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Supporting monitoring effects of genetically modified organisms by GIS-technologies and geodata – an overview

Winfried Schröder[1], Gunther Schmidt[1]

1 *Lehrstuhl für Landschaftsökologie, Universität Vechta, Postfach 15 53, 49364 Vechta, Germany*

Corresponding author: *Winfried Schröder* (wschroeder@iuw.uni-vechta.de)

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Abstract

The approval of genetically modified organisms for deliberate release and placing on the market requires environmental risk assessment and environmental monitoring. Methodological approaches and implementation of both tasks are still controversially discussed. This article analyses principles of environmental monitoring of genetically modified organisms as published in the Guideline 4330 Part 1 of the Association of German Engineers. Thereby, the article concentrates on the characterisation of the receiving environment affected by cultivation of genetically modified organisms and the representativeness of monitoring systems to assess large-scale implications of the cultivation of genetically modified organisms. Based on this, the article introduces statistical and geoinformatic measures as well as relevant geodata to deal with these issues.

Keywords

Genetically modified organisms, geodata, environmental monitoring

Introduction

The authorization of genetically modified organisms (GMO) for deliberate release and placing on the market follows specific regulations in the EU and its member states. The implementation of relevant aspects of Environmental Risk Assessment (ERA) and Environmental Monitoring (EM) is still under discussion. The controversy is about how to regulate release of only those genetically modified plants (GMP) that do not cause unacceptable risks to human health and the environment (Züghart et al. 2013). From basic ecological reasoning it is clear, that even a systematic and stepwise structured risk assessment cannot cover all risk relevant questions, especially combinatory effects emerging in areas of large extent and over long times. EM is essential to deal with unanticipated and undesirable effects. Monitoring data help in detecting post-market effects due to GMP cultivation. With regard to natural variability and together with baseline data, EM data should be used to establish cause-relationships by differentiating whether monitored environmental changes in, for instance, non-target population abundances relate to GMP cultivation and/or are caused by other environmental or agronomic drivers. Additionally, modelling approaches are a supplementary tool to analyse potential combinatory effects of GMP cultivation (Reuter et al. 2008, 2012). In the described context, ERA and EM should be linked closely. While ERA is testing hypotheses about potential hazards and underlying processes experimentally as far as feasible, some questions remain which go beyond an experimental scale and, thus, require EM. Additionally, EM should deal with the spatial validity and relevance of the hypotheses tested in ERA. To reach this, according to the VDI guideline 4330 Part 1, GMP EM should rely on sound sampling methodologies and on geographic information system (GIS) techniques including spatial statistics and mapping techniques. In Germany, several research projects dealt with these issues, and some of the main results are considered within this article. In the following, it is shown that available geodata are useful to describe the receiving environment in the near and far vicinity of GMP fields. Statistical analyses and classification of geodata are presented which serve to derive ecoregions or, e.g., climatic and agricultural patterns, and, thereby, help for assessing the representativeness of running or planned GMP EM sites and for investigating adverse ecological effects of GMP release on different spatial scales and for different agricultural regimes (Breckling et al. 2003; Graef et al. 2008; Reuter et al. 2010; Schmidt and Schröder 2011; VDI 2006). These issues are explained in more detail by Schröder and Schmidt (2012).

Spatial estimation and mapping

According to the available data, geostatistical methods as well as multivariate statistics can be used for analysing and mapping spatial data as derived by GMP EM. Geostatistics, for instance, comprise methods to calculate surface predictions from data points (Krige 1984, Matheron 1971). To this end, spatial auto-correlation is examined by Variogram Analysis. Based on the calculated variogram model, several Kriging methods can be used for spatial predictions (Olea 1999). Cross-validation quantifies how well the spatial estimated values at locations without measurements fit with the point measurements.

Multivariate Statistics such as cluster analysis or tree based models such as Classification and Regression Trees (CART) serve spatially differentiating the multiple relationships between geodata stored in a GIS. Based on these relations, spatial predictions in time and space become possible (Hornsmann et al. 2008; Pesch et al. 2011; Schröder et al. 2006a). In the context of GMP dispersal, Cluster Analysis can be used to integrate measurement data from different meteorological networks with different coverage in a GIS environment for defining representative climatic regions. Climatic regions together with an ecological land classification were used to stratify the receiving environment in order to select a representative number of sites for the modelling of GMP dispersal (Schmidt and Schröder 2011).

Geodata

Application of models referring to the dispersal and persistence of GMP or to simulate, e.g., possible effects of GMP on non-target organisms and food webs as well as planning and facilitating GMP EM with respect to coexistence issues in agricultural landscapes depend on the availability of data on meteorology, land use, and local biodiversity. The following will give an overview of geodata for monitoring and modelling adverse effects of GMP at the landscape level.

Landuse data can be obtained from either satellite images, GIS data collected during field experiments, cadastral surveys provided by local land registries, vertical air-photographs, or the Common Agricultural Policy notifications, each type of source being used at different scales and consequently provide different spatial and semantic resolutions. Data on land use patterns and the cultivation of crops in Europe are available at the Statistical Office of the European Communities (EUROSTAT, http://epp.eurostat.ec.europa.eu). To some extent, data on field geometries providing detailed information on agricultural land use can be obtained from the InVeKoS (Integrated Administration and Control System) data base. In fact, due to legal restrictions and inconsistencies in data harmonisation related to federal responsibilities, availability of these data is difficult (Schmidt and Schröder 2012). Based on remote sensing data, CORINE Landcover maps are offered by the European Topic Centre on Land Use and Spatial Information (EIONET, http://terrestrial.eionet.europa.eu/CLC2000) (Keil et al. 2005).

For analyses of GMP impacts in landscapes, meteorological data are needed as well. These are, for example, data on precipitation, air temperature, sunshine duration, the number of frost days, and wind conditions. Climate affects growth, persistence and dispersal of GM crops and their pollen and seeds. These data could be retrieved from meteorological stations. For instance, the German Weather Service operates about 4,400 precipitation sites, 660 stations for air temperature and 220 for solar radiation measurements. For Europe, free data sets with a resolution of 10 arc minutes (~ 20 × 20 km) are available at the Climatic Research Unit (CRU; http://www.cru.uea.ac.uk/~timm/grid/CRU_CL_2_0.html) in Norwich, UK (New et al. 2002). For modelling the pollen transport, phenological data on the flowering of GM crops should be considered, too. It should be taken into account that global warming might have changed the temperature induced beginning of oilseed rape and maize bloom (Englert et al. 2008). The dynamics of GMO pollen transport can be described by compiling and processing data on wind direction and velocity. The wind direction influences the transport direction of the pollen and, thus, potential exposition areas. Given a constant emission rate, the wind velocity affects the range and the transport speed of air-borne pollen and leads to a dilution (stretching), as with higher wind velocities a larger air volume passes the source surface and the concentration per unit volume is reduced (Oke 1987).

Data on soil texture and soil types are available from the FAO: 1) Digital Soil Map of the World (about 10 × 10 km²) (http://www.fao.org/nr/land/soils/digital-soil-map-of-the-world/en) and 2) Harmonized World Soil Database (about 1×1 km²) (http://www.fao.org/nr/land/soils/harmonized-world-soil-database/en). Data on the potential natural vegetation which can be used for ecological land classifications can be obtained from the Federal Agency of Nature Conservation (BfN) in Germany (Bohn et al. 2005). The PNV map stratifies Europe into more than 700 PNV units. The PNV can be defined as the vegetation that would establish without human interference under present climatic and soil conditions and is an integral indicator for the ecological conditions in terrestrial ecosystems (Schröder et al. 2006a).

For detecting adverse effects on biodiversity a link between GMP and biodiversity monitoring is imperative (SCBD 2000, 2004). With a widespread commercial release of GMP, the extent of adverse biodiversity effects can be expected to become substantial. For instance, biodiversity monitoring is able to detect the potential spread of GM crops, the potentially enhanced mortality of non-target organisms, and it may also draw a more general picture on potential effects on the countryside biodiversity. In Europe, several biodiversity monitoring networks exist due to the Convention on Biodiversity (CBD) which commits its signatory countries to identify and monitor their biodiversity. However, these monitoring networks are poorly connected and data are usually available only on local or national levels (Vieno and Toivonen 2005). Whereas the monitoring of birds and butterflies is well established over long periods in some European countries (e.g. in the UK > 30 years), allowing an assessment of changes at several trophic levels and geographical scales (Thomas 2005), monitoring is not equally well established across taxonomic groups relevant for GMP EM. Only few monitoring schemes for plants exist (EuMon database, http://eumon.ckff.si/monitoring/search.php). As of September 2012, EuMon database comprised 633 complete monitoring schemes (456 species schemes, 177 habitat schemes) covering approximately 4,000 species and addresses of 239 monitoring coordinators and institutions. Furthermore, the database contains information on sampling methods. The reporting guidelines for biodiversity monitoring of the European Habitats Directive suggest that an annual change as low as 1% should be detectable. For GMP monitoring, this change must be extractable from the background noise of sampling variability and population fluctuations. This is only possible, if a considerable amount of sites is frequently and accurately monitored and if reference areas, i.e. areas without potential influence of GMP, are monitored at the same time with the same accuracy. 15 (3.8%) of the monitoring schemes in the EuMon database enable detecting a 1% annual change, another eight schemes 5% annual change. Even though the EuMon database is the largest collection of metadata on biodiversity monitoring available, it is not comprehensive and might be confounded by biases (Schmeller and Henle 2008).

Besides the EuMon database, there are only few more data sources where information on biodiversity or distribution of plant species – that may, for instance, serve as crossbreeding partners of GMP – may be obtained: the Global Biodiversity Information Facility (GBIF, http://www.gbif.org), the European Forest Genetic Resources Programme (EUFORGEN, http://www.euforgen.org/distribution_maps.html). In Germany, the Federal Agency for Nature Conservation (BfN) maintains the web application FloraWeb (http://www.floraweb.de) where information on about 3,500 plant species are stored containing details on, e.g., taxonomy, biology, and spatial distribution of plants in Germany. A java applet allows for mapping selected plant species in a spatial differentiation based on cadastre maps (scale 1 : 25,000; ≈ 11 × 11 km²).

Selection of representative GMP monitoring sites by help of an ecological land classification

The federal nature protection law (§ 6 BNatSchG), the environmental monitoring concept of the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU 2000) as well as the preamble of the administrative agreement between the German government and the federal states on the exchange of environmental data specify the following targets that should be complied with when carrying out environmental monitoring: 1. The monitoring should be coordinated and based on harmonised or standardised methods (Keune and Mandry 1996) so that the data can be compared and used for statistical analysis and modelling. 2. The monitoring data should allow for spatial extrapolation in order to bridge geographical gaps and for supporting long-term research on environmental changes. The flow of data should be efficient and the data should be available for scientists, especially for statistical testing of hypotheses and modelling data.

Small plots and laboratory studies are unlikely to prove sufficient for GMP evaluation. Therefore appropriate monitoring schemes covering areas of large extent and modelling is needed to determine the impact on the landscape from GMP trait characteristics (Craig et al. 2008). GMP ERA and EM should comprise the evaluation of the characteristics of the GMP and its effect and stability in the environment, combined with ecological characteristics of the environment in which the introduction will take place. Thus, EM of GMP impacts should be implemented regarding description, explanation and modelling of environmental changes potentially due to GMP cultivation.

The requirements mentioned above imply that the EM network should cover the ecologically defined land classes (i.e. ecoregions being characterised by distinct environmental conditions) in the respective country without gaps by a statistically adequate number of EM sites. This ecological representativeness is crucial for the validity of the EM sampling data (Cao et al. 2002; Tirler et al. 2003). Thus, monitoring and modelling of GMP dispersal should be performed at locations which are representative for larger areas with respect to those factors which potentially influence the dispersal or persistence of GMP. Following this concept, ecoregions can be used to generalize modelling results calculated for specific agricultural and environmental conditions at single locations to those areas where similar conditions exist, i.e. regions being part of the same ecoregions (Schmidt and Schröder 2011). Additionally, GMP EM should take place in areas exposed to GMP, preferably cultivated fields and their environment, but should include also regions with no or unknown GMP exposure as reference areas. On a case-by-case basis depending on the GMP characteristics, the selected indicators, checkpoints and related analytical methods should consider relevant different spatial and temporal scales (Graef et al. 2005; VDI 2006). The number of monitoring sites and regions needs to be sufficient to support statistical analysis of results based on good scientific practice (Bühler 2006; Stein and Ettema 2003). For each GMP, monitoring design and data analyses should be based on appropriate scales of space and time and quality and quantity of data to be representative and interpretable. Criteria for selecting monitoring sites and regions include: representativeness of sites cultivated with specific GMP, with an emphasis on regions repeatedly cultivated with GMP; representativeness of ecological regions containing the spectrum of relevant indicators; availability of sites already monitored within other environmental programmes; and areas with environmental conditions facilitating spread or survival of GMP (Wilkinson et al. 2000; Züghart and Breckling 2003).

In order to check the representativeness of existing EM networks which might be appropriate for EM GMP or for establishing specific EM GMP networks, ecoregionalisations are appropriate measures. For Europe and Germany, ecological land classifications were calculated by means of multivariate statistics and based on digital maps depicting the spatial patterns of ecologically relevant land characteristics. For both, Germany and some federal states, ecoregions were calculated by applying CART and using surface maps on climate, altitude, soil, and potential natural vegetation (Graef et al. 2005; Schröder et al. 2006a, 2006b). The according maps have a spatial resolution of 2×2 km² and 1×1 km², respectively. The land classification calculated for Europe by means of CART (Hornsmann et al. 2008) subdivides the whole territory into ecoregions mapped in a grid with a cell size of about 20×20 km². Data used for calculating the ecoregions are maps on the potential natural vegetation (PNV, Bohn et al. 2005), on altitude (Global Land One-kilometer Base Elevation GLOBE, Hastings et al. 1998), on soil texture (Digital Soil Map of the World DSMW, FAO 1996) as well as on monthly averages on air temperature, sunshine duration, relative humidity, and precipitation (Global Climate Dataset CL 2.0, New et al. 2002). The PNV was set as the target variable whereas the above mentioned maps on altitude, soil texture, and climate were chosen as predictors. In order to obtain a concise amount of ecoregions the most detailed map depicting the spatial pattern of about 200 ecoregions was reduced to 40 ecoregions.

Conclusions

The GMP EM is an important element of the regulatory framework for GMO in Europe and needs to be conducted according to scientifically sound methods and quality criteria to generate data which have to be robust and conclusive. The selection of parameters, methods, experimental designs, locations and the timeframe for GMP EM needs to ensure that adverse effects of GMP can be detected reliably and as early as possible. To reach this end, guidelines such as VDI 4330 Part 1 are needed attempting to harmonize and standardize the GMP EM design.

VDI 4330 Part 1 describes that the environmental effects of GMP may vary with the characteristics of different receiving environments in terms of, e.g., climate, soils, land use patterns or geographic distribution of wild relatives of certain GMP. Therefore data derived by ERA or EM should be collected in those regions which are representative for respective ecological and agronomic characteristics which potentially could influence the spread and impacts of GMP. Thus, spatially differentiated monitoring schemes are needed, in particular with regard to biodiversity (e.g. non-target organisms) and ecological processes and functions (e.g. soil functions) in which these organisms are involved. Exposure assessment is crucial for GMP EM aiming to assess whether relevant parameters, e.g. certain non-target species, have to be investigated during monitoring. In combination with an effect assessment, the exposure assessment allows the evaluation of species which may be at risk. Geodata, ecological land classification, spatial estimation and GIS techniques in combination with dynamic modelling are fundamental to address effects on a landscape scale and long-term implications, to analyse and evaluate the appropriateness of existing monitoring programs or data for GMP EM, to design adaptations or extensions of the scope of GMP EM if they are inappropriate to address the specific requirements for GMP EM.

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