Institution: University of Bath

Unit of Assessment: B10 Mathematical Sciences

Title of case study: Spatio-temporal modelling of forest health data in Germany: impact on forest management in response to pollution and climate change

Period when the underpinning research was undertaken: 2005 - 2020

Details of staff conducting the underpinning research from the submitting unit:

Name(s):	Role(s) (e.g. job title):	Period(s) employed by submitting HEI:
Nicole Augustin	Senior Lecturer, previously Lecturer	September 2005 – January 2020
Simon Wood	Professor of Statistics	January 2006 – November 2015

Period when the claimed impact occurred: 2014 - 2020

Is this case study continued from a case study submitted in 2014? N

1. Summary of the impact

Forests are important economically, ecologically and recreationally. They provide timber, sustain wildlife habitat and act as a carbon sink for many ecosystems. Thus, it is crucial to monitor forest health and use this information in forest management decisions.

At University of Bath, we have developed methods using Generalised Additive Mixed Models (GAMMs) to estimate spatio-temporal trends of forest health. This methodology has been developed in close collaboration with forestry experts in Germany. It has been adopted for official reporting in the national survey of German forest soil, and in reports on forest health for the states of Baden-Württemberg (BW), Saxony, and North Rhine-Westphalia, thereby improving the monitoring of forest health in Germany. These reports have major impact on regional and national strategic policy decisions on forest maintenance. In particular, the research has had significant influence on spending decisions of the EUR40,000,000 emergency planning budget of BW on forest strategy.

2. Underpinning research

A spatio-temporal model for forest health

Paper [1] presents a spatio-temporal model developed by Augustin and Wood at University of Bath with scientists at the Forest Research Institute (FRI) in Baden-Württemberg (BW). The method uses Generalised Additive Mixed Models (GAMMs) to capture spatial and temporal correlations in the data and to incorporate important predictors of measures of forest health. Previous methods ignored correlations in the data, leading to biases in trend and variance estimates. The methods in [1] avoid such problems, producing accurate estimates and confidence statements. The improved estimates of spatio-temporal trends allow earlier identification of forest deterioration and enhance understanding of its causes. In paper [1] the methodology is demonstrated in an analysis of defoliation in spruce trees in BW from 1985 to 2007. Paper [2] reports an analysis, using the model developed in [1], of defoliation in spruce, beech, pine and oak trees across 13 regions of Germany from 1989 to 2015.

Optimising the monitoring grid resolution

The condition of forest trees in Germany has been monitored since the late 1980s. Standard practice has been to create a 16 × 16km grid, mark a sample of 24 trees at each grid location, then record measurements for these trees annually. However, different grid densities occur: in BW, 4 × 4, 8 × 8 and 16 × 16km grids have been used, while in other states the grid density has changed over time.

Paper [2] examines the suitability of different monitoring grid resolutions. The paper reports a simulation study comparing different survey grid resolutions. The analysis shows that, while a 16 x 16km grid is sufficient to model nationwide time trends, an 8 × 8km grid is needed in order to estimate spatio-temporal trends, especially for oaks. Thus, a finer grid resolution is crucial for the early detection of hotspots with a high rate of defoliation.

Modelling tree health and mortality

The book chapter [3] uses the methods proposed in [1] and [2] to model the nutritional status of trees across Germany and to relate defoliation to soil condition and weather variables.

3. References to the research

1. Augustin, NH, Musio, M, von Wilpert, K, Kublin, E, Wood, SN & Schumacher, M 2009, 'Modeling spatiotemporal forest health monitoring data', *Journal of the American Statistical Association*, vol. 104, no. 487, pp. 899-911. https://doi.org/10.1198/jasa.2009.ap07058

2. Eickenscheidt, N, Augustin, NH & Wellbrock, N 2019, 'Spatio-temporal modelling of forest monitoring data: Modelling German tree defoliation data collected between 1989 and 2015 for trend estimation and survey grid examination using GAMMs', *iForest*, vol. 12, no. 4, pp. 338-348. https://doi.org/10.3832/ifor2932-012

3. Eickenscheidt, N, Puhlmann, H, Riek, W, Schmidt-Walter, P, Augustin, N & Wellbrock, N 2019, Spatial Response Patterns in Biotic Reactions of Forest Trees and their Associations with Environmental Variables in Germany. in *Status and Dynamics of Forests in Germany: Results of the National Forest Monitoring.* Ecological Studies, vol. 237, Springer Verlag, pp. 311-354. https://doi.org/10.1007/978-3-030-15734-0_11

4. Details of the impact

(a) **Improved current reporting of forest health.**

Research at University of Bath is the underpinning methodology for analyses of forest data in official national and regional reports: forest health for the state of Baden-Württemberg (BW) from 2014 to 2019 [A-F]; the national survey of forest soil produced for the German Ministry of Food and Agriculture in 2016 [G]; the forest soil report for Saxony in 2018 [H]; and the report on the forest condition in North Rhine-Westphalia in 2020 [I].These reports are prepared for policy makers to guide strategy and funding decisions at both state and national level.

The BW reports use the research from paper [1], for example, the 2019 report [F, p. 20 translated from German] states:

> *"The needle/leaf loss is calculated as a function of the age of the tree, the spatial position and the time, whereby correlations in time and space are taken into account (Augustin et al. 2009). The model enables an age-adjusted representation of the space-time trend …".*

An example of the results of this modelling for BW in 2019 [F, p 20, Figure 18] is shown below in figure 1.

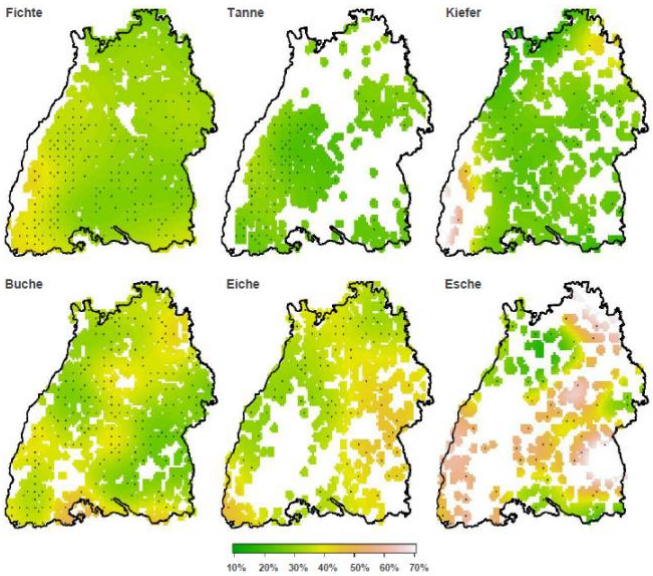

Abb. 18: Räumliche Verteilung der Nadel-/Blattverluste der Hauptbaumarten Baden-Württembergs, altersbereinigt auf das mediane Alter der jeweiligen Baumart

Figure. 1: Spatial distribution of the needle/leaf losses of the main tree species in Baden-Württemberg, age-adjusted for the median age of the respective tree species

(Fichte: Spruce, Tanne: Fir, Kiefer: Pine, Buche: Beech, Eiche: Oak, Esche: Ash)

The national survey of German forest soil [G, p. I-387, translated] states:

> *"Irregular grids are just one of the various properties of the crown loss data, due to which the space-time evaluation becomes a statistical challenge. … For the space-time modelling of these data, Generalized Additive Mixed Models (GAMMs) show promise (Augustin et al. 2009, Wood 2006a)".*

and the survey presents analyses that use GAMMs to model forest health across the whole of Germany. An example [G, p. A-42, Figure A-11-13] of results obtained is shown in figure 2:

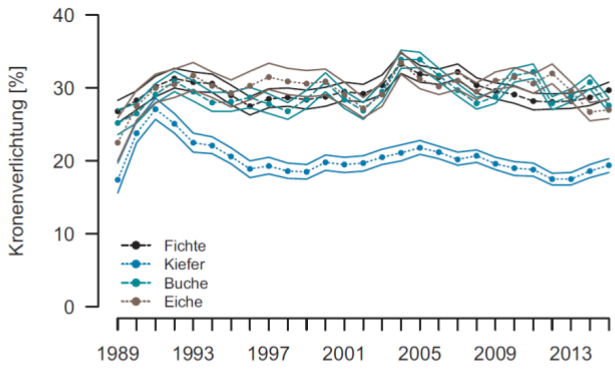

Abb. A-11-13: Geschätzte mittlere Kronenverlichtung mit Vertrauensbereich für die vier Hauptbaumarten von 1989 bis 2015 unter Verwendung von Raster 2 (16 x 16 km EU-Raster von 2014) und einem bundesweit einheitlichen Bestandsalter von 120 Jahren.

Figure 2. Estimated mean crown thinning with confidence interval for the four main tree species from 1989 to 2015 using grid 2 (16 x 16 km EU grid of 2014) and a nationwide uniform age of 120 years.

The forest soil report for Saxony [H, p.18, translated] refers to paper [1]:

"The space-time modelling was done with generalized Additive Mixed Models (GAMMs; Augustin et al. 2009 …)".

Impact of the methods in [1] and [2] on forest management policy is confirmed by a Head of Department at LANUV, Nordrhein-Westfalen [J]:

"I was a co-author of Thünen Report 43 [G] *… I have been involved in writing the Forest Condition Report for North-Rhine Westphalia 2020* [I]*. Both these reports present analyses using the methodology of Augustin et al (2009)* [1] *and Eickenscheidt, Augustin and Wellbrock (2019)* [2]*. The reports form the basis for determining forest management policy (like tree species choice or liming activity): in the case of the first report at national level, and for the second report at state level".*

(b) Guidance on sampling scheme to ensure effective monitoring of forest health

In order to take policy decisions early enough to protect tree species it is crucial to detect hotspots with a high rate of defoliation in a timely manner. The research in paper [2] highlighted the need to consider carefully the grid size used in order to make effective local decisions on hotspots. The national survey of German forest soil reflects this finding in stating [G, p. I-387, translated]:

"Generalized Additive Mixed Models can also be used to check the suitability of grid densities and to identify weak points".

and goes on to recommend the adoption of 8 x 8 km grids to protect the oak in the national guidance [G, p. I-454, translated]:

"A nationwide statement about temporal and spatial trends of crown defoliation, with the help of GAMMs, is necessary to identify risk areas at an early stage. There are weak points for all four main tree species, in particular for the oak. … Most of the federal states affected now report for these weak points on grid sizes of 8 x 8 km … . In the case of the oak, a nationwide consolidation to the 8 x 8 km grid should be considered".

(c) Forest management strategies to mitigate nutrient deficiency and climate change

The book chapter [3] models the relationship between forest health and soil condition and weather variables and reports that soil condition can exacerbate the effects of adverse weather conditions. The 2019 report for BW [F, pp. 3-4, translated] paints a bleak picture following the extreme heat and drought of 2018 and 2019:

"… tree species that we have previously classified as climate-resilient have suffered from the effects of heat, drought and storms in recent years … Against the background of the dramatic situation in the forests of Baden-Württemberg a summit took place in Stuttgart on September 2, 2019 [2 September 2019]. Representatives from the fields of forestry, agriculture, nature conservation … were invited. The draft of the Baden-Württemberg emergency plan drawn up by the ministry was discussed with the participants".

The key role of our research in addressing these problems is explained in the letter [K] from the Head of the Soil and Environment Department of the Forest Experimental and Research Institute, BW:

"The space-time model developed by Augustin and Wood has been used for our yearly reports of forest health in Baden-Württemberg every year since 2006. The results and analysis presented in these reports form the basis for policy decisions in the state. A key example is in 2019 when an emergency plan with a yearly budget of 40 Million Euros [EUR40,000,000] was set up by the Ministry of Rural Space and Consumer

Protection of Baden-Württemberg. This was followed in 2020 by a longer term forest strategy. Actions which directly follow from the recommendations in the reports of 2019 and preceding years, which are based on analyses using the methods of Augustin and Wood, include:

- *Site and tree species suitability maps as a basis for decision-making are firmly established in operational forest management.*
- *Updated maps on site conditions (climate, soils, hydrology, nutritional status) for upcoming reforestation and forest conversion are provided.*
- *Forest soil mapping will be promoted and implemented in a timely manner where initial mapping is still pending in private and corporate forests.*
- *Trials of comparative plantings of potentially sustainable tree species will be expanded.*
- *By means of a site-specific damage analysis, further bases and indications for a future-oriented forest conversion with climate-sensitive stands as well as adapted silvicultural procedures will be developed.*

The nature of the policy actions and their alignment with the analysis in the reports are evidence of the impact the work of Augustin and Wood [1] has had on policy".

5. Sources to corroborate the impact

[A to F] *Waldzustandsbericht (Report on Forest Condition),* Forstliche Versuchs- und Forschungsanstalt (Forest Experimental and Research Institute), Baden-Württemberg, 2014 to 2019.

[A] https://www.fva-bw.de/fileadmin/publikationen/wzb/ws2014.pdf

[B] https://www.fva-bw.de/fileadmin/publikationen/wzb/ws2015.pdf

[C] https://www.fva-bw.de/fileadmin/publikationen/wzb/ws2016.pdf

[D] https://www.fva-bw.de/fileadmin/publikationen/wzb/ws2017.pdf

[E] https://www.fva-bw.de/fileadmin/publikationen/wzb/ws2018.pdf

[F] https://www.fva-bw.de/fileadmin/publikationen/wzb/ws2019.pdf

[G] *Dynamik und Räumliche Muster Forstlicher Standorte in Deutschland. Ergebnisse der Bodenzustandserhebung im Wald 2006 bis 2008 (Dynamics and spatial patterns of forest locations in Germany. Results of the soil condition survey in the forest 2006 to 2008).* (2016) Thünen Report 43,Thünen-Institut, Braunschweig. https://www.thuenen.de/media/publikationen/thuenen-report/Thuenen_Report_43.pdf

[H] *Saechsischer Waldbodenbericht. Aktueller Waldbodenzustand and dessen Veraenderung (Saxon Forest Soil Report. Current Forest Soil Condition and its Changes)* Schriftenreihe, Heft 30. Staatsbetrieb Sachsenforst. p. 160. 2018. https://publikationen.sachsen.de/bdb/artikel/32359

[I] *Waldzustandsbericht Nordrhein-Westfalen (Forest Condition Report for North Rhine-Westphalia)* 2020. https://www.umwelt.nrw.de/fileadmin/redaktion/Broschueren/waldzustandsbericht_2020_kurzfassung.pdf

[J] Letter from Head of Department at the Landesamt für Natur (LANUV), Nordrhein-Westfalen, 21 December 2020.

[K] Letter from Head of the Soil and Environment Department at the Forstliche Versuchs- und Forschungsanstalt Baden-Württemberg, 18 December 2020.