Institution: University of Bath

Unit of Assessment: Mathematical Sciences

Title of case study: Monitoring and management of German forest

1. **Summary of the impact**

Forests are economically, recreationally and ecologically important, providing timber and wildlife habitat and acting as a carbon sink, among many ecosystem services. They are therefore extremely valuable to society, and it is crucial to ensure that they remain healthy. A statistical model has been developed in Bath to estimate spatio-temporal trends of forest health from monitoring data. This work has led directly to more efficient data collection, and to new and improved interventions to mitigate the impact of pollution and climate change (such as soil liming to control acidity and reforestation regimes). The methodology has been adopted for official reporting in the yearly '**Waldzustandsbericht** (Report on Forest Condition)' [A-E] of the German state Baden-Wuerttemberg (BW), which is 39% forested, an area of 14,000km^2 with an estimated stock value of 17 billion US$.

2. **Underpinning research**

The statistical model [1] is a result of an on-going collaboration between Augustin (Senior Lecturer at Bath, appointed as a Lecturer in 2005) and the Forest Research Institute (FRI), BW, Germany, part of the Ministry of Rural Affairs and Consumer Protection of BW, together with Wood (Professor at Bath since 2006). Augustin had previously collaborated on research with the FRI while working in Germany, but the Bath grants and consultancy agreements from the FRI [2] and the Royal Society [3] led directly to her new method for the spatio-temporal estimation of tree health [1]. Data on forest health from other German states are collected differently; the BW data are the most dense in terms of spatio-temporal resolution, and are therefore the most suitable for method development.

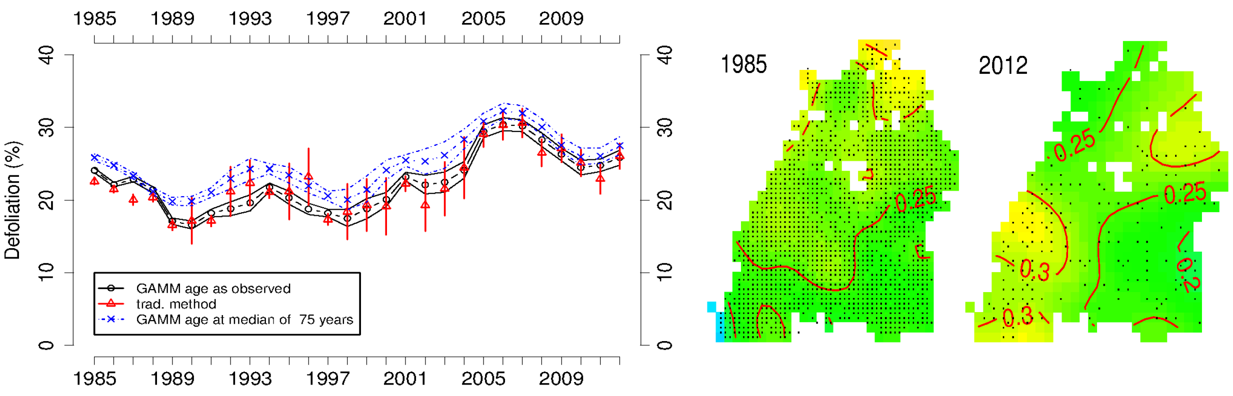

Figure Temporal (left) and spatial (right) estimates of spruce tree health, indicated by defoliation in the crown. **Left**: temporal trend estimates from the *traditional method* are the red triangles with 95% confidence intervals; temporal trend estimates from the *new method* with age as observed and standardised for age are the black circles and the blue crosses respectively, both with Bayesian 95% confidence bands. **Right**: spatial maps for spruce of median age, unobtainable with the traditional method. The black dots indicate the sampling locations, the red isolines indicate the level of defoliation in the crown (yellow is high defoliation of at least 30%, green is medium defoliation at 25%).

The traditional method (Fig. left, red triangles) estimates mean defoliation separately for each year using summary statistics from the monitoring surveys. The method delivers temporal but not spatial trend estimates, and the attached confidence intervals do not take the spatio-temporal correlation and age structure of the data into account. It cannot be used for inference, since ignoring correlation in the data may result in biased trend and variance estimates.

The new method uses the framework of generalized additive mixed models (GAMMs). Augustin, Wood and collaborators developed a new modelling approach that accounts for possible spatial and temporal correlation and incorporates important predictors [1] while being computationally efficient in parameter estimation. The model for the response mean tree defoliation was developed using the moderately large annual BW monitoring data, which were sampled on a grid with yearly varying resolutions of 4X4 km, 8X8 km and 16X16 km. Hence each year from 1983 to 2012, a subset of the 1910 unique grid locations were chosen, and 24 trees were sampled at each, giving in all 180,000 observations of individual tree crown defoliation. The model included space-time interactions, as the temporal trend of defoliation differs between areas with different characteristics and pollution levels. It also included a non-linear effect of mean tree age, the most important predictor variable, allowing the separation of trends in time, which may be pollution-related, from trends that relate purely to the ageing of the survey population, as shown in the left panel of the Figure.

GAMMs allow for non-linear effects of explanatory variables, random effects, general correlation structures for cases where the data are not independent and any response with a distribution from the exponential family. The novel aspect of [1] is a scale-invariant tensor-product smooth of the space-time dimension, which improves on existing methodology for estimating spatio-temporal trends. These tensor-product smooths allow combinations of different basis functions most suitable for the dimensions of space and time as well as time-varying spatial estimates. Hence the smoothness parameters and penalties can be separate for time and space, avoiding the need to make arbitrary choices about the relative scaling of space and time. In addition to a temporal trend due to site characteristics and other conditions modelled with the space-time smooth, random temporal correlation at site level is accounted for by an auto-regressive moving average (ARMA) process. The method does not rely on a regular grid and allows incorporation of a wide range of correlation structures. The model can incorporate non-linear effects, e.g. for mean tree age, the most important predictor. It provides predicted spatial maps of defoliation and marginal estimates of average defoliation over time with Bayesian confidence bands (Fig.), hence allowing estimation of trends in forest health and identifying possible causes of health deterioration, so that rapid or unusual change, in particular, can be detected as early as possible.

Communication of results and future development. Spatio-temporal trends based on [1] are communicated to policy makers and forest managers via the Waldzustandsbericht BW. Since 2011 Augustin has been named as a coauthor of these yearly reports [A–E], but she has made substantial contributions since 2006. She has also co-authored an article in a forest trade journal (AFZ - Der Wald) on the impact of forest ecosystem monitoring, recommending the introduction of a permanent liming campaign as a tool to mitigate effects of pollution [F]. The main output [1] has been cited in several articles of AFZ-Der Wald. The citations of [1] show that the methods are widely used, with applications in fisheries, epidemiology and ecosystem monitoring through satellite images. Software implementing the methods of [1] has been made available to scientists at other forestry institutes in Germany on request. Augustin has a PhD student working on spatio-temporal modelling of the entire European forest health monitoring data from the UNECE International Cooperative Programme on Assessment and Monitoring of Air Pollution Effects on Forests (http://icp-forests.net).

3. References to the research

References that best indicate the quality of the underpinning research are starred.

[1]* Augustin, N.H., Musio, M., von Wilpert, K., Kublin, E., Wood, S. and Schumacher, M. 2009. Modelling spatio-temporal trends of forest health monitoring data. The Journal of the American Statistical Association. 104(487): 899-911. DOI: 10.1198/jasa.2009.ap07058.

[2] Augustin (PI). 'Modelling Forest Inventory Data' , Forestry Research Institute Baden-Wuerttemberg. 01/09/05 – 31/07/08 £52 754. Grant.

[3] Augustin (PI). 'Spatio-temporal modelling of tree defoliation monitoring data', The Royal Society. 01/04/06 – 31/05/09. £61 237. Grant.

4. Details of the impact

The main impact-related insights from the research are as follows.

● The estimated trends provide evidence for increased defoliation of the main species, spruce, between 2004 and 2009, compared to previous years since 1985 (Fig.), with a similar trend for beech, the second most common species [E].

● Results also suggest that there has been a switch in the primary drivers of damage: initial damage can be associated solely with pollution, while more recent damage is also associated with drought years due to climate change. In addition to pollution, climate change has become the most severe threat to forest health in Europe, as some of the main species no longer thrive in the changed climatic conditions.

● The spatial trends highlight areas where intervention to improve forest health is required, such as liming to control acidity or planting species which are better suited to the new climate conditions.

The research has led to ***improved forest health monitoring and management,*** and we give four examples below.

(a) Spatio-temporal models developed in Bath are used for monitoring and management. The methodology has been adopted for the yearly official report on forest health of the federal state BW, the 'Waldzustandsbericht/Report on Forest condition in BW' [A–E], which drives the policy of the Ministry of Rural Affairs and Consumer Protection, BW, Germany. In the foreword of the 2012 report, the BW Minister for Rural Affairs and Consumer Protection, Alexander Bonde, refers to the Bath-developed methodology and results [E, pp 3–4].
"*The Waldzustandsbericht makes it possible … [for us] to make management recommendations. … This is how trends can be recognised and strategies for sustainability of our multi-functional forests can be developed. … [It] is the basis for counteractive measures including policy on air pollution control, ground liming and the creation of robust mixed forest stands. ... We use modern and scientifically backed methods and instruments of forest ecosystem monitoring to secure sustainability of species diversity [and] wood production as well as the protective and recreational function of our forests, so that we can benefit from it in future." (translation by Augustin)*

(b) Improved sampling scheme in terms of cost-efficiency and precision. Funded by [2, 3], Augustin carried out a simulation study to optimise the sampling scheme based on the spatio-temporal model developed in Bath [1, A, B]. In particular, this work results in a substantial cost saving.
"The spatio-temporal model developed by Dr Augustin in collaboration with the FRI BW and others (see [1]) was crucial in assessing the cost-efficiency of the sampling scheme for monitoring tree health in BW. After about 20 years of changing sampling grids between resolutions 4x4km, 8x8km and 16x16km depending on available survey funds, a sampling grid of 8x8km is now used in BW. This change in policy was a direct consequence of a simulation study carried out by Dr Augustin which in turn was based on [1]. This study showed that the much cheaper and EU-wide used 16x16km grid resolution was not adequate in terms of detecting changes in defoliation at a relevant magnitude. The results also showed that the 4x4km grid resolution was unnecessarily low for achieving the required precision, and hence wasteful in terms of resources. ***This resulted in a yearly cost-saving of 100,000 Euros.*** [Our emphasis.] *The simulation study also showed up problem areas with very high prediction errors which could then be dealt with by inserting additional sampling locations."* [G]

(c) Improvement of forest growth conditions by reversion and mitigation of pollution effects on the soil through a forest liming programme. Spatial trend estimates of defoliation produced in Bath [A, B] were used by forest health managers to establish the need and planning of a forest liming programme in BW [C, F p.23].

"Moreover the reduction of sampling density in the crown condition survey enabled direct linking of the survey schemes on crown condition, forest nutrition and soil condition. Thus synoptic evaluation of data from these diverse monitoring schemes have been enabled [H] which are a sound basis for practical countermeasures of harmful effects of environmental change, like e.g. increasing deficiency in forest nutrition caused by acid rain and subsequent soil acidification. A central strategy for mitigating the effects of acidification is soil protective liming.

Since 2006 Dr Augustin has produced spatio-temporal trend estimates of defoliation based on [1] for the yearly Report on Forest Condition / Waldzustandsbericht published by the Forstliche Versuchs- und Forschungsanstalt BW (FVA), Freiburg available at http://www.fva-bw.de/). The spatial trends she produced in 2008 and 2009 [A, B] established the need for a forest liming programme, and were used by the FVA in its plans for such a programme in Baden-Württemberg [C, F].

The aim of the forest liming programme is in the long term not only to reverse the acidification of the soil, but also to reduce the acid stored in the soil. The liming programme entails on average a yearly liming of 15,000 ha with a dosage of 3t/ha. This is altogether 45,000 t of lime which is applied by turbine blowers from tractors or helicopters. In order to reverse the effects of acidification in the soil caused by pollution and improve growth condition a long-term yearly liming programme over the next 30 years is envisaged. ***Without Augustin's work [1] it would have been more difficult to convince the state government to fund the programme, and we would have much less confidence in a positive outcome."*** [G]. [Our emphasis.]

(d) Adaptation to climate change. *"The spatio-temporal trends of tree health produced in Bath highlighted particular areas where tree health is deteriorating due to a combination of climate change and soil condition. This contributed to a change in forest management to plant better suited trees and robust mixed stands. The spatio-temporal model of Augustin et al. [1] on crown condition allowed for proper identification of the spatial "hotspots" of crown damages and revealed that they changed from areas with soils, most susceptible to acidification (e.g. Black Forest) to lowland areas which are most susceptible for drought. This new spatial pattern of severe crown damages is observed since the year 2000 and is a strong indication for new, climate change-related drought stress."* [G]

The research contributes to the conservation of the natural forest environment in BW. Forest managers, policy makers and members of the public will therefore benefit from securing the economic production, recreational opportunities, ecological features and ecosystem services of the forest, including its biodiversity and its role as a sink for atmospheric carbon dioxide.

5. Sources to corroborate the impact

[A–E] Report on Forest Condition / Waldzustandsbericht, Forstliche Versuchs- und Forschungsanstalt Baden-Wuerttemberg, Freiburg. 2008-2012. http://www.fva-bw.de/publikationen/index3.html.

[F] von Wilpert, K. Schaeffer, J. Holzmann, S., Hug, R. Meining, S, Zirlewagen, D. and **Augustin, N.** 2010. Ableitung eines langfristigen Kalkungsprogramms. Was Waldzustandserfassung und Forstliche Umweltueberwachung bewirkt haben. AFZ- Der Wald. pp. 20-25. Heft 3/2010. http://ww.afz-derwald.de.

[G] Head of Department for Soil and Environment. FRI, BW. Supporting Letter.

[H] Musio, M., v. Wilpert, K., Augustin, N. (2007): Crown condition as a function of soil, site and tree characteristics. European Journal of Forest Research. 126/1, 91-100, doi:10.1007/s10342-006-0132-8.