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Epidemiological analysis of ozone and nitrogen impacts on vegetation – Critical evaluation and recommendations

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HIGHLIGHTS

- Epidemiology of air pollution impacts on vegetation is under strong development.
- Epidemiological data analysis is a good tool to validate dose-response relationships.
- It allows analysis of interactions between environmental impacts and site factors.
- It contributes to the understanding of ecological processes.
- Recommendations on mapping of predictors and on the statistical analysis are made.

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ABSTRACT

For human health studies, epidemiology has been established as important tool to examine factors that affect the frequency and distribution of disease, injury, and other health-related events in a defined population, serving the purpose of establishing prevention and control programs. On the other hand, gradient studies have a long tradition in the research of air pollution effects on plants. While there is no principal difference between gradient and epidemiological studies, the former address more one-dimensional transects while the latter focus more on populations and include more experience in making quantitative predictions, in dealing with confounding factors and in taking into account the complex interplay of different factors acting at different levels. Epidemiological analyses may disentangle and quantify the contributions of different predictor variables to an overall effect, e.g. plant growth, and may generate hypotheses deserving further study in experiments. Therefore, their use in ecosystem research is encouraged. This article provides a number of recommendations on: (1) spatial and temporal aspects in preparing predictor maps of nitrogen deposition, ozone exposure and meteorological covariates; (2) extent of a dataset required for an analysis; (3) choice of the appropriate regression model and conditions to be satisfied by the data; (4) selection of the relevant explanatory variables; (5) treatment of interactions and confounding factors; and (6) assessment of model validity.

1. Introduction

1.1. The need for epidemiological studies

The deposition of nitrogen (N) and ozone (O_3) are important drivers of global change and have a high potential for affecting ecosystems (Bytnerowicz et al., 2007). Ground-level O_3 concentrations have

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increased since the pre-industrial age to a present annual average of 35–50 ppb in the mid-latitudes of the Northern Hemisphere (Fowler et al., 2009; IPCC, 2013; Cooper et al., 2012; Lefohn et al., 2014). Deposition of reactive N has globally increased from 32 Mt y^{-1} in 1860 to ~112–116 Mt y^{-1} at present (Reay et al., 2008). Current projections estimate still a slight increase of N deposition on the global scale between 2000 and 2100 (Fowler et al., 2013), while projections for O_3 are more complex and depend on emission scenarios for precursors and climate change (Young et al., 2013; IPCC, 2013).

Epidemiology is defined as the study of the factors that affect the frequency and distribution of disease, injury, and other health-related events in a specified population for the purpose of establishing prevention and control programs. Ecological gradient studies have a long tradition in the research of air pollution effects on plants. The effects of SO_2, N deposition or tropospheric O_3 have been quantitatively assessed under field conditions. While there is no principal difference between gradient and epidemiological studies, the former address more one-dimensional transects while the latter focus more on populations and includes more experience in making quantitative predictions, in dealing with confounding factors and in taking into account the complex interplay of different factors acting at different levels. Our paper gives an overview over statistical methods used in population epidemiology to quantify risk factors of diseases within populations of plants.

Apart from the quality and type of the vegetation response variable, the following aspects are important in such studies: (1) spatial and temporal aspects in preparing predictor maps of N deposition, O_3 exposure and meteorological covariates; (2) extent of a dataset required for an analysis; (3) statistical approaches available, choice of the appropriate regression model and conditions to be satisfied by the data; (4) selection of the relevant dependent and explanatory variables; (5) treatment of interactions and confounding factors; and (6) assessment of model validity. This paper provides recommendations for these aspects.

While it is beyond controversy that the dependent variable must have a high quality (see also Wacholder, 1995), the other aspects have been less often addressed. Predictors used in the data analysis must also be of high quality. This holds true for pollutants, co-varying meteorological variables or other confounding factors. The preparation of pollution or meteorological maps may be impeded by the regional distribution being affected by landscape variation and local emission sources.

Statistical approaches used in human epidemiology may provide suggestions for the extent of the dataset required, the type of analysis suited for the data, the dealing with interactions and confounding factors and the assessment of model validity. Epidemiological studies play an important role in the assessment of impacts of air pollution on human health and in deriving effects-based ambient air quality guidelines (WHO, 2006; Krzyzanowski and Cohen, 2008; WHO, 2013). Effects-based air pollution control policy aiming at non-exceedance of WHO air quality guidelines is an important objective. As an example, the revised 1999 Gothenburg Protocol to Abate Acidification, Eutrophication and Ground-Level Ozone under the Convention on Long-range Transboundary Air Pollution (LRTAP Convention, UNECE) specifically refers to the WHO air quality guidelines for O_3 and for particulate matter PM2.5 (UNECE, 2013a).

The revised 1999 Gothenburg Protocol covers the protection of environment, natural ecosystems, crops and materials by means of critical levels and loads. While the critical loads for protecting ecosystems or single sensitive receptors from excessive N deposition are based both on exposure-response relationships and gradient studies (Bobbink and Hettelingh, 2011; Bobbink et al., 2010), the critical levels for O_3 depend on the availability of exposure-response relationships from experimental studies with single plant species, in the case of trees with relatively young individuals, or from experiments carried out at specific ecosystem sites (e.g. Büker et al., 2015; Mills et al., 2011a). Experimental studies including open-top chamber or open-air exposure facilities certainly give important insights in effects mechanisms and allows the derivation of quantitative exposure-response relationships if the exposure levels are environmentally relevant. However, it remains an open question how far the results can be generalized to complex environmental field conditions, to a mix of plant species with different sensitivity and age, to long forest rotation periods and in the end to different ecosystems covering wider geographical areas. Also, interactions with other pollutants and environmental variables are rarely studied in simulated experiments.

Epidemiological approaches have the potential to address such questions by studying a sufficiently large number of sensitive receptors located in ecosystems at different sites under varying environmental conditions of impact factors of specific interest. Thus, like in the assessment of impacts of air pollution on human health, controlled experiments to assess air pollutant impacts on vegetation would benefit from being complemented with epidemiological studies (Adami et al., 2011).

Principally, the epidemiology of effects of air pollutants on receptors of the environment, e.g. plant growth, can be investigated by applying the same methods as used for the epidemiological assessment of human health impacts (Silman and Macfarlane, 2002; Altpeter et al., 2005; WHO, 2013; Braun et al., 2014; UNECE, 2014). Attention has to be paid to a careful study design, to the choice of appropriate measurable endpoints and explanatory variables, to appropriate spatial and time resolutions, to addressing potential confounding factors and to selecting appropriate statistical methods for interpreting the exposure-response relationships. The International Cooperative Programme on Effects of Air Pollution on Natural Vegetation and Crops (ICP Vegetation) operating under the LRTAP Convention has initiated expert workshops to discuss the prerequisites for applying epidemiological methods to air pollution effects on vegetation and to formulate methodological recommendations. As a part of this activity, this article aims at: (i) providing an overview of the main features of epidemiological approaches for investigating air pollution impacts on vegetation under field conditions; (ii) summarizing methodological aspects with focus on statistics and mapping; (iii) providing examples of promising and successful studies; and (iv) discussing future developments.

1.2. Recent examples of epidemiological studies in plant ecosystem research

To illustrate the advantage of epidemiological studies in plant ecosystem research, we present here a few case studies in temperate ecosystems highlighting the impacts of different environmental stressors as well as the importance of explanatory variables other than air pollution. These case studies were selected because of the significance of their results for the understanding of ecological processes, the quality of their data analysis and the demonstration of the role of confounding factors. Examples of how epidemiological data analysis has been used in the study of plant responses to air pollution are given in Table 1. Frequent confounding factors are age, time and stand density as well as meteorology and altitude. An important problem is the co-linearity between sunny and warm weather conditions with drought stress and high levels of O_3.

The importance of considering appropriate covariates (e.g. soil moisture and different meteorological variables) and of good air pollution estimates for quantitative conclusions is illustrated by Sutton et al. (2008). They reexamined the dataset by Magnani et al. (2007) who related net ecosystem production data from 16 forest sites to N deposition. In the original study, N deposition was quantified as wet deposition only and modeled at a large scale. A temperature covariate was included as mean annual temperature. Magnani et al. (2007) concluded that 1 kg N may sequester 725 kg C, which is an extremely high estimate. Sutton et al. (2008) improved the spatial resolution of the wet N deposition, included dry N deposition, annual growing degree days above 5 °C and soil moisture deficit expressed as the ratio of actual to potential evapotranspiration. With these improvements applied in a multiple