2002). Challenges and opportunities for science in reducing nutrient over-enrichment of coastal ecosystems. Estuaries 25, 744–758.

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[7] Lassaletta, L., Billen, G., Grizzetti, B., Anglade, J., Garnier, J., (2014). 50 year trends in nitrogen use efficiency of world cropping systems: the relationship between yield and nitrogen input to cropland. Environmental Research Letters 9, 105011. https://doi.org/10.1088/1748-9326/9/10/105011

Currently a number of ERIs at the European level routinely monitor Nr of compounds in the atmosphere (NOx, PM) as well as in groundwater (nitrate) as part of European environmental legislation. Tall tower stations have been linked to allow inverse modeling of GHGs (including N_2O) by scientists (TTORCH, InGOS) which can be extended by satellite information on NOx and N_2O from platforms like ENVISAT. Biosphere-pedosphere interaction on Nr compounds in soils and groundwater are being investigated in natural ecosystems but are much more relevant in agricultural systems that are exposed to high levels of fertilizer nitrogen. Many agricultural research institutes over Europe collect this information, but without systematic interaction across national borders. All these sectoral activities require an overarching approach. Nitrogen budgets describing all linking elements between environmental pools or source sectors need a coordinated scientific effort, open data and interactive maps.

A need for coordinated scientific effort and ERIs connectivity to tackle nitrogen cycle complexity

Monitoring the multitude of nitrogen processes, sources and impacts over time is key to understanding the complexity of nitrogen cycles but also to provide comprehensive continental-scale assessment covering all main effects of nitrogen. This reflects the extreme complexity of the nitrogen cycle, with research communities tending to separate by scientific specialization and specific ERIs. For instance researchers of atmospheric chemistry may understand well the complexity of photochemical ozone production based on oxidized nitrogen gases but possibly have limited awareness of carbon-nitrogen interactions in forestry, agroecosystem, on the biodiversity implications of nitrogen deposition, or of the consequences of nitrogen-phosphorus interactions for 'dead zones' in coastal waters. Despite the number of ERIs and the huge scientific expertise at the European level on different aspects of the nitrogen problem, the limited degree of coordination among ERIs and the partitioning of specialized scientific communities hinder the development of effective mitigation strategies to the different environmental threats. We need to reinforce ERIs linkages and ensure coordination alongside existing scientific communities synergies in order to actively mitigate the risk of Nr on ecosystem system services.

Shifting toward an open-data culture among ERIs and creating interactive maps

As mentioned above ERIs measurements of reactive N do exist, but the data acquired and information produced remain scattered, sectored, incomplete and non-global. Data description (metadata) is not sufficiently honored and therefore incomplete – as a result, even accessible datasets require further interpretation. As a result, scientific knowledge is not fully harnessed by environmental research community, rarely reaches decision-makers, especially at the local land management or policy scale. It also doesn't reach consumers, who are keen to support farmers who make effective changes in their nitrogen uses.

Development of collaborative platforms and tools are not, by themselves, bearing fruits. Competition still dominates among ERIs; datasets are increasingly considered as "private". Trust and training around ERIs staff in data sharing early on would contribute to develop a culture of open data in the academic, research, and technology sectors. Note that in some regions, open data on land improvements could lead to issues with personal safety and land tenure. For those situations, and for farmers who simply prefer privacy, there are methods of cloaking and aggregating data before it is published, while maintaining adequate scale and location to show meaningful even local trends. More research and development will be needed to address these aspects, while continuing to work towards fully open data sets across ERIs.

Interactive reactive N data maps are a compelling form of engagement for many ERIs and their scientific communities contributions, they can be a central organizing tool for communities to think about landscape function across whole systems and the role of the nitrogen cascades in those systems. A set of composite images showing changes in ecosystem function and services can get farmers and policy makers up out of their chairs, walking to the screen, talking animatedly to each other and pointing to squares and circles of varying shades of green surrounded by brown. With a little extra information, a rich community conversation can emerge.

2. SIMULATING AND MONITORING O_3 AND CO_2 DEPOSITION / COUPLING /INTERACTION

Tropospheric ozone is a secondary photochemical pollutant produced from precursor species such as nitrogen oxides (NOx) and volatile organic compounds (VOC)[8]. Since the pre-industrial period, concentrations of tropospheric ozone (O_3) have doubled in the northern hemisphere[9]. O_3 is a strong toxic oxidant for plants, responsible for decreases in carbon assimilation in plant ecosystems. Damages to plants occur when the molecule penetrates stomata and rapidly reacts in intercellular spaces. Typical damages are visible leaf injury, premature leaf senescence, reduced assimilation and altered allocation of carbon[10,11,12]. Moreover, environmental variables such as light, temperature, and water availability play a major role in regulating the stomatal aperture and hence ozone removal. This reactive molecule is present in trace concentration in the atmosphere (less than 100 ppbv), and is very hard to measure compared with other non-reactive greenhouse gases. UV based and new chemiluminescence sensors now allow precise and fast measurements so that Eddy Covariance can be applied to study O_3 fluxes at a scale relevant to ecosystems. Direct flux measurements in the field, associated with latent heat flux measurements allow the partitioning of total O_3 fluxes into its various sinks in the soil-plant-atmosphere continuum:

- Stomata
- Adsorption on Plant surfaces
- Gas-phase reactions with reactive VOCs and NOx

Experimental evidence from around the world suggests that stomata alone are responsible for a quota of about 40 to 80% of O_3 removed by vegetation [13].
Several research programs are investigating O_3 damage to vegetation. The International Co-operative Programme on Assessment and Monitoring of Air Pollution Effects on Forests operating under UNECE Convention on Long-range Trans-boundary Air Pollution (CLRTAP) is a network of around 800 plots established at the major forest types of Europe. There is potential to study forest conditions and to correlate this with O_3 although the trace gas is measured with passive samplers at low time resolution. The ICP-Vegetation program

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[11] Matyssek R, Clarke N, Cudlin P, Mikkelsen TN et al (2013). Climate change, air pollution and global challenges: understanding and perspectives from forest research developments in environmental science, vol 13. Elsevier, Amsterdam, p 622.

[12] Fares, S., Matteucci, G., Scarascia Mugnozza, G., et al. (2013). Testing of models of stomatal ozone fluxes with field measurements in a mixed Mediterranean forest. Atmos Environ, 67, 242–251. Available at: http://linkinghub.elsevier.com/retrieve/pii/ S1352231012010527

[13] Ducker, J. A., Holmes, C. D., Keenan, T. F., Fares, S., Mammarella, I., William Munger, J., & Schnell, J. (n.d.). Synthetic ozone deposition and stomatal uptake at flux tower sites 1. Biogeosciences. https://doi.org/10.5194/bg-2018-172.

coordinates experiments to determine the effects of ozone and develops models to estimate the influence of climatic conditions on the responses of plants to ozone, and establish critical levels for the effects of O_3 on vegetation with maps reporting regional distribution of O_3 risk. A network of direct high frequency ozone concentration and flux measurements is missing to link these excellent programs.

So far, ozone risk assessment has been based on manipulative experiments. While being able to control O_3 exposure, perturbation of the growing condition such as open top chambers may not represent realistic conditions in forests. Present regulations used to set critical O_3 levels, is mostly based on estimates of an accumulated exposure over a threshold concentration (e.g. AOT40, SUM0), while scientific consensus finds flux estimates more accurate as they include the effects of plant physiology and different environmental parameters that control uptake of ozone (not just exposure).

Long-term Eddy Covariance measurements of O_3 and CO_2 offer a great opportunity to estimate the effects of O_3 on carbon assimilation at high temporal resolution making it possible to study the effect of climate changes on photosynthetic mechanisms. O_3 may play a major role as a limiting factor. Recent studies suggest that wavelet analysis and multivariate statistical analysis may support interpretation of O_3 damage to vegetation when the co-variations of O_3 with environmental factor such as light and temperature are properly taken into account. Neural network analysis is promising where long-term observations are available.

The ECLAIRE program founded a network of European experiments for contrasting ecosystems and climates, combined with meta-analysis of unpublished datasets, to quantify how climate change alters ecosystem vulnerability to tropospheric O_3 and N deposition, including interaction with increased CO_2. For the first time a network of ozone flux measurements has been designed, unfortunately the program ended in 2015. Some of the ECLAIRE sites conferred into the ICOS infrastructure. Although ICOS has very high running costs, the platforms do not include protocols for O_3 measurements. It is strongly recommended to perform O_3 measurements especially in combination with manipulative experiments in the same ecosystems object of long-term observation.

Coupling carbon and ozone flux measurements: harnessing opportunities in long-term monitoring networks

Net ecosystem exchange (NEE) is the net CO_2 flux directly measured with EC, while Gross Primary Productivity (GPP) is derived from NEE and is the closest variable measured above canopy which can be associated to photosynthesis[14]. Carbon and ozone fluxes are coupled, as observed in agriculture and forest ecosystems[15]. In all seasons, stomatal O_3 fluxes show a particularly strong correlation in relation to GPP and NEE. While stomatal conductance has

[14] Lasslop, G., Reichstein M, Papale, D et al. (2010). Separation of net ecosystem exchange into assimilation and respiration using a light response curve approach: critical issues and global evaluation. Global Chang Biol. 16, 187–208. Available at: http://doi.wiley.com/10.
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[15] Fares, S., Vargas, R., Detto, M., et al. (2013). Tropospheric ozone reduces carbon assimilation in trees: estimates from analysis of continuous flux measurements. Global Chang Biol, 19, 2427–2443. Available at: http://doi.wiley.com/10.1111/gcb.12222.

been traditionally estimated from evapotranspiration measured with Eddy Covariance, in recent years studies have ventured alternative methods to calculate stomatal O_3 fluxes from carbon assimilation based on leaf-level measurements and semi-empirical algorithms scaled at the level of canopy and compared with GPP.

Ozone effects on vegetation are often tested according to land surface models[16]. The majority of these models consider the photosynthetic rate and stomatal conductance coupled according to the Farquhar/BWB model[17]. This implies that the effects of O_3 damage on photosynthesis and stomata are coupled to each other as O_3 damage to cell walls leads to changes in internal CO_2 concentration - which in turn cause changes in stomatal aperture.

However, direct feedback is not always responsible: as demonstrated by Fares et al.[18], the relationship between GPP and stomatal conductance changes in response to exposure to different levels of O_3 concentrations. Additional findings[19] demonstrated that O_3 induces a stomatal sluggishness which delays plant response to climatic drivers. A recent study resorted to the Community Land Model (CLM)[20] to demonstrate the separate modification of photosynthetic rates and stomatal conductance (G) through a cumulative ozone uptake is more representative of plant responses to ozone exposure.

Decoupling photosynthesis and G reduces water use efficiency, with smaller impact of ozone on carbon assimilation. Continuous long-term data acquisition of ozone fluxes via EC and other micrometeorological techniques are therefore important to parameterize models. Using wavelet analysis in combination with statistical multi-regressive analyses constitutes a promising approach when relevant time series data is available (at least one continuous year at a 30 min time resolution). These sorts of measurements are already demonstrating carbon assimilation and stomatal O_3 fluxes are tightly correlated, with possible reductions of carbon losses up to 19% in crop and Mediterranean forest ecosystems[21].

The goal for statistical analysis of O3 effects based on long time series will require refining advanced methodologies in distinguishing O_3 effects from several covariates such as irradiance,

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[16] Yue, X., Unger, N. (2014). Ozone vegetation damage effects on gross primary productivity in the United States. Atmos Chem Phys, 14, 9137–9153. Available at:,www.atmos-chem-phys.net/14/9137/ 2014/

[17] Bonan, G.B., Lawrence, P.J., Oleson, K.W., et al. (2011). Improving canopy processes in the Community Land Model version 4 (CLM4) using global flux fields empirically inferred from FLUXNET data. J. Geophys. Res. Biogeosciences, 116. Available at: http://onlinelibrary.wiley.com/doi/10.1029/2010JG001593/full.

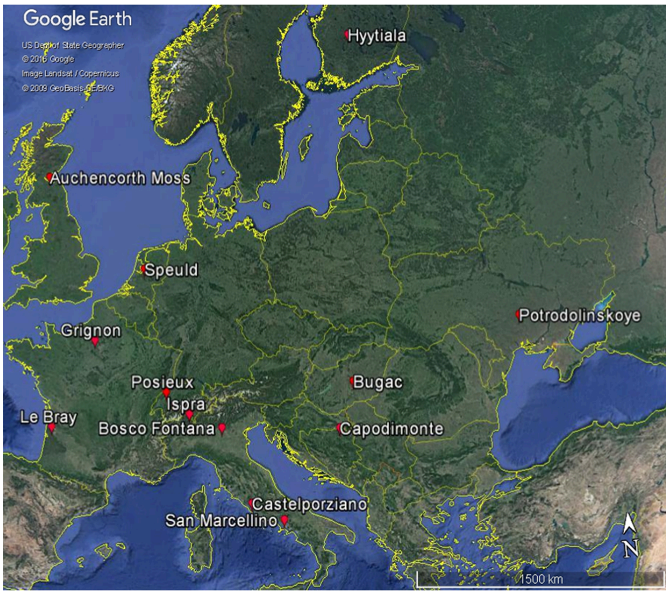
[18] Fares, S., Vargas, R., Detto, M., et al. (2013). Tropospheric ozone reduces carbon assimilation in trees: estimates from analysis of continuous flux measurements. Glob Chang Biol, 19, 2427–2443. Available at: http://doi.wiley.com/10.1111/gcb.12222.

[19] Hoshik Hoshika, Y., Katata, G., Deushi, M., et al. (2015). Ozone-induced stomatal sluggishness changescarbon and water balance of temperate deciduous forests. Sci Rep, 5, 9871. Available at: http://www.ncbi.nlm.nih.gov/pubmed/25943276

[20] Lombar dozzi, D., Levis, S., Bonan, G., et al. (2012). Predicting photosynthesis and transpiration responses to ozone: decoupling modeled photosynthesis and stomatal conductance. Biogeosciences, 9, 3113–3130. Available at: www.biogeosciences.net/9/3113/2012/.

[21] Fares, S., Vargas, R., Detto, M., et al. (2013). Tropospheric ozone reduces carbon assimilation in trees: estimates from analysis of continuous flux measurements. Glob Chang Biol, 19, 2427–2443. Available at: http://doi.wiley.com/10.1111/gcb.12222.

temperature and vapour pressure deficit (VPD). As stressed by Hardacre et al. (2015)[22], a better model parameterization of O_3 deposition in its various sinks depends on long-term flux measurements, at least over a full seasonal cycle, from land cover classes broadly representative of a wider region. With regards to Europe, 13 key agricultural and forest sites were found where O_3 flux measurement studies have been carried out for at least one vegetative season (Figure 1).



Ecosystem	Site	Since	O_3 analyser	Network
Forest	Hyytiala - FI	2012	High frequency gas analyser (LOZ-3) / Fast Ozone analyser – Sextant	ECLAIRE EEFDC
	Speuld – NL	2012	Fast Ozone analyser – Sextant	ECLAIRE
	Bosco Fontana - IT	2012	Chemiluminescence Ozone Fast Analyser (COFA)	ECLAIRE EEFDC
	Ispra Forest - IT	2012	Fast Ozone Sensor FOS - Sextant / Slow ozone sensor 49C - Thermo	ECLAIRE
	Castelporziano - IT	2012	Fast-response O3 sensors - NOAA	ECLAIRE EEFDC
	Le Bray - FR	2003	Fast O3 chemiluminescent based close-path sensor (ATDD V2.0)	EEFDC
Grassland	Bugac - HU	2012	Fast O3 analyser - Enviscope	ECLAIRE
	Auchencorth Moss - UK	2012	Rapid Ozone Flux Instrument (ROFI)	ECLAIRE
	Posieux - CH	2012	Fast O3 analyser - Enviscope	ECLAIRE
Cropland	Grignon - FR	2004	Fast O3 analyser - Sextant	ECLAIRE EEFDC
	Potrodolinskoye - UE	2012	Rapid Ozone Flux Instrument (ROFI)	ECLAIRE
Urban forest	Capodimonte - IT	2015	1108 Ozone Analyzer – Dasibi / Fast Ozone analyzer - Sextant	EEFDC
Urban	San Marcellino - IT	2014	Fast analyser (FOS Sextant) and slow analyser (2B-Technologies, 205).	EEFDC

Figure 1. Figure 1. Map of some agricultural and forest sites where ozone fluxes have been measured for at least one vegetative season. Data were selected from the ECLAIRE website (http://www.eclaire-fp7.eu/) and EUROPE FLUX database (http://gaia.agraria.unitus.it/home/sites-list)

We would thus contend that field observations, especially when using existing forest monitoring networks, is the best method for studying and improving our understanding of O_3 effects.

Path forward and ERIs improvement

Field observations represent the best method for studying O_3 effects, especially when using existing forest monitoring networks. The use of passive samplers to sample O_3 conditions at high-temporal frequency cannot be achieved. More efforts should be devoted to collect direct measurements of ecophysiological features of vegetation. The importance of achieving long-term measurements of O_3 fluxes, in parallel with all ancillary measurements and carbon fluxes is highly recommended. This can only be achieved through a coordinated improvement of existing ecological infrastructures currently investigating CO_2 fluxes and plant ecophysiology[23]. Interpreting ecophysiolological responses to O_3 and climate change through combing O3 measuremnts from a coordinated network of flux sites and modelling would

[22] Hardacre, C.,Wild, O., Emberson, L. (2015). An evaluation of ozone dry deposition in global scale chemistry climate models. Atmos Chem Phys, 15, 6419–6436. Available at: http://www.atmos-chem-phys.net/15/6419/2015/

[23] Fares, S., Conte, A., & Chabbi, A. (2017). Ozone flux in plant ecosystems: new opportunities for long-term monitoring networks to deliver ozone-risk assessments. Environmental Science and Pollution Research. https://doi.org/10.1007/s11356-017-0352-0

support our understanding of O_3 damage to vegetation, provided O_3 covariations with environmental factors (such as light and temperature) are able to be properly taken into account.

While the scientific community has established long-term ERIs to measure carbon assimilation in response to climate changes (i.e. the ICOS infrastructure), the adoption of low-cost and fast O_3 sensors for EC measurements would constitute a valuable effort in bettering our understanding of carbon assimilation in response to environmental stresses thus supporting ozone-risk assessment. Such an effort would also help attain national commitments within the recent European Parliament directive 2016/2284 on the reduction of national emissions of certain atmospheric pollutants (including O_3) which suggests carbon fluxes may be used as a key indicator for monitoring air pollution impacts on terrestrial ecosystems[24].

[24] Marco, A. De, Proietti, C., Anav, A., Ciancarella, L., Elia, I. D., Fares, S., … Leonardi, C. (2019). Impacts of air pollution on human and ecosystem health , and implications for the National Emission Ceilings Directive : Insights from Italy. Environment International, 125, 320–333. https://doi.org/10.1016/j.envint.2019.01.064.

3. ARCTIC OBSERVATION, WITH SPECIAL FOCUS ON CH_4

Climate change will continue to have significant effects across the globe and in no region will these effects be greater than the Arctic[25,26]. Although human activity is increasing in the Arctic region, it is primarily through human-induced climate change that the Arctic region is currently most affected. The Arctic has increased in temperature by 0.6° Celsius each decade for the past 30 years. This change is approximately double the global average and is projected to increase at even faster rates in the future[27] as part of a phenomenon referred to as the Arctic amplification. This will have unprecedented effects on both the oceanic and continental systems of the region: mitigation has become a large scientific and societal imperative — firstly for Arctic natives who rely on subsistence harvests (fish, caribou, seal, walrus, water fowl, etc.) and whose shoreline and hunting and fishing habitats are rapidly disappearing.

Changes in the cryosphere present a series of challenges, opportunities and risks that have yet to be fully understood with regard to feedback loops and albedo changes that can further amplify the impacts of climate change. Permafrost contains large quantities of water as well as carbon and methane made up of plant and animal remnants stored in soil for hundreds to thousands of years. Increased warming in the Arctic can thaw a deeper portion of the active layer or completely free an area of permafrost, converting the area from a carbon sink into a carbon-emitting system. Temperatures in the Arctic permafrost have risen by up to 2° Celsius over the past decades, and permafrost limits have retreated northwards by up to 100 km in parts of the Arctic. Warming regional seas in the Arctic are also causing thawing of sub-sea permafrost. None of the climate projections in the latest IPCC AR5 include carbon emissions from thawing permafrost, despite estimations that Arctic permafrost stores as much as twice the amount of carbon present in the atmosphere. These potential emissions will interfere with the objective of keeping the global temperature increase below the 2° Celsius target[28]. Releases of methane over vast areas, especially in the Russian Arctic tundra will reduce significantly the “emission budget” affordable to humans to remain below a global 2°C temperature increase and certainly not within the 1.5°C target[29].

Thawing permafrost is a significant source of greenhouse gases, as thawing soil and subsequent decomposition of organic matter by microbes release CO_2 and methane greenhouse gases into the atmosphere. Tundra wildfires following thawing permafrost further add to greenhouse gas emissions. Current estimated fluxes of arctic CH_4 from biological and geological processes are

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[25] IPCC 2014

[26] Hobbie, J.E., Shaver, G.R., Rastetter, E.B., Cherry, J.E., Goetz, S.J., Guay, K.C., Gould, Kling, W.A. (2017). Ecosystem responses to climate change at a Low Arctic and a High Arctic long-term research site Ambio. 46, 160–173. doi: 10.1007/s13280-016-0870-x

[27] IPCC 2013

[28] Nisbet, E. G., Manning, M. R., Dlugokencky, E. J., Fisher, R. E., Lowry, D., Michel, S. E., Lund Myhre, C., Platt, S. M., Allen, G., Bousquet, P., Brownlow, R., Cain, M., France, J. L., Hermansen, O., Hossaini, R., Jones, A. E., Levin, I., Manning A. C., Myhre, G.,Pyle, J. A., Vaughn, B., Warwick, N. J., White, J. W. C. (2019). Very strong atmospheric methane growth in the four years 2014‐2017: Implications for the Paris Agreement, Global Biogeochemical Cycles https://doi.org/10.1029/2018GB006009

[29] Gasser, T., et al., (2018). Path-dependent reductions in CO_2 emission budgets caused by permafrost carbon release, Nature Geosci., https://doi.org/10.1038/s41561-018-0227-0.

relatively moderate. They have, however, the potential to become the main emission source in global atmosphere, with rates not previously seen in human history. This is due to biological processes that transform carbon into CH_4, large arctic sources of C (2/3 of all C stored globally), changing environment that fosters this transformation and spatially heterogeneous venting of geologic sources (through the sea) that are difficult to regionally quantify.

The Arctic Ocean's shelves extend beyond Northern Russia and these are also emitting methane through gas hydrate destabilization. In the Arctic oceanic and coastal environments, a relatively new source of CH_4 has been reported in methane hydrate gas production, which is venting through the oceans and this could potentially significantly contribute to atmospheric concentrations. It is considered cold water temperatures (providing slow reaction rates), near coastal areas (bio-accumulation sources) and deep water (pressure) are essential to the formation of those deposits. But as ocean temperatures warm, there is real concern regarding accelerated release of solid methane hydrate into gaseous CH_4 due to its destabilization. Attempts to estimate methane hydrates fluxes are more expensive than terrestrial CH_4 research, as they require ships, ship time and sea floor observatories (EMSO). Because of such constraints, measurements are typically collected through ad-hoc cruises and even when large deposits are formed, their fluxes into the atmosphere are spatially heterogeneous. However, with methane hydrates being a potential energy source, energy exploration may serendipitously help scientists access and study these CH_4 reserves.

While still a minor component of the global CH_4 budget[30], this source term has a strong potential for large amplification due to a combination of water temperature increase including Atlantic warm water intrusion [31,32] and shoreline erosion. Biogenic methane release from thawing subsea permafrost in the East Siberian Arctic Shelf, notably, has been shown to overcome anaerobic oxidation in the upper sediment layer and to be able to reach the water column and eventually the atmosphere [33].

A need for an adequate infrastructure to monitor CH_4 fluxes

Processes responsible for the release of CH_4 from natural land sources appear to be closely linked to temperature and precipitation and vulnerable to climate change. Such atmospheric processes are considerably more complex for CH_4 than for CO_2. As such, processes and drivers that govern methanogenesis and CH_4 reduction and consumption are the subject of active

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[30] Berchet, A., Bousquet, P., Pison, I., Locatelli, R., Chevallier, F., Paris, J.-D., Dlugokencky, E. J., Laurila, T., Hatakka, J., Viisanen, Y., Worthy, D. E. J., Nisbet, E., Fisher, R., France, J., Lowry, D., Ivakhov, V., and Hermansen, O. (2016). Atmospheric constraints on the methane emissions from the East Siberian Shelf, Atmos. Chem. Phys., 16, 4147-4157, https://doi.org/10.5194/acp-16-4147-2016.

[31] Biastoch, A., et al. (2011). Rising Arctic Ocean temperatures cause gas hydrate destabilization and ocean acidification, Geophys. Res. Lett., 38, L08602, doi:10.1029/2011GL047222.

[32] Serov, Pavel, et al. (2017). "Postglacial response of Arctic Ocean gas hydrates to climatic amelioration." Proceedings of the National Academy of Sciences 114.24: 6215-6220.

[33] Sapart, C. J., Shakhova, N., Semiletov, I., Jansen, J., Szidat, S., Kosmach, D., Dudarev, O., van der Veen, C., Egger, M., Sergienko, V., Salyuk, A., Tumskoy, V., Tison, J.-L., and Röckmann, T. (2017). The origin of methane in the East Siberian Arctic Shelf unraveled with triple isotope analysis, Biogeosciences, 14, 2283-2292, https://doi.org/10.5194/bg-14-2283-2017.

research. Among others, our inability to discern to which extent different physical mechanisms transport CH_4 from the soil and the biosphere into the atmosphere (i.e., ebullition, diffusion, aerenchyma pumping or pressure pumping) hamper ground-based measures. Recent aerial measures of CH_4 in the North American Arctic derived from the CARVE project demonstrated emissions are not regionally homogenous, but show higher concentrations along large riverbeds and different geologic substrates, which themselves require additional research in their own right.

Current observatories and research infrastructure in the Arctic is limited, primarily due to difficult logistical and climatic conditions. Constrained to a select number of countries they include Interact (pan-Arctic field stations), the European ICOS research infrastructure tower-based observatories, including also ocean and atmospheric measurements (see Figure 2), NSF NEON and US NSF AEON tower-based projects, US DOE NGEE bio-geochemistry study, French-Russian YAK-AEROSIB airborne campaigns, and EMSO European Multidisciplinary Seafloor and water-column Observatory.

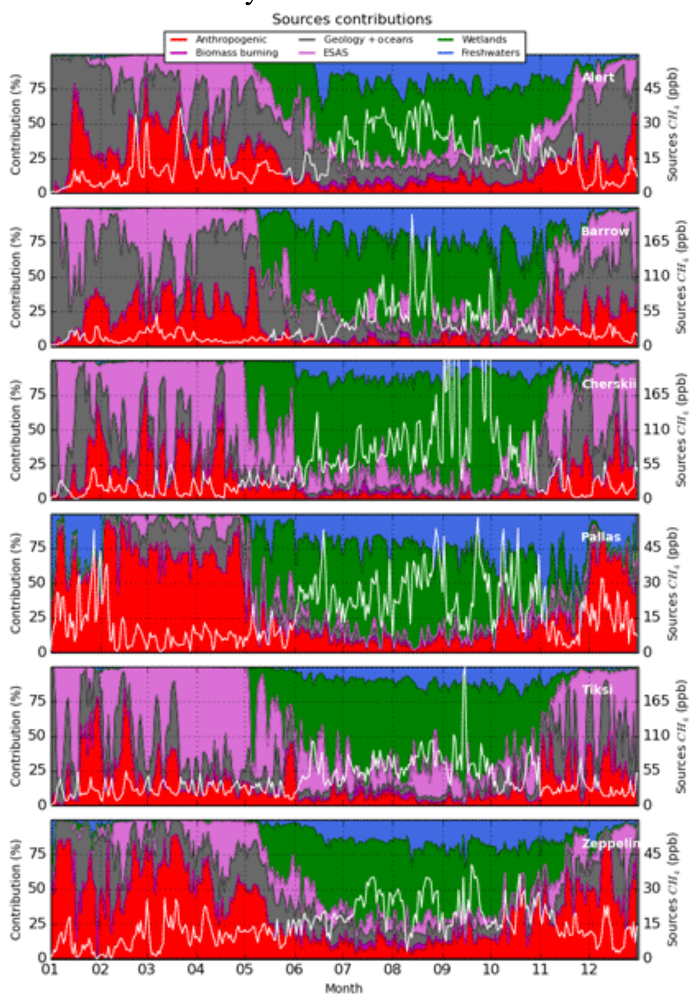

Figure 2. The current atmospheric methane measurement network (here: Alert, Canada, Barrow, USA/Alaslka, Cherskii, Russia, Pallas, Finland, Tiksi, Russia, Zeppelin, Norway/Svalbard) is sensitive to a combination of regional emissions including anthropogenic, wetlands, and Arctic ocean sources[34].

[34] Thonat, T., Saunois, M., Bousquet, P., Pison, I., Tan, Z., Zhuang, Q., Crill, P. M., Thornton, B. F., Bastviken, D., Dlugokencky, E. J., Zimov, N., Laurila, T., Hatakka, J., Hermansen, O., and Worthy, D. E. J. (2017). Detectability of Arctic methane sources at six sites performing continuous atmospheric measurements, Atmos. Chem. Phys., 17, 8371-8394, https://doi.org/10.5194/acp-17-8371-2017.

Most of these programs have been campaign based and long-term, consistent measurements (ground, air and sea) are lacking, as are consistent CH_4 measurement methodologies (i.e., CH_4 filtering, gap-filling procedures, spatial distribution of tall towers measuring CH_4 which currently does not exist and flask sampling, etc...). To improve our understanding of Arctic methane sources there will be a need to collect complementary measurements including tracers such as methane isotopologues and volatile organic compounds (VOCs). A wider atmospheric observational network targeted at locations with high regional sensitivity is recommended, complemented by airborne observations. After 2020, the MERLIN space mission for methane measurement, based on an active lidar technique, should bring a valuable complement to the ground based network. Modelling frameworks able to analyse these data streams and adapted to the Arctic situation are also needed. The European ERA-PLANET/iCUPE project (https://www.atm.helsinki.fi/icupe/) is currently preparing their model for an Arctic-oriented observation system. European RIs activities in the Arctic, especially related to climate change, need to expand their coverage. In particular the underlying role of Research Infrastructures such as ICOS and EMSO is critical, and these should be regarded as critical infrastructure in this region. There is also a need to increase public awareness to highlight the societal relevance and the long term importance of these measurements. Logistics to conduct science in the Arctic is clearly challenging, with limited access, extremely cold temperatures and 24h of daylight during the summer (and 25 h of polar night in the winter).

Answering these research questions is required to respond to strong societal imperatives, and this would warrant release of new immediate resources to researchers working in the challenging conditions of the Arctic. CH_4 releases into the Arctic appear to have international implications for society; many circumpolar countries have a stake in this issue. Through the Arctic Council and in accordance with the Galway declaration, intergovernmental cooperation tools should be exploited to overcome legal and geopolitical barriers and conduct appropriate research across boundaries across the Arctic.

CONCLUDING REMARKS

The challenges of food production for humans will most probably increase the future release of reactive nitrogen Nr,[35] which in turn will impact agriculture, land and aquatic ecosystems and human health. In each of these sectors, a changing climate and greater Nr release can then interact in a variety of ways, further complicating attempts to manage and maintain key ecosystem services. Moreover the exchange of GHG and Nr between the biosphere and the atmosphere is largely controlled by external drivers (cf. climate, deposition, management and land use) and will therefore be significantly affected by the predicted future changes in these drivers. Such huge challenges requires strengthening linkages between ERIs and strategic coordination - collaboration on an international front through generation of new infrastructures and experiments that look at the combined effect of various drivers of Nr fluxes, such as CO_2, temperature and water. Such multi-factorial experiments will be extremely important to develop an understanding of the effects of multiple drivers and their interactions on N budget and Nr. and provide highly cost-effective integration to adequately assess impacts on ecosystem services.

Regarding the **ozone** stress (O_3) on plant systems, new opportunities arise in enhancing existing monitoring networks such as ICOS and ICP-FOREST. The ICOS research infrastructure has planned to prioritize equipment for the EC flux measurements of greenhouse gases in key agricultural and forest sites in Europe, according to a rigorous protocol ratified by the scientific community. Adding O_3 sensors to ICOS would represent a win-win strategy. Existing monitoring networks such as ICP-FOREST level II sites have proven their validity in representing long-term changes in forest response to climate drivers. They nevertheless present notable weaknesses in relation to monitoring certain stressors (including O_3) with insufficient accuracy and temporal frequency necessary to effectively study O_3 effects on vegetation. Previous field observation[36] found little evidence of O_3 effects on forest vegetation (ie. crown transparency and basal area increment). This presents a sharp contrast with observations from manipulative experiments (i.e. open-top chambers), where tree saplings are exposed to known concentrations of ozone-enriched air. The latter studies often report large scale damage due to O_3 exposure, clearly using young saplings in artificial experiments may not realistically reflect the conditions of a forest, the need for long term accurate, high resolution monitoring of O_3 to establish the true impact of O_3 in the field though is quite clear.

In the direction of long-term monitoring ozone impacts on vegetation, the LIFE MOTTLES project (LIFE15 ENV / IT / 000183) establishes a long-term monitoring strategy in three EU countries (Italy, Romania and France) in order to produce new scientifically sound critical levels for the protection of forests against O_3. MOTTLES aims to implement a network of monitoring stations able to report ozone concentrations in real time together with meteorological parameters, modeling the flow of ozone through the stomata in response to climate change, promoting a series of metrics for ozone-risk assessment as new criteria and

[35] Erisman, J.W., Sutton, M.A., Galloway, J., Klimont, Z., Winiwarter, W., 2008. How a century of ammonia synthesis changed the world. Nature Geosci 1, 636–639. https://doi.org/10.1038/ngeo325

[36] Bussotti, F., Ferretti, M. (2009). Visible injury, crown condition, and growth responses of selected Italian forests in relation to ozone exposure. Environ Pollut, 157, 1427–1437. Available at: http:// linkinghub.elsevier.com/retrieve/pii/S0269749108004843

legislative standards that can be used to protect forests from the effects of ozone. Such an effort could be replicated for a larger number of monitoring stations in Europe, in synergy with other existing experimental monitoring stations such as ICOS, where most of the variables needed to estimate critical levels are already being measured.

Lastly, the spatial coverage of current terrestrial, atmospheric and marine infrastructure is not sufficient to understand the state of **methane** sources in the Arctic and how they are changing in response to climate change. Improvement of existing observatories to measure a wider range of parameters, proxies and tracers would enhance the capability to derive appropriate information on methane sources. Specific campaigns targeting heterogeneous and complex landscapes and ecosystems would support the large scale view of long term monitoring across the Arctic. The influence of the Arctic region feeding back on global warming is uncertain, and the path to meeting the Paris Agreement goals is less clear when potential feedbacks from CH_4 release in the Arctic are factored in. Current limited resources allocated to estimating CH_4 fluxes from the Arctic could be better utilized through better coordination of activities and a focus on cross-disciplinary efforts. Furthermore, given that the current coverage is so low, even a small number of measurements in previously almost unstudied locations (e.g. over the Arctic Ice sheet, wetland and permafrost areas in Siberia) could significantly improve the present state of the knowledge.