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Modelling Potential Impacts of Land-Use Change on BVOC-Emissions by Bioenergy Production in Germany

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Abstract— Due to the rising energy demand from regenerative sources, short rotation plantations for biomass production are increasingly established in Germany and other European countries. Using species such as poplar or willow needs only minor fertilization, makes management easy, does not violate biodiversity issues and yields similar amounts of biomass than planting herbaceous species. However, in contrast to most agricultural and forest species, poplars emit large quantities of isoprene. Since isoprene is highly reactive and participates in photochemistry and aerosol formation, regional air pollution pattern are expected to change if significant proportions of land coverage would be replaced by poplar plantations.

We carried out a simulation study in order to estimate the amount of isoprene emitted if poplar plantations would be planted on all non-forested areas in Germany and differentiated the result by site conditions suitable for agricultural production. Using only the 10 (or 35) % of agricultural land that is least suitable for growing food and fodder, we produced a regional explicit emission inventory based on a land-use change scenario that concentrates on solid bioenergy production on marginal lands.

The results show that the emission increase due to an extensive replacement of agricultural area and grasslands by poplar plantations is reaching a magnitude which can be expected to impact air pollution, i.e. to increase aerosol formation that are possibly affecting local weather pattern in turn. The effect is particularly high in hot summers because emissions increase exponentially with temperature. Notably, the emission increase is particularly high in the relatively warm vicinities of the largest German cities Berlin (large areas of marginal agricultural lands) and Munich (many suitable grassland sites), indicating the importance of future investigations of feedbacks between climate, anthropogenic and biogenic emission for air quality and local weather.

Index Terms—Isoprene Emission, LandscapeDNDC, Short-Rotation Cropping, Poplar Plantations

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1 Introduction

The rising demand of bioenergy as a substantial part of the transformation of the German energy supply system rises the question of how and where these biofuels will be grown. The current concentration on rapeseed and maize is heavily criticized due to negative impacts on greenhouse gas emission, biodiversity and other issues. On the other hand rising demand for firewood either for personal use or industrial combustion is leading to an increasing demand that cannot be supplied from forestry anymore. Therefore, short rotation coppices (SRC) with poplar or willow are considered to grow on a large scale - with current estimates of area coverage reaching from 0.3 to 2.5 million hectare.

To estimate not only biomass production but also environmental impacts, complex simulation models are needed that integrate carbon sequestration and biomass accumulation with impacts on greenhouse gas emission, nitrate percolation, and air pollution. Only an integrative view can consistently estimate the response to environmental drivers including biological feedbacks. Therefore, the LandscapeDNDC model has been developed (Haas et al. 2012). It has been parameterized for hybrid poplar and applied on regional scales already (Werner et al. 2012). It is also equipped with model routines that estimate biogenic emissions of volatile organic compounds, especially isoprene, in dependence on temperature, radiation, seasonality, and drought (Behnke et al. 2012, Grote et al. 2010). Isoprene is highly reactive and is a major contributor to photochemistry and ozone production. It is also involved in methane degradation and the formation of secondary organic aerosols which affect cloud formation and radiation regime. It is also noteworthy that poplar is a species that belongs to the largest isoprene emitters worldwide. Therefore, we were interested in the response of regional isoprene emissions to a considerable land-use change towards increased short-rotation coppice in Germany.

2 Methodology

In this study, the process-based model LandscapeDNDC has been applied to estimate the potential isoprene emission under hypothetical land use change scenarios, focussing on increasing area of short rotation coppices with hybrid poplar. Initialization is based on the European modelling database developed within the NitroEurope project (http://www.nitroeurope.eu) as used by Werner et al. (2012) and Cameron et al. (2012). The database consists of soil, land-use, climate, and management information based on NitroEurope Calculation Units (NCUs), spatial units of land with common soil or climatic conditions, comprising Germany from the full NitroEurope spatial database (data source: http:// afoludata.jrc.ec.europa.eu/index.php/experiment/detail/2) into 1442 polygons with contribution of agriculture. Although only NCUs are considered that contain arable land, many of these polygons also include other land-uses, including grasslands and forests. Nevertheless, each polygon is now presented as if only containing agriculture.

Soil properties were provided by the NitroEurope soil data. For each profile section soil attribute data for organic carbon, clay content, soil pH, bulk density, and thickness were provided and each strata section was further subdivided into 2 cm (A), 5 cm (B), and 10cm (C) layers with no initial litter layer on top. Poplar saplings were initiated with 10,000 saplings per ha and 0.5 m initial plant height. Daily minimum and maximum temperature and precipitation data were provided for further calculations. Annual nitrogen deposition was applied as wet deposition (e.g., during rainfall events). No additional nitrogen fertilization was considered. To limit short-term climatic effects on the simulation outcome, we simulated biomass yields and isoprene emissions from short-rotation (6 year) poplar plantations for the time slice 2000–2005. The time step for all model processes is daily, except for photosynthesis and isoprene emission which are calculated hourly using temperature and solar radiation values derived from daily data.

All locations were ranked according to precipitation (precip), growing degree days (GDD) and soil organic carbon (corg) and an suitability index was calculated to characterize the site according to common agricultural practice: the P index (low: less suited for agricultural biomass production, high: well suited for biomass production):

$$P - index\,(0,1\,\ldots) = \frac{\frac{Precip}{Precip_{max}} + \frac{GDD}{GDD_{max}} + \frac{Corg}{Corg_{max}}}{Precip_{max} + GDD_{max} + Corg_{max}} \qquad (1)$$

where: Precip = average annual precipitation, Corg = organic carbon content in topsoil. Max is maximum value of a given parameter for all calculation units located in Germany.

3 Results

It is interesting to note that most of the agricultural area including pasture in Germany seems to be well suitable for growing poplar in short rotation coppice. Only if the water capacity falls below 100 mm (2 % of the sites), biomass growth is significantly reduced. Throughout the whole simulation period, growth is even slightly negative related to precipitation (not shown), indicating that radiation (which increases with decreasing precipitation) is more important than water supply. Furthermore, growth is related to soil organic matter (which is linearly correlated with nitrogen content) and temperature (also correlated to GDD). Optimum growth is obtained only above an organic carbon content of app. 2 %, which is available at about half of the sites. Growth increases only about 10 percent across the range of annual average temperatures covering 6 to 11 ^{o}C. Overall, the P-index, which is designed to indicate suitability for agricultural production is only slightly indicative for SRC productivity.

Isoprene emission is most significantly correlated with growing degree days (Fig. 1, Top), a proxy for global radiation and slightly less significantly related to annual average temperature (Fig. 1, Middle). The influence of precipitation is only slight and negative for the same reason as indicated for biomass development (Fig. 1, Bottom). It also shows that emission is only affected by severe drought which happens seldom and throughout periods of limited length.

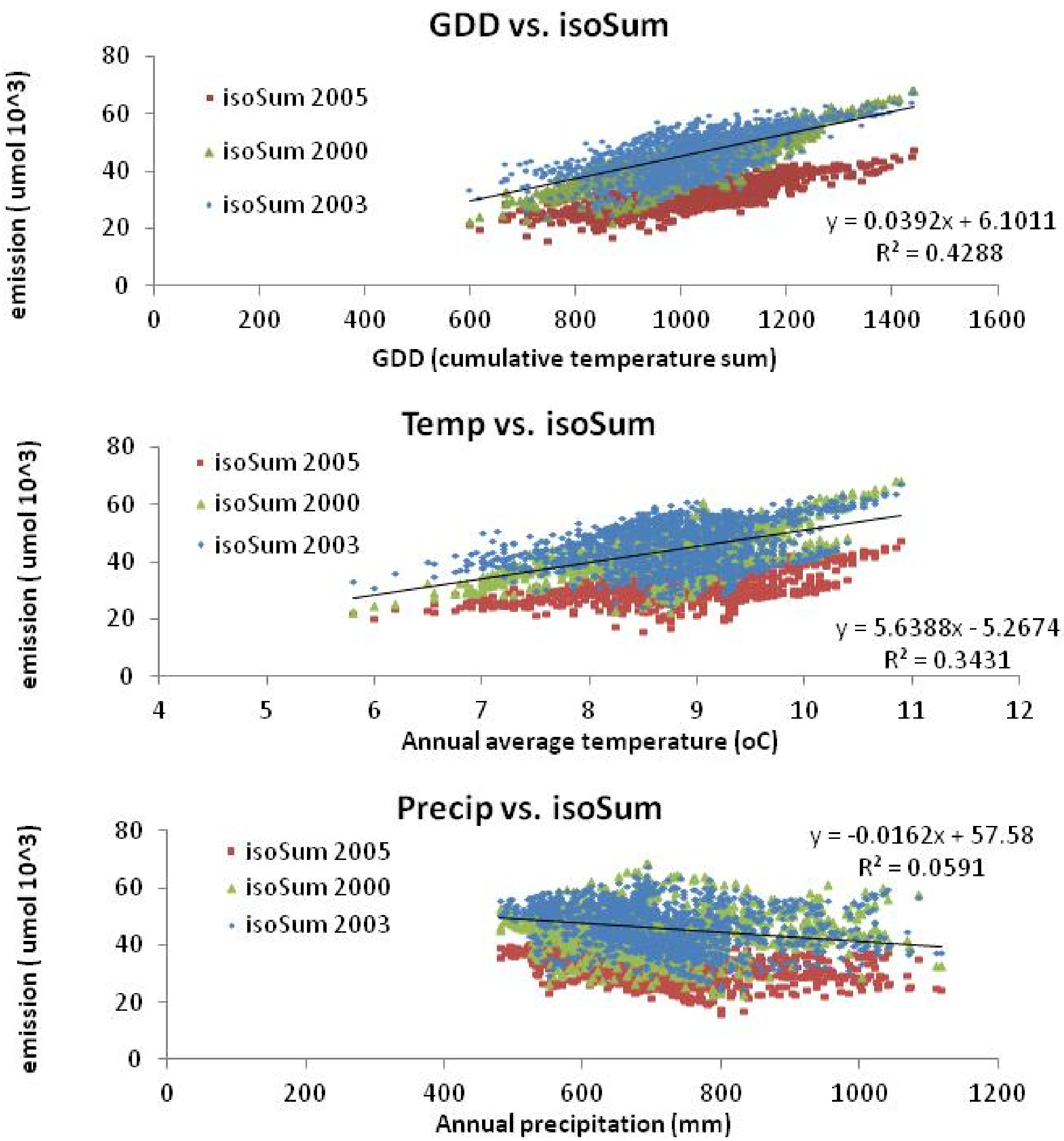

Fig. 1: Statistical relationships between environmental conditions and annual isoprene emission sums. Top: Growing degree days (GDD), Middle: Temperature (Temp), and Bottom: Annual precipitation (Precip). Emissions of different years are presented in different colors.

The temporal distribution of emission varies with the temperature development of a year (Fig. 2). Therefore, it is generally highest in mid-summer and drops steeply towards the end of the vegetation period. The distribution is affected by the particular temperature pattern during the year, e.g. a warm period in autumn has postponed the decline in the year 2000, but can also be reduced during extreme drought periods such as in summer 2003, where emissions where highest in June and August.

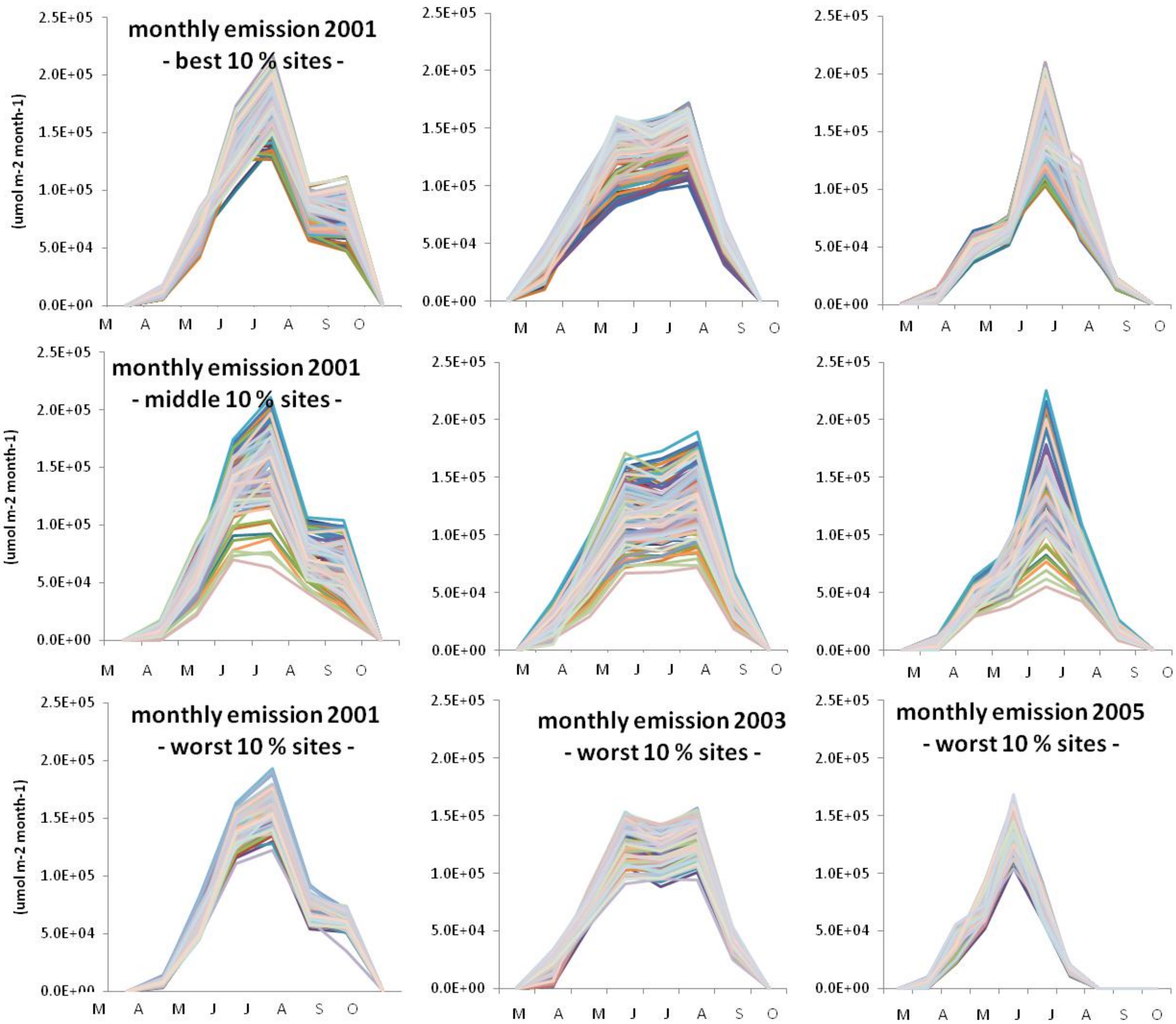

Fig. 2: Seasonal distribution of isoprene emission for 30 % of the investigated sites during three different years. Columns represent the different years 2001 (left), 2003 (middle), and 2005 (right). Rows represent emissions at sites with different site quality according to P-index valuation, showing sites of highest production (top), middle and smallest productivity (middle and bottom).

There are only small differences in the average and maximum emission rates at sites of different agricultural suitability. However, the variation of emission within the top and worst 10 % sites (according to P index distribution) is considerable less than for the middle 10% of the sites, indicating that these groups includes high GDD (positive related to emissions) with high precipitation or corg values (negatively related to emission). In addition, it is apparent that at the worst 10 % sites GDDs are relatively small leading to less autumnal emission than in the better ranked groups.

The regional distribution of emissions (Fig. 3) shows that an extensive replacement of agricultural area by poplar plantations would increase isoprene emissions particularly in the Rhine valley, in Bavaria, and in Eastern Germany (Brandenburg, Saxony). This greatly corresponds with radiation and temperature distribution. Particularly in warmer years such as 2001 and 2003, potential emissions rates would be very high in the vicinity of Berlin, Munich and Stuttgart, some of Germany's largest cities. This pattern changes a bit, if the land-use change is restricted to the areas with the lowest 10 (1.4 Mio ha-1) or 35 (2.3 Mio ha-1) % agricultural production (not shown). In this case, eastern German emissions are largely decreased, while emissions are still concentrated in the vicinity of Munich due to large areas of land used for grazing.

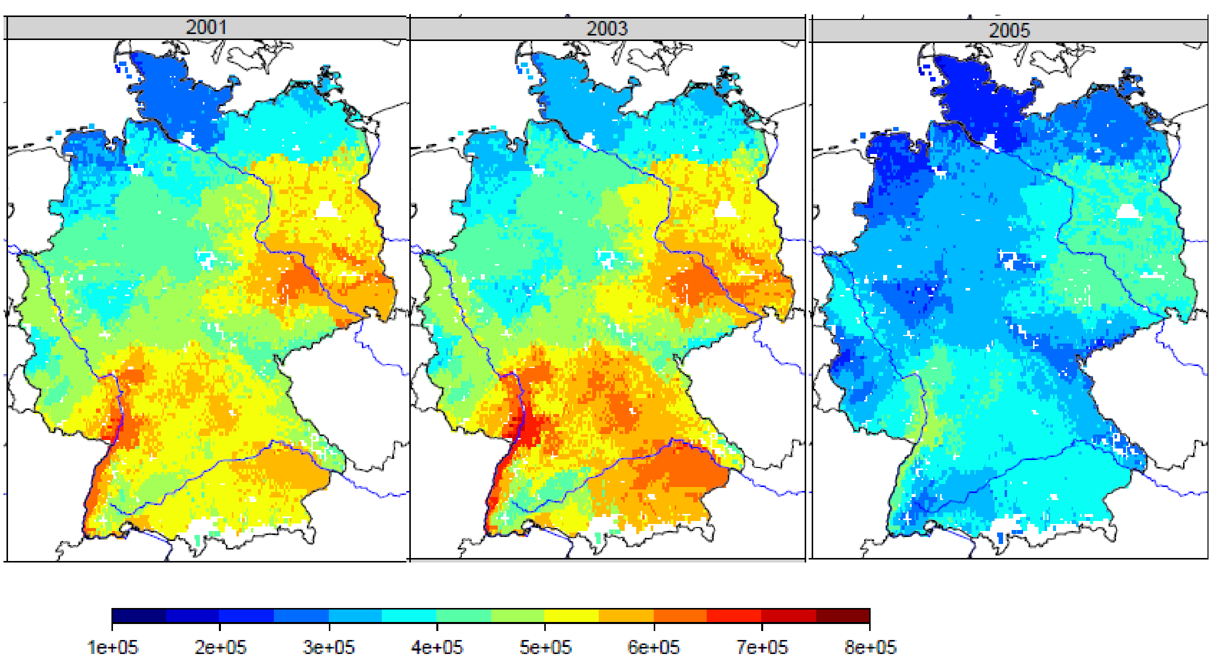

Fig. 3: Potential isoprene emission (µmol m^{-2} a^{-1}) inventory for three different years based on poplar short-rotation plantations fully covering the area of Germany.

4 Discussion

Since it is expected that climate change will lead to higher temperatures so that summers similar to that in 2003 will occur much more frequently, future environmental conditions will also be much more favourable for isoprene emission. At the same time it is envisaged to convert large areas currently occupied by low-emitting crops, grasses and herbaceous species with fast growing poplar plantations known as a high isoprene emitter. This will inevitably lead to increased biogenic emissions and our analyse – disregarding all simulation uncertainties – show that the areas likely to increase emissions most are those close to densely populated regions. Given the important role that isoprene plays in photochemistry and ozone production, future investigations should concentrate on the mechanisms that affect air quality – with potential impacts on human health and plant productivity. Using high resolution inventories and models that are able to capture the most important environmental impacts, it is now possible to provide adequate emission input into coupled air chemistry/ climate models.

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