Enhanced sensitivity of a mountain bog to climate change as a delayed effect of road construction

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SUMMARY

Trees of *Pinus rotundata* (bog pine) characterise many bogs in the mid-altitude mountains of central Europe (Switzerland, East and South Germany, Czech Republic). The research described here focuses on recent changes in the growth of bog pine on the Ennersbacher Moor, a mountain mire in the Black Forest (south-west Germany). An increase in the cover of bog pine is usually caused by drainage and subsequent drawdown of the water table. However, this bog has not been drained or directly disturbed in any other way. One possible explanation is that a road constructed in 1983 along one margin of the bog has diverted part of its water supply. Even though the road was designed to conduct potentially salt-contaminated drainage water away from the bog, its construction did not cause an immediate vegetation response in the 1980s and 1990s. Therefore, I hypothesise that it enhanced the sensitivity of the bog to climatic stress, predisposing it to a succession that was eventually triggered by a series of drought years in 2009–2011. Data collected near the centre of the bog over the period 1998–2014 indicate not only a distinct change in the relationship between height and trunk circumference of the trees, but also an increase of dwarf shrub cover and changes in the composition of *Sphagnum* communities. Although the pH of near-surface water may have increased slightly over this period, pH and EC values remain within typical ranges for raised bogs in the Black Forest. Examination of peat profiles reveals that the peat is more highly humified now than it was in 2002, and water table records from 2012–2014 show a greater amplitude of fluctuation than water table data collected in 1998–2001. Even though its mean level is only 105 mm below the ground surface, the water table is now observed to fall rapidly to depths of at least 350 mm during both wet and dry summers. Mapping surface (meso)topography and flow lines from the adjacent slope shows that the Ennersbacher Moor is not domed in this direction, so that water arriving from upslope would reach the bog centre if the road were not present. Overall, the results support the hypothesis that the observed succession is a delayed effect of construction of the road.

KEY WORDS: biometrics; Black Forest; bog pine; catchment; flow lines; interflow; raised bog; water table

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INTRODUCTION

The Black Forest is a wooded mountain range occupying an area of approximately 160 × 60 km in the Federal State of Baden-Württemberg, south-west Germany. Its highest peak is the Feldberg (1,493 m a.s.l.). Within the Black Forest, bogs occur both on the exposed gneissic or granitic bedrock in the southern part of the range and on the overlying sandstone in the north. Most of these now have sparse or dense stands of bog pine (*Pinus rotundata var. arborea* and *var. pseudopumilio*). Pollen records from several Black Forest mires including Horbacher Moor (Lang 1984), Kohlhüttenmoos (Lang 2005), Lindauer Moor (Dietz 2001), Rotmeer (Lang 2005) and Steerenmoos (Rösch 2000, Rohrer 2006) show low levels of pine pollen before the Middle Ages, when anthropic alteration of the land and forests commenced. The possible character of natural bog pine stands before human intervention can be observed on present-day wet limnic mires whose fringes have only small numbers of bog pine trees with stunted growth, low production and, therefore, low release of pollen and seeds. Thus, it seems probable that the observed increase of pine in Black Forest pollen records since the Middle Ages reflects an encroachment of pine onto the bogs caused by drainage and by land use changes in their catchments.

A recent dieback of bog pine at several sites in the southern Black Forest prompted a detailed investigation of the ecological conditions in three bogs (von Sengbusch 2004). The dieback was obviously not caused by acid rain or enhanced nitrogen deposition and was restricted to drained bogs with altered pine population dynamics. The highly diverse open pine stands, with individuals of different age classes and snag (standing but dead or dying) trees next to one another had been replaced by even-aged tree canopies. In other words, instead of continuous recruitment, the pine displayed

discontinuous population dynamics with recruitment only after breakdown of the tree canopy. The dieback was identified as a delayed effect of drainage and succession whereby the trees had reached a growth limit. Similar effects were later demonstrated in 35 other pine bogs (von Sengbusch 2006).

In these two previous studies (von Sengbusch 2004, 2006) it was shown that, in 38 populations of bog pine in the Black Forest and two populations of Scots pine (*Pinus sylvestris)* in Finland, there is a non-linear correlation between height (h) and circumference (c) of the trees. The underlying distributions of h and c express growth models that can describe the growth of a single tree if the environment is more or less stable, and the relationship between h and c (the growth function) is a key characteristic for the distribution of growth in the trees. In wet habitats the sink for photosynthetic assimilates is obviously in the trunk and low branches, whereas in dry peatland the sink is in the terminal buds. Thus, when the mean water table is high, the trees assume stunted (short) growth forms with thick trunks; and the more the water table sinks relative to the peat surface, the more the trees develop taller and slimmer growth forms. Indeed, if the growth function is well understood for a particular geographical region, it can be used as an index of peat wetness for individual sites within that region.

Koslowski *et al*. (1991) found that the vertical growth of several pine species was rapidly reduced after a period of waterlogging of the roots. It is possible that the underlying mechanism is the influence of periodic waterlogging of fine roots on the release of phytohormones. The role of cytokinins in regulating the source-sink relationship in plant growth is described by Roitsch & Ehness (2000), and one of the most important locations for the production of cytokinins and giberellins is in the roots (Reid & Bradford 1984, Lyr *et al*. 1992).

The Ennersbacher Moor used to be regarded as a "reference bog". It was one of three pine bogs in the southernmost Black Forest which were not drained and seemed to be characterised by relatively natural conditions. There were (and still are) no ditches and no indications of peat cutting anywhere on the site. The surface displayed only weak hummock-hollow structure and *Sphagnum* lawns predominated in areas of open mire. This bog was famous for the stunted growth of its trees, some of which were more than 240 years old with circumferences exceeding 0.75 m but only 2.5 or 3 m tall.

The growth of trees in Ennersbach seemed to be controlled by high water levels and the growth of *Sphagnum* mosses. The fine roots were confined to a shallow layer of peat (51–56 % of the fine root mass in the uppermost 40 mm, 77–88 % above -80 mm)

and were well colonised by mycorrhizal fungi (unpublished data of Patrick Kuss, Department of Geobotany, University of Freiburg, 2003). The root collars of almost all pine saplings were between 100 and 200 mm below the surface due to overgrowth by *Sphagnum* mosses and peat, and the stalks of *Andromeda polifolia* and *Vaccinium uliginosum* were also rapidly overgrown by *Sphagnum*.

Since 2010, the density of the tree canopy has increased substantially and the biometrics of the trees have obviously changed. The photographs in Figure 1 show that the initially rounded shrubs have grown taller. Moreover, there is copious pine recruitment all over the bog surface, *Vaccinium uliginosum* has spread, and almost all of the wet hollows have disappeared or become covered by dense *Sphagnum* lawns, indicating drier conditions. As two other growing bogs in the vicinity have not been affected by such a succession, climate change can be ruled out as the primary cause.

In this article I test an alternative hypothesis that the changes were triggered by a road that was constructed in the lagg upslope of the bog in 1983. The hypothesis does not assert that the road was the primary driver of succession but rather that its presence ultimately led to enhanced sensitivity to climate change and, therefore, caused a succession in conjunction with the prolonged drought periods that occurred from 2003 to 2011 (von Sengbusch 2011).

Dierssen & Dierssen (1984) inspected the Ennersbacher Moor during construction of the road, as part of a survey of all mires in the Black Forest. The bog was clearly ombrotrophic as there were no plants in its centre that indicated the influence of mineral soil water, and these authors assumed that the bog was slightly domed so that much of the water entering the lagg would be diverted around the perimeter of the dome. Nonetheless, they warned that construction of the road was a serious threat to the bog, especially as the upslope embankment of the road was to be sealed with plastic sheeting so that water from the slope that would previously have entered the lagg could no longer follow its natural flow paths. According to Edom (2001) the lagg on the upslope side of a mountain bog is a hydromorphological element that receives and slows down the water arriving as lateral interflow from the mineral catchment, but the hydraulic gradients are such that it then continues directly downslope towards the centre of the bog (i.e. the surface profile is not domed in this direction). Ombrotrophic conditions arise at the bog centre because, beyond the lagg, the transport of nutrients with the interflow will decrease with increasing distance from the mineral catchment due to mixing with rainwater and the accumulation of ions by organic matter. If this is the

hydrological mechanism that originally supported the Ennersbacher Moor, it seems even more likely that it could have been altered by the presence of the road.

The aim of the research reported here was to record any changes in vegetation, peat quality, water quality and water table regime that may result from the presence of the road; to quantify these changes as far as possible; and to undertake a detailed examination of landscape topography to clarify the routes of flow lines.

Figure 1. Upper photograph: the open bog pine canopy on the Ennersbacher Moor in 1999, showing the rounded crowns of the trees and the cottongrass-dominated field layer. Below: two photographs taken at the same location (Plot E1) in the centre of the bog in 1999 (left) and 2014 (right). The piezometer (see later in text) is visible at bottom centre of the right-hand picture.

METHODS

Study sites

The Ennersbacher Moor lies in the south-east of the Black Forest (47° 42′ 36.16″ N, 08° 05′ 46.47″ E), within a zone of transition from atlantic to continental climate. Average annual precipitation (1998–2013) at the bog is 1600 mm. Its area is 8.88 ha and it is located at an altitude of 927 m a.s.l. on a saddle west of Dachsberg, immediately downslope from the Dachsberg road (Figure 2). Dierssen & Dierssen (1984) reported that the mire-centre vegetation consisted of *Sphagnum*-rich open pine stands belonging to a typical *Pino mugo-Sphagnetum*, and lacked minerotrophic plant species. Biometric and dendrological research was carried out between 1998 and 2002 (von Sengbusch 2004). Subsequently (2002–2004), the Ennersbacher Moor was included in a monitoring programme that investigated 38 mire sites in the southern and central Black Forest, in order to create a database of ecological conditions in pine stands on peatlands (von Sengbusch 2006).

Recent (2012–2014) water table data (for comparison with data from the Ennersbacher Moor) were collected at two Black Forest petlands that occupy saddles in the sandstone mountain ridge approximately 114 km to the north, namely the Hohloh Mire (48° 42′ 51.9″ N, 08° 27′ 34.89″ E; 984 m a.s.l.) and the Wildseemoor (48° 42′ 16.60″ N, 08° 25′ 00.29″ E; 907 m a.s.l.). Average annual precipitation in this area is also 1600 mm. Both of these peatlands were drained in the 19th century, after which they were colonised by bog pine. At the Hohloh Mire (part of a ~170 ha peatland), the piezometer is in a terrestrialised pool which is one of only three remaining patches of open growing mire. About 8 % of the Wildseemoor (total area ~185 ha including 65 ha of bog) is open growing mire, and the piezometer is located in a 1.2 ha clearing with *Sphagnum*-cottongrass (*Sphagnetum magellanici*) communities.

Pine biometrics

Four plots of area ~80 m^2 were established in 1998 on a transect running from the marginal spruce forest (lagg) to the centre of the Ennersbacher Moor. In 1999 the heights (*h*) and circumferences (*c*) of all pine trees and shrubs in the margin and bog-centre (E1) plots were measured using a tape measure, a folding metre stick and a tree altimeter (BL7, Carl Leiss, Berlin). In 2013 *h* and *c* were measured again for 20 trees and shrubs in Plot E1 (only).
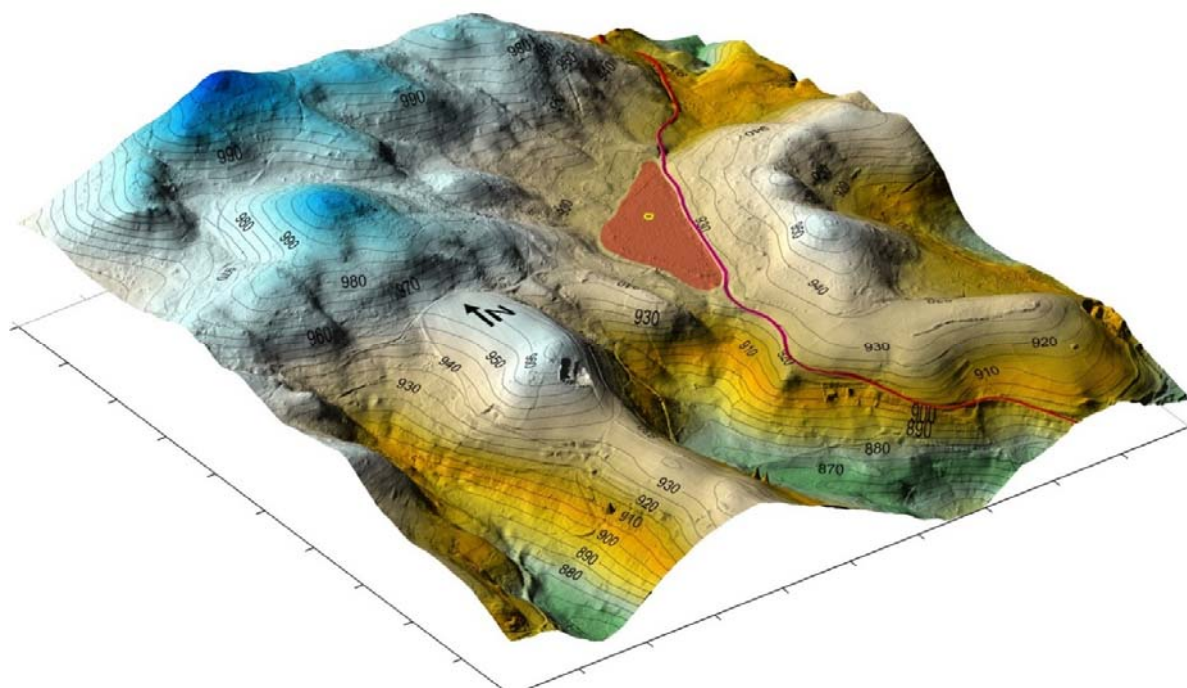

Figure 2. The Ennersbacher Moor (red area, 8.88 ha) and surrounding mountains. Pink line = Dachsberg road; yellow circle = Plot E1; spacing of grid ticks = 200 m; contour interval = 5 m; altitudes in m a.s.l.; datum Germany DHDN Gauss zone 3 (conversion method: Bursa-Wolf; conversion target: WGS84; ellipsoid: Bessel). Figure created using *Surfer 12* software from German Federal State of Baden-Württemberg laser scan data; Geobasisdaten © Landesamt für Geoinformation und Landentwicklung Baden-Württemberg, www.lgl-bw.de, Az.: 2851.9-1/19.

Data analyses were carried out using *SPLUS*, a commercial software system implementing the S programming language (Tibco Software Inc.). Applications developed for *SPLUS* are often compatible with the free statistics software "R". For the data collected at Plot E1 in 1999 and 2013, the relationships between h and c were described by the growth function:

$$h \cong bc^a + k \qquad [1]$$

where a (the growth factor), b and k are constants. Equation 1 was then integrated over the range $c = 0.2$–0.6 m to derive the growth integral:

$$\int_{c=0.2}^{c=0.6} h \, dc = \frac{bc^{(a+1)}}{(a+1)} + kc \qquad [2]$$

The growth integral expresses the form of the trees within each population as a single numerical value which can be used, for example, in multivariate analyses of data from large samples of bog sites (von Sengbusch 2006). The lower limit of integration is chosen because trees with $c < 0.20$ m have seldom been encountered. This procedure was developed in order to simplify the comparison of growth functions between populations exhibiting different relationships (e.g. logarithmic, exponential, Michaelis-Menten) between h and c, for which growth integrals may be derived using an online integrator (integrals.wolfram.com) if necessary.

Ground vegetation
In 1999 the cover of the most important cormophytic plants was recorded for the whole of both Plot E1 and the plot at the bog margin. *Sphagnum* species were recorded by Kuss (2003) in a 280 m^2 plot surrounding Plot E1. In 2013 mosses, liverworts and cormophytes were recorded and the cover of cormophytes and *Sphagnum* species estimated for the whole of Plot E1.

Peat stratigraphy
During an analysis of pine bog conditions in the Black Forest carried out in 2002, six peat cores (0 to -200 mm depth) were extracted from Plot E1 for NH$_4$ and bulk density determinations with a home-made "root borer" (a 400 mm length of 55 mm diameter steel tubing with a 40×220 mm window whose edges were sharpened). Degree of humification was estimated by the squeezing method of von Post & Granlund (1926) for the -40 to -80 mm and -160 to -200 mm layers (only). Four additional 0 to -200 mm cores were collected for description of the peat.

In May 2014 two peat cores (1 m long) were taken with an Eijkelkamp Russian-type peat borer (chamber 500 mm long and 60 mm in diameter), one below *Calluna vulgaris* and one below *Sphagnum angustifolium*. These cores were examined for plant remains in the field using a hand lens (×10) and an Eschenbach (Germany) T40 two lens system (×40). Humification was estimated by the von Post method and through assessment of the colour, proportion of plant fibres and condition (pulpy or not) of the peat. A third one-metre core was taken in September 2014 and stored in a freezer at -20 °C until the peat could be examined in the laboratory. After thawing, the peat from this core was disintegrated with deionised water and single *Sphagnum* stem and branch leaves were taken for examination under a Russian MBC-10 stereomicroscope (×40) and a Carl Zeiss science microscope (magnification ×80–1600).

Meteorological data
Precipitation has been recorded since 1951 at a German Weather Service (DWD) station in the village of Wolpadingen (880 m a.s.l., 1.3 km south-east of the site). Air temperature has been recorded daily since 1961 at a weather station in Lenzkirch (860 m a.s.l., 20 km north of the bog). The appropriate data were taken from the DWD database and used to calculate monthly rainfall and monthly mean temperature values for the years 1998–2013 inclusive.

Water table regime
Water table depth was measured during the growing season each year from 1998 to 2001 in four 35 mm diameter PVC dipwells (with perforated walls) in each of the four plots. The measurements were captured manually during site visits at intervals of two weeks, using a graduated probe with LED lamp that lit when the lower end of the probe made contact with the water table. Data for the mire-centre plot only (Plot E1) are presented here

In April 2012 a piezometer with a data logger (ATP10 Beaver, made by Aquitronic Umwelt-messtechnik GmbH, Kirchheim-Teck) was mounted in a filter tube (a PET tube 50 mm in diameter with narrow horizontal slits at 5 mm spacing) in Plot E1. Piezometer readings were logged at hourly intervals. These measurements are being conducted as part of a hydrological survey encompassing ten bogs and fens in the southern Black Forest. Discrepancies of more than 30 mm between piezometer and filter tube readings at some of these sites indicated a need for calibration. The piezometer at the Ennersbacher Moor was calibrated using six additional filter tubes (35 mm diameter, with horizontal slits) located within Plot E1. The water table was recorded manually in the six filter tubes on two dates and a mean water table depth for each date was calculated.

As the piezometer readings were 6 mm above the mean values of the filter tube readings on the two dates in question, all of the piezometer readings were corrected by this amount.

For all measurements of water table depth, the bog surface was defined as the level at which a solid *Sphagnum* mass is formed when the *Sphagna* are pressed onto the peat by snow in winter, which is below the surface formed by the *Sphagnum* capitula in summer. This means that a piezometer reading indicating water table 20 mm above the surface does not necessarily mean that the loose *Sphagnum* lawns, which may be 40–50 mm thick, will be inundated.

The data from the piezometer were transformed into a density function using SPLUS 2000. The water table data can be depicted as a frequency histogram if the observations are classified into defined ranges (e.g. -0.1 to -0.12 m, -0.12 to -0.14 m, *etc*.). The density of the frequency is calculated by dividing the relative frequency (frequency value of each class divided by the total number of observations) by the width of the classes. The density plot relates density to the class values with the width of the classes approaching zero.

Water quality
In 2000, pH was measured at 150 mm depth in unsaturated peat at Plot E1 using a Stelzner (Germany) spike electrode and a Greisinger GMH3530 pH meter, on five dates between 01 April and 31 October (ten observations per date). On one occasion in 2014 (15 September), pH was measured with a Greisinger QpH70 instrument with automatic temperature control, and electrical conductivity (EC) with a HANNA HI99300 instrument, in the six additional filter tubes at Plot E1 and between the *Sphagnum cuspidatum* plants in four hollows east of Plot E1. The pH of soil solution from a 40 mm diameter hole, newly drilled to 200 mm depth, was measured at four locations within Plot E1; although there were very few millilitres of water in each borehole because peat humification was H6. There was no free water in the lagg due to the dry conditions, but pH and EC were measured at 200 mm depth in a mud-bottom hollow (peat humification H8–H10). The conductivity values were not rectified for proportion of H^+ cations. The pH meter was calibrated twice with pH4 and pH7 standards and the meter was tested for drift every five minutes. Mean concentrations of H_3O^+ ions were calculated from the antilogarithms (base 10) of the pH values.

Landscape topography and flow lines
Laser scan data, recorded from an aeroplane by the State Office for Geo-Information, are available for the whole of the German Federal State of Baden-Württemberg (www.lgl-bw.de). A 3D surface map of the Ennersbacher Moor and surroundings was created from these data using *Surfer 12* software. Flow lines indicating the direction of lateral water flow were drawn (digitised) by hand, running perpendicular to smoothed surface contour lines (based on a reduced-resolution interpolation grid), using the software feature "spline polyline".

RESULTS

Pine biometrics
The key results of the biometric analysis are shown in Table 1. Over the 15-year period 1999 to 2014, the growth factor *a* increased from 0.24 to 0.36, whereas the slope of the growth function (*b*) increased only slightly and the growth integral shifted from 1.07 m² to 1.57 m². The growth functions derived for the centre of the site in 1999 and 2014 are compared in Figure 3. Except for one point, all of the 2014 observations lie above the 1999 growth curve. The mean of residuals *versus* the 1999 function is 0.8 m and the standard deviation is 0.49 m.

Ground vegetation
The vegetation data collected at Plot E1 in 1999 and 2013 are compared in Table 2. Kuss (2003) reported cover values for *Sphagnum magellanicum* (65 %) and *Eriophorum vaginatum* (60 %) (from a 280 m² plot surrounding Plot E1) but did not mention *Sphagnum angustifolium*.

The vegetation in Plot E1 obviously changed between 1999/2003 and 2013, in that the cover of dwarf shrubs increased and the cover of *S. magellanicum* declined. The moss layer is now dominated by small-leafed *Sphagna* such as *S. capillifolium* ssp. *rubellum* and *S. angustifolium* growing in patches. On sunny days *S. angustifolium* dries out earlier than *S. capillifolium* (observations in May and June). Although intermediate forms of

Table 1. Summary of changes in the biometric characteristics of trees at the Ennersbacher Moor, 1999–2014.

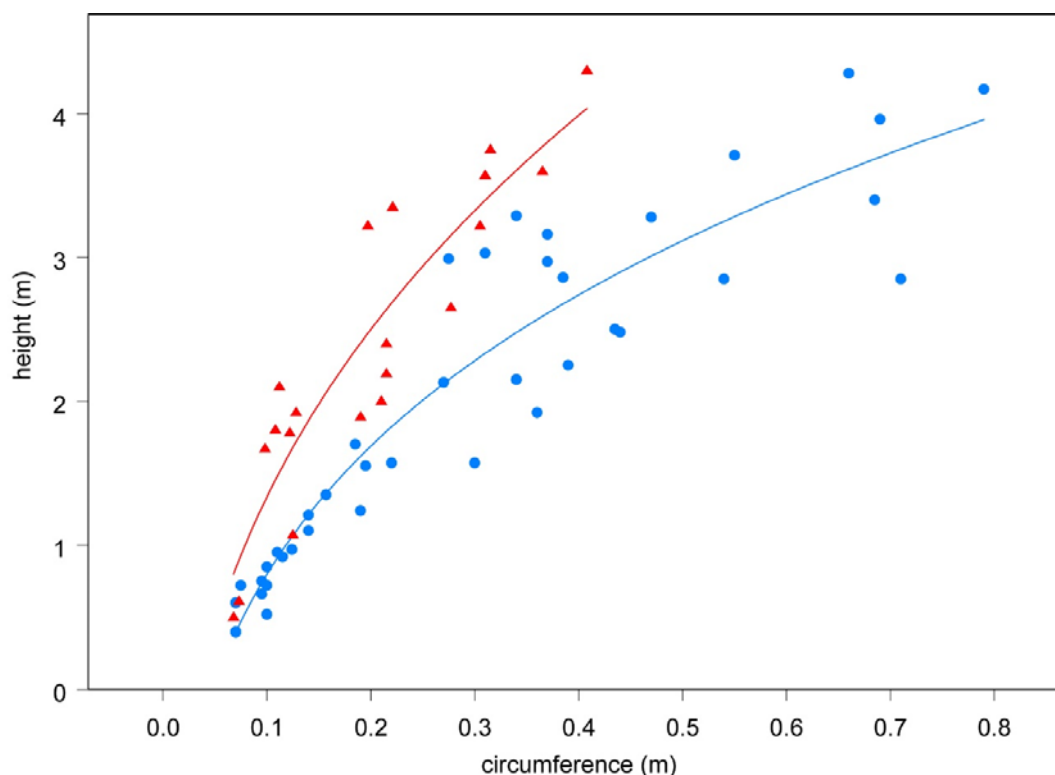|		1999	2014
Number of observations		40	20
Residual sum of squares		6.19	3.58
Parameters:	*a*	0.24	0.36
	b	8.48	9.44
	k	-4.05	-2.82
Growth integral $_{0.2-0.6\,m}$		1.07 m²	1.57 m²

Figure 3. Graph of height (*h*) *versus* circumference (*c*) of pine shrubs and trees at Plot E1 in 1999 (blue circles) and 2013 (red triangles), with fitted growth function curves. One outlier point for 2013 has been removed.

S. rubellum and *S. capillifolium* occur in Plot E1 (stem leaves not clearly lingulate but hyaline cells 60–80 % septate), most of the plants have short (0.9 mm) stem leaves and are only weakly fibrillose or lack fibrils, and are thus identified as *S. capillifolium* ssp. *rubellum* according to Smith (2004). Several liverworts are found amongst the *Sphagna* and in small, shaded depressions.

Vaccinium uliginosum and bog pine are spreading throughout the whole bog, and only the small clearings between the groups of pine at the bog centre are still dominated by cottongrass. About 12 m south and 4 m west of Plot E1 there are two hollows covered by dense *Sphagnum cuspidatum* lawns where single plant clusters (about 30 plants in each hollow) of *Sphagnum balticum* can be found. This is a rare species in Baden-Württemberg, where only a few isolated populations remain.

Peat stratigraphy
The peat cores collected in 2002 (von Sengbusch 2006) had an average humification of H3 (n=6) in the -40 to -80 mm layer and of H5 (n=6) in the -160 to -200 mm layer. Two of the four additional cores had a layer of medium humification (H6) at -10 to

-70 mm (below *Calluna*) whereas there was only slightly humified *Sphagnum* peat (H2) down to -100 mm in the other two cores. The H2 *Sphagnum* peat was also found at other locations in Plot E1.

In 2014 the youngest peat sampled (-30 to -70 mm) was slightly humified (H3) and consisted of brown *Sphagnum* leaves. Below *Calluna* the peat contained many fine roots and small patches of amorphous components. The peat at -70 to -150 mm was pulpy with humification H5–H6. From -150 to -300 mm the peat had high humification beneath both *Calluna* (H7–8) and *Sphagnum* (H6–7) (Figure 4). At -300 to -650 mm (below the recent minimum levels of the water table) it could easily be seen that the bog centre was formerly covered with *Sphagnum* lawns and cottongrass, as the peat (H4) consisted mainly of yellow-brown *Sphagnum* leaves, with some cottongrass (*Eriophorum vaginatum*) and very few fine roots of bog pine and shrubs.

Evidence of a period with *Acutifolia* peat formation was present from the surface to -270 mm in the profile. About 90 % of the peat at -100 to -200 mm consisted of *Sphagnum rubellum* leaves. The stem leaves of *S. rubellum* could be identified under the microscope by their lingulate form, 0.9–1.2 mm

Table 2. List of plant species and % cover values recorded in Plot E1 (80 m^2) at the centre of the Ennersbacher Moor in 1999 and 2013. nr: not recorded. Nomenclature follows Oberdorfer (2001) for vascular plants and Smith (1990, 2004) for liverworts and mosses.

Species	year	
	1999	2013
Carex pauciflora	-	<1
Drosera rotundifolia	-	<1
Eriophorum vaginatum	40	40
Calluna vulgaris	10	10–12
Melampyrum pratense ssp. *paludosum*	-	1–2
Oxycoccus palustris	-	3–5
Vaccinium myrtillus	0	1–2
Vaccinium uliginosum	20	30
Sphagnum magellanicum	nr	10
Sphagnum angustifolium	nr	40
Sphagnum capillifolium ssp. *rubellum*	nr	40
Aulacomnium palustre	nr	1–2
Calypogeia sphagnicola	nr	<1
Cladopodiella fluitans	nr	<1
Cephalozia connivens	nr	<1
Cephalozia lunulifolia	nr	<1
Mylia anomala	nr	<1
Pleurozium schreberi	nr	1–2
Polytrichum strictum	nr	1–2

length, and consistently septate hyaline cells (Smith 2004). Stem leaves of *S. angustifolium* were not found. Two of the cores contained mixed *Acutifolia* and *Cymbifolia* peat at -270 to -340 mm, and a period of *Cymbifolia* peat formation was detected below -340 mm (down to -650 mm). The layer from -650 mm to -1000 mm was characterised by decomposed (H5–7) *Sphagnum*-cottongrass peat with some *Calluna* twigs. There was no *Cymbifolia* peat in the -340 to -650 mm layer of the core investigated in the laboratory but, rather, H4 *Sphagnum* peat (stems and stem leaves of *S. rubellum* identified) with remnants of cottongrass (*Eriophorum vaginatum*). Fine roots of bog pine were found from -10 to -80 mm in only one of these three cores.

Meteorological data

Mean annual precipitation (1998–2013) at Wolpadingen was 1608 mm, and the mean for the growing season (April–October) was 822 mm. Table 3 lists monthly precipitation totals for the growing seasons of 1998 to 2013 inclusive, and months with less than 66 % of the mean monthly precipitation (88.5 mm) are highlighted. Total precipitation for 1998 was less than the annual mean due to a dry period in spring and early summer, whereas 1999 was rather wet. There were several short dry periods in 2003, and dry periods of eight or more weeks in 2005, 2009, 2010 and 2011. Overall, 2003 was an extremely dry year, and many springs and brooks in the Black Forest dried up completely in July that year. The amount of rainfall during the growing season of 2012 was almost the same as in 2000; in 2012 it was 41 mm more and in 2013 it was 9 mm less than the 1998–2013 average.

The analysis of air temperature data from Lenzkirch (Figure 5) revealed a rise in growing season temperature of 1.8 °C between 1961 and 2013.

Figure 4. Peat profile below *Sphagnum angustifolium*, depth 0–500 mm (above) and 500–1000 mm (below).

Table 3. Monthly rainfall totals (mm) at the Wolpadingen meteorological station, April to October 1998–2013. Mean annual precipitation = 1608 mm; shading indicates months with less than 66 % of mean precipitation. Data for 2014 are not included because DWD had not (yet) published this information at the time of writing.

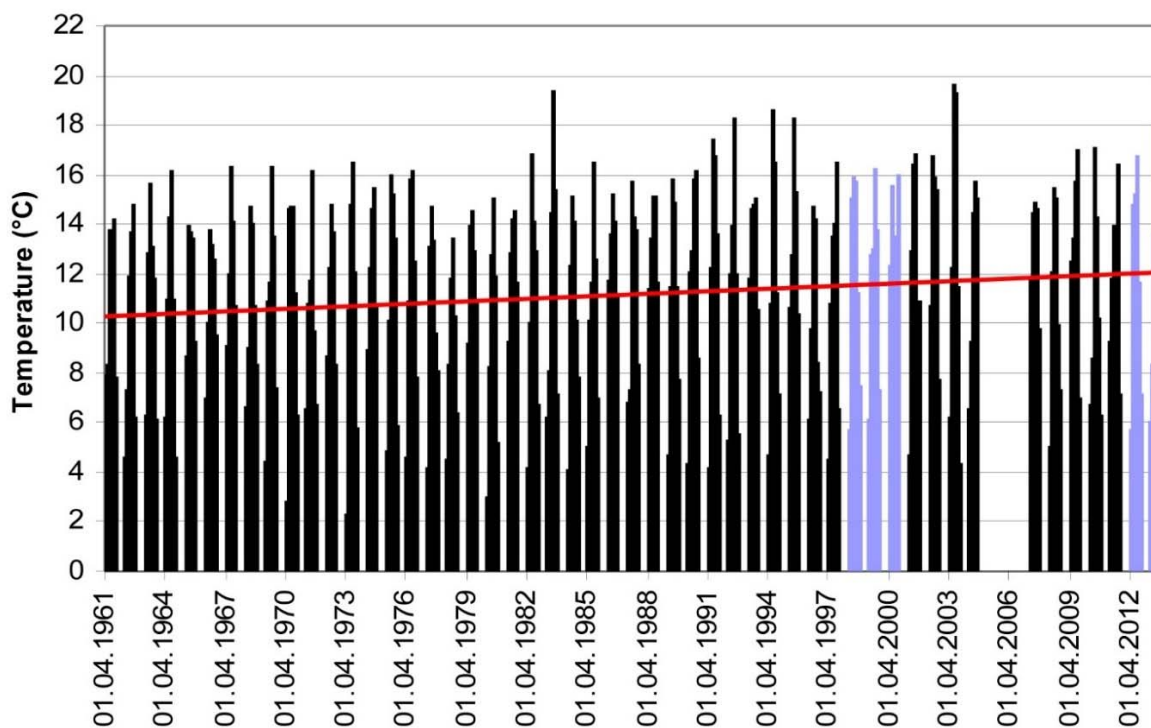| period	year															
	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Apr	145	179	70	205	63	81	73	123	180	6	148	23	33	19	112	159
May	17	160	173	134	128	117	121	135	164	268	54	92	180	26	89	125
Jun	86	150	64	145	80	24	82	64	54	238	71	154	70	128	192	54
Jul	96	125	253	159	169	93	96	126	65	178	92	177	80	144	109	125
Aug	136	104	89	65	118	91	173	105	301	111	131	42	203	94	127	75
Sep	227	149	86	201	88	32	74	56	110	100	121	79	73	50	96	148
Oct	306	72	122	104	291	208	230	68	130	6	154	55	68	86	138	129
Apr–Oct	1013	939	857	1013	937	646	849	677	1004	907	772	621	707	547	863	815
May–Oct	868	760	787	808	874	565	776	555	823	901	623	598	674	527	751	655

Figure 5. Monthly mean air temperatures recorded at Lenzkirch for the growing season (April–October), 1961–2013. Red line = linear regression. The data for 1998–2000 and 2012–2013 (focus periods for this study) are represented by the blue bars. No data are shown (or available) for a period in 2005–2006 when this weather station was out of action.

Water table regime

Even though there was an early dry period in 1998 (Table 3), the minimum water table level recorded at Plot E1 during the summers of 1998 and 1999 was -0.35 m. In contrast, the summers of 2012, 2013 and 2014 lacked prolonged dry periods, but the water table was recorded below -0.3 m and even below -0.4 m on several occasions (Figure 6). The decline of water table level reached maximum rates of 0.03–0.04 m (30–40 mm) per day in June–August.

The density plots (derived from frequency distributions) of water table data collected between 01 July 2012 and 01 July 2014 at the Ennersbacher Moor, Hohloh Mire and Wildseemoor are shown in Figure 7. This period was chosen to include the only dry period of 2014 (in June), in addition to the two that occurred during 2013 (Table 3); the piezometers at the latter two sites having been commissioned at the end of May 2012. The density distributions are conspicuously asymmetric (skewed), with longer tails towards deep water table. The range of the distribution for Ennersbach is +0.02 m to -0.42 m and it peaks at -0.08 m. The water table regime is characterised by a high frequency of levels between -0.03 and -0.15 m and numerous observations below -0.30 m. The curves summarising the water table regimes at the other two mires over the same period (i.e. under similar weather conditions) both peak between the surface and -0.08 m (Wildsee -0.01 m, Hohloh -0.07 m) and do not extend below -0.30 m.

The density (frequency) distributions for all of the water table records represented in Figures 6 and 7 are summarised in Table 4. The area below a density function is divided into two equal halves by the median, which is closer to the mire surface than the mean in most cases. Skewness (deviation from a normal distribution) reflects the separation between the mean and modal (peak) values, which would be identical in a normal distribution.

At the Ennersbacher Moor, the total ranges of water table levels recorded (using piezometers) during the growing seasons of 2012–2014 were substantially greater than those recorded (manually) during the growing seasons of 1998–2000 (309–402 mm *versus* 149–261 mm); and the minimum water levels were deeper (-348 to -420 mm *versus* -213 to -350 mm). From the simultaneous (2012–2014) piezometer data for three different mire sites, the total range of water table fluctuations at Ennersbach was 440 mm *versus* 253–293 mm at Wildseemoor and Hohloh Moor, and the deepest water level recorded was -440 mm *versus* -189 to -245 mm.
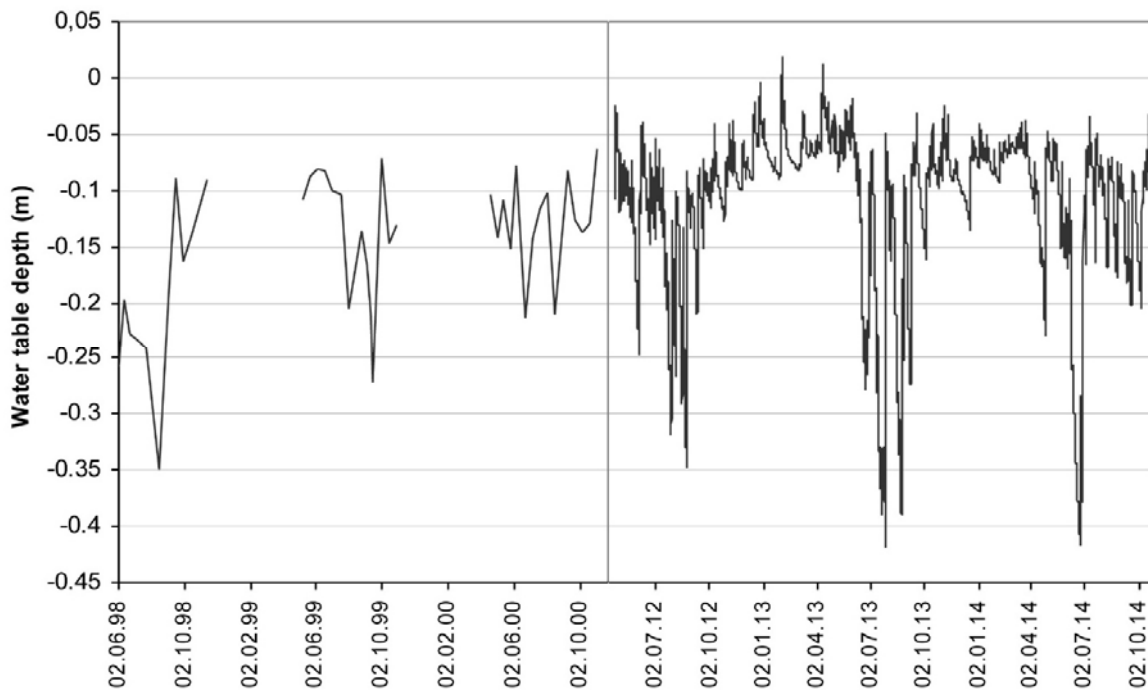

Figure 6. Water table depths below ground surface recorded at the centre of the Ennersbacher Moor in 1998/1999/2000 (left) and 2012/2013/2014 (right). The labels on the horizontal axis are calendar dates.
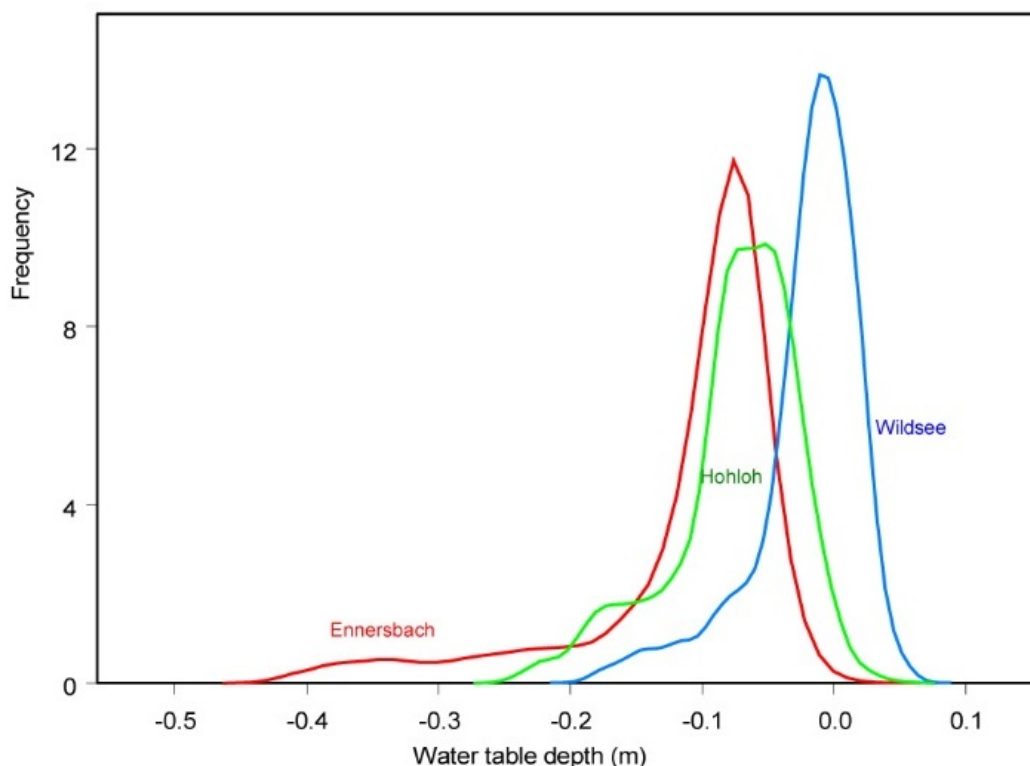
Figure 7. Density (frequency) curves prepared from 17,520 observations of water table depth below the ground surface (piezometer data 01 July 2012 to 01 July 2014) in Plot E1 at the Ennersbacher Moor (red curve), and data collected using similar equipment over the same period at plots on two growing mire sites in the northern Black Forest. The experimental plot on the Hohloh Mire (green curve) is located in a terrestrialised bog pool, and the plot at Wildseemoor (blue curve) within the site's largest remaining expanse of open mire.

Water quality
In 2000 the pH ranged from 3.2 to 3.5, and the mean concentration of H_3O^+ for the five measurement dates was 0.49 mmol L^{-1} (SD = 0.1 mmol L^{-1}). In 2014 the pH values measured in the filter tubes ranged from 3.54 to 3.68, which corresponds to a mean H_3O^+ concentration of 0.25 mmol L^{-1} (SD = 0.03 mmol L^{-1}); the pH in *Sphagnum cuspidatum* hollows ranged from 3.37 to 3.51 (mean H_3O^+ concentration 0.36 mmol L^{-1}, SD = 0.04 mmol L^{-1}); the soil solution in the freshly drilled holes in Plot E1 had pH between 3.28 and 3.32 (mean H_3O^+ concentration 0.50 mmol L^{-1}, SD = 0.02 mmol L^{-1}); and pH in the mud-bottom hollow in the lagg was 4.05. The values of EC measured in the filter tubes ranged from 50 to 67 µS (mean 61.3 µS, SD = 5.7 µS); in the *Sphagnum cuspidatum* hollows the range was 70 to 79 µS (mean 75 µS, SD = 3.2 µS); the EC of soil solution in the freshly drilled holes in Plot E1 was between 75 and 86 µS (mean 81.3 µS, SD = 4.2 µS); and in pulpy peat in the lagg it was 142 µS (although this measurement was unreliable).

Landscape topography and flow lines
Because the bog was clearly ombrotrophic, Dierssen & Dierssen (1984) assumed that it was domed. There are still no plants in the centre of the bog that indicate the influence of mineral soil water. On the other hand it is clear from the surface map (Figure 8) that, in the zone from the watershed to about 150 m north of this line, the bog is not domed above the eastern lagg. The central part of the bog surface lies at the same altitude as the lagg to the east, or even below it. Therefore, we can infer that interflow from the adjacent slope may have been able to infiltrate the peat and reach the centre of the bog before the road was constructed.

During construction of the road in 1983, it was decided to incorporate a seal made from plastic sheeting into the eastern (upslope) embankment (Figure 9) to prevent interflow water from seeping into the lagg after possible contamination by road salt. Lateral flow arriving from the slope is now intercepted by an open channel, from which several sumps connect to an underground plastic drain pipe running parallel to the road (Figure 9, bottom right).

Table 4. Summary statistics of water table level data collected (left side) at the Ennersbacher Moor during the growing seasons of 1998–2000 (manual readings at intervals of two weeks) and 2012–2014 (hourly piezometer readings); and (right side) at the Ennersbach, Wildsee and Hohloh mires during the period 01 July 2012 to 01 July 2014 (hourly piezometer readings). Units: mm; datum level: ground surface; SD: standard deviation.

Statistic	Ennersbacher Moor: growing season (May–October)						July 2012–July 2014		
	1998	1999	2000	2012	2013	2014	Ennersbach	Wildsee	Hohloh
Maximum	-89	-72	-64	-39	-18	-33	20	64	48
Third quartile	-150	-90	-103	-99	-72	-84	-66	6	-40
Median	-198	-119	-126	-112	-97	-106	-85	-12	-67
Mean	-198	-136	-127	-144	-141	-134	-110	-20	-75
SD	77	59	43	55	98	79	77	41	48
First quartile	-237	-162	-142	-141	-193	-155	-120	-33	-90
Minimum	-350	-272	-213	-348	-420	-418	-420	-189	-245
Total range	261	201	149	309	402	385	440	253	293
No. readings	11	14	15	4384	4384	4384	17520	17520	17520
Skewness	0.262	1.073	0.768	1.691	1.201	1.923	2	1.45	0.95

The water is thus conducted away to the north or the south, depending on position relative to the watershed. The effect on the water supply to the bog can be demonstrated by superposing the upslope catchment and flow lines on the surface map in Figure 8. This shows that the road reduces the catchment upslope of the centre of the bog by 4.85 ha, and shortens the flow lines from 165–275 m to 100–165 m.
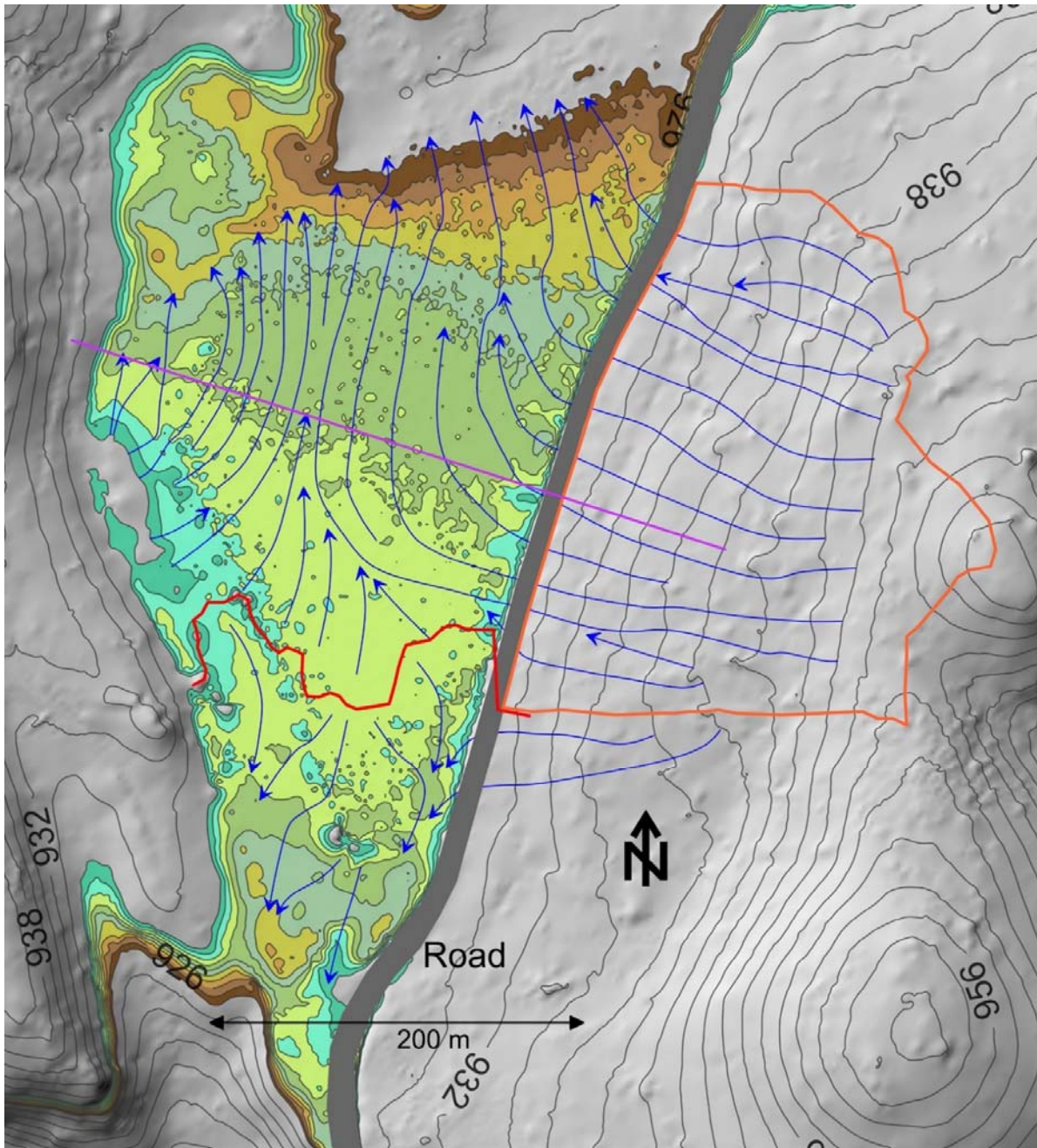
DISCUSSION

Vegetation dynamics
Plot E1 at the Ennersbacher Moor yielded the lowest growth integral of 38 mire sites that were investigated in 2002. The value (1.57 m^2) derived in 2013 no longer qualifies it for this 'reference' position within the range of integrals (1.1–3.8 m^2) derived for raised bogs in the Black Forest as a whole. According to the results of von Sengbusch (2006) the recent distribution of vertical and diameter growth is typical for the transition from natural open bog to 'stagnating bog', which is rich in *Calluna vulgaris* or *Vaccinium uliginosum* and lacks wet hollows. On the basis of water table data for the year 2003 (unpublished data of Sebastian Frenzel, diploma thesis, University of Freiburg), the observed change in value of the growth integral at Ennersbach corresponds to lowering of the mean growing-season water table by about 50 mm.

In addition to the increase of *Vaccinium uliginosum* noted in Table 2, changes in surface microtopography that are consistent with this scenario have been observed in the central parts of the bog, where the hummock-hollow pattern has weakened since 1998. All of the small former pools in the hollows are now covered by dense lawns of *Sphagnum cuspidatum* and, apart from some isolated shoots of *Sphagnum balticum* in three or four terrestrialised hollows, no other typical hollow species (e.g. *Carex limosa, Rhynchospora alba, Scheuchzeria palustris*) are present.

The decline of *Sphagnum magellanicum* in favour of *Sphagnum capillifolium* ssp. *rubellum* and *Sphagnum angustifolium* cannot automatically be attributed to a change in site conditions because

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Figure 8. Digital surface map of the Ennersbacher Moor, showing surface contours of the landscape (grey) with 2 m vertical intervals and those of the bog (coloured) with 30cm vertical intervals over the range 925.4 to 928.1 m a.s.l.; the bog's watershed (red line); the boundary of the upslope catchment on its northern side that no longer supplies water to the bog (orange); flow lines (blue arrows); and the line of the surface profile presented in Figure 9 (pink line). The last open clearings are situated to the north of the pink line. Altitudes in m a.s.l.; datum Germany DHDN Gauss zone 3 (conversion method: Bursa-Wolf; conversion target: WGS84; ellipsoid: Bessel).
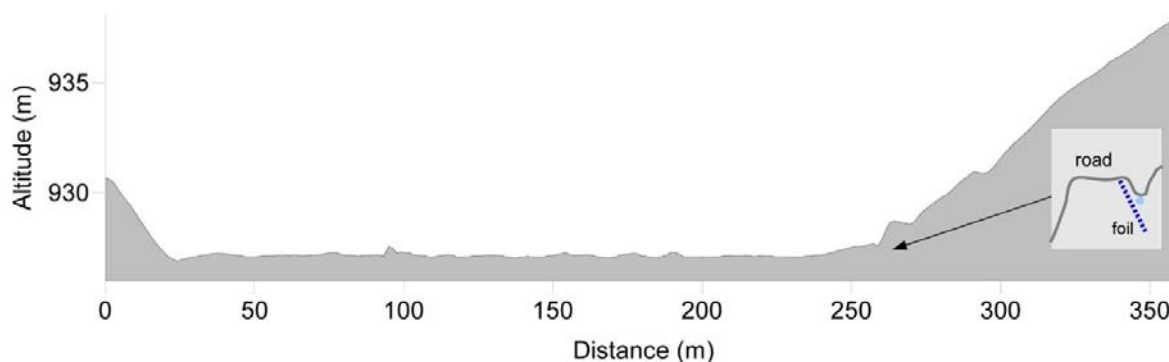
Figure 9. Above: surface profile for the pink transect line in Figure 8 (the western end of transect is at the left-hand side of this diagram). The road (more detailed cross-section inset) is at 260 m on the distance scale. In the inset sketch, the blue dotted line represents the plastic sheeting ('foil') and the paler blue dot the plastic water pipe that was laid beneath the roadside ditch. Below: northward view along the road from the top of the embankment leading down to the Ennersbacher Moor (left-hand photograph); and the interior of one of the sumps connecting the surface channel on the upslope side of the road (top left of frame) to the underground plastic drain pipe at centre frame (right-hand photograph).

small-scale cycles of *S. rubellum*, *S. recurvum* and *S. magellanicum* have been reported from several bogs in the Black Forest (Hölzer & Hölzer 1988a, 1988b, 1995, 2002; Dietz 2001, Rohrer 2006). These cycles reflect a gradual decrease in wetness and are often but not always triggered by burning of the mire surface, which creates a layer of charcoal or ash in the peat. However, there is no stratigraphical evidence of burning at the Ennersbacher Moor. In this case that the replacement of *S. magellanicum* by *S. capillifolium* ssp. *rubellum* may be due to other factors like trampling by deer, increased mineralisation, or micro-site features such as shading by dwarf shrubs and pine.

S. angustifolium has a broad ecological amplitude in the Black Forest and occurs in raised bogs as well as in poor fens. According to the relevés of Dierssen & Dierssen (1984) it has high consistency amongst the five sub-associations of the *Sphagnetum magellanici* (560 relevés) and occurs most frequently in the *Sphagnetum magellanici typicum*. Therefore, *S. angustifolium* can be regarded as a typical attendant of *S. magellanicum* in a raised bog. On the other hand, *S. angustifolium* can grow in the *Caricetum nigrae* (Dierssen & Dierssen 1984; 8 relevés), the *Caricetum rostratae* (Dierssen & Dierssen 1984; 5 relevés) and even in mud-bottom communities like the *Caricetum limosae* (Dierssen & Dierssen 1984; 6 relevés).

As the bog surface was sparsely forested in the 1980s, one would expect to find only slightly humified *Sphagnum* peat in the acrotelm. The rather high levels of decomposition actually observed were unexpected, especially in view of the fact that the root

collars of newly recruited pine have already been overgrown by *Sphagnum* mosses, indicating that there is still a net growth of peat in the bog. It is possible that roe deer using the bog as a retreat help to inhibit the growth of pine and *Sphagnum* at sites like Plot E1 where the tree canopy is still open. Red deer were observed to be affecting the bogs of the Kaltenbronn (northern Black Forest) in this way during research carried out in 2013 (unpublished data from Ministry of Agriculture Project No. 63-8831.21546-91-1207GL "Ecosystem functions of mires on the Kaltenbronn").

The remnants of *Sphagnum* in the peat indicate a shift from the formation of *Cymbifolia* to *Acutifolia* peat at a depth of about -350 mm. Hölzer & Hölzer (1988a, 1988b, 1994, 1995, 2002) and Dietz (2001) have reported evidence for cycles of succession among *Sphagnum* species from several bogs in the Black Forest (and in the Lautermoor in the upper Rhine Valley). These cycles were often induced by burning of the mire surface, the post-fire succession beginning with the establishment of *Sphagna* belonging to the *recurvum* group and proceeding through a *Sphagnum rubellum* stage to the establishment of *S. magellanicum*. *S. angustifolium* was never distinguished in the *S. recurvum* remains, but *S. fallax* was. It is possible that *S. angustifolium* has been present in the centre of the Ennersbacher Moor for some time but has not been preserved in the peat because its leaves (especially the stem leaves) have soft cell walls. Hajek & Beckett (2008) and Hajek (2009) reported that there are substantial differences in litter quality (the construction of cell walls) and decomposition rates between hummock and hollow species of *Sphagnum*.

It could not be shown from the three peat cores collected for this work that the vertical distribution of fine bog pine roots now differs from that reported by Kuss (2003). However, a shallow (100 mm) layer of aerated peat is sufficient to enable bog pine to maintain an almost closed canopy in the northern Black Forest (von Sengbusch 2011). Perhaps we face a self-enhancing process, namely that when the altered water regime no longer allows the water table to rise above the mire surface (which probably periodically kills some of the fine roots under natural conditions), the recruitment rate of bog pine increases. As the root collars of most pine shrubs are overgrown by *Sphagnum* mosses, they stimulate the growth of hummocks and, thereby, enlargement of the aerated rhizosphere. Further research is needed on the growth requirements of bog pine.

Changes in water quality and hydrology
The pH values measured near the centre of the bog in 2014 are higher than those measured by the author in 2000 and the values (3.20–3.26) reported by Kuss (2003). However, the difference in readings may arise because, in 2000 and 2003, pH was measured in unsaturated peat rather than in soil water. The values of EC (50–86 µS) are typical for raised bogs in the Black Forest. EC values of 45–75 µS have been measured in two ongoing projects at Harzmoos and the Hinterzartener Moor (southern Black Forest), whilst Dierssen & Dierssen (1984) report EC values of 30–100 µS from the Hinterzartener Moor as well as for another site (Hirschbädermoor). The higher pH and EC values in the lagg of the Ennersbacher Moor may reflect the influence of the road, and especially the presence of salt which is pushed off the road by snow-clearers, but more reliable measurements will be needed to confirm this. The seepage of salt-enriched soil solution from the lagg towards the centre of the bog might also be considered as a possible explanation for any confirmed changes in both pH and EC at Plot E1, which is 83 m from the road. However, the data collected so far provide little evidence that changes in water quality could be a significant driver of the observed vegetation changes.

In the KLIWA (2011) project (an assessment of climate data for Baaden-Württemberg and Bavaria) it was shown that there has been a gradual shift of precipitation from summer to winter since 1960, which promotes the occurrence of dry periods during the summer season as illustrated by the data from Wolpadingen presented in Table 3. Effects on bog hydrology were confirmed by research carried out on mires in the northern Black Forest during 2009, which showed that the peat severely dried out and *Sphagnum* photosynthesis ceased during the summer of that year (von Sengbusch 2011). In addition to the occurrence of dry periods, the gradual rise in air temperature in the southern Black Forest illustrated by Figure 5 is also likely to affect water availability, by gradually promoting evaporation as the availability of energy increases with each passing decade.

The mean water table of -110 mm (July 2012–July 2014) at Plot E1 on the Ennersbacher Moor is close to the surface and apparently favourable for peat growth. On the other hand Figure 6 shows a clear difference between the ranges of water table fluctuations recorded in the years 2000 and 2012, which had identical precipitation sums for the growing season (Table 3). Thus, it appears that water table drawdown occurs under wetter conditions now than in 1998–2001.

Natural (growing) bogs reflect a compromise between high water storage capacity and low hydraulic conductivity (Joosten 1993). They possess a variable mechanism to regulate lateral fluxes of water and avoid high discharge during periods of low

precipitation that operates through the transmissivity profile (Ingram & Bragg 1984, van der Schaaf 2002). Low phreatic levels correspond to low acrotelm transmissivity and, thus, low flux. Van der Schaaf (2002) suggests that the feedback loop of phreatic level, transmissivity and flux explains the peculiar nature of peat growth. If peat quality is altered towards higher humification, the porosity and hydraulic conductivity will decrease. According to Edom (2001) and van der Schaaf (2012), doubling the volume fraction of organic matter can reduce the hydraulic conductivity by a factor of 10–100. A higher volume fraction of organic matter and a lower porosity enhance the amplitude of water table oscillations (Edom 2001). This could help to explain the high rates of water table decline on warm summer days in 2012–2014.

Thus, the comparison of water table records from Plot E1 of the Ennersbacher Moor might be interpreted to indicate that the self-adjusting ability of the bog has been impaired, as even short dry periods cannot be buffered as effectively as they were 12 years ago. On this basis, it seems possible that the water table could descend to -0.5 or -0.6 m during drought periods such as those that occurred in 2003 and 2009 (Table 3).

However, at least some of the observed change in amplitude of the water table fluctuations may be an artefact of the observation methods themselves. Specifically, the time interval between the (hourly) piezometer records of 2012–2014 was much shorter than that between the manual observations (every second week) of 1998–2001, and this would increase the probability of recording the extremes of oscillation. Bragg *et al*. (1994) report that 80–85 % of the full range of water level fluctuations in maximum-minimum recording dipwells (WaLRaGs, diameter 102 mm) was captured by manual reading at intervals of approximately two weeks over a period of 15 months, and only 42–45 % by ten manual readings at irregular intervals over a period of 28 months. On the other hand, the recent simultaneous observations using piezometers at different mires in the Black Forest also indicate an enhanced drawdown of the water table at Ennersbach during dry weather (Table 4), and this adds further evidence to support the hypothesis that the water table regime here has been modified by the presence of the road. Obviously, hourly monitoring of the water table fluctuations at Plot E1 should continue in order to gain further insights into whether or not the site's hydrological regime is undergoing real changes.

Catchment-level changes
Analysis of the topographical map (Figures 9, 10) confirmed the hypothesis that the centre of the

Ennersbacher Moor is not domed above the eastern lagg at the present time. Therefore, if it can be assumed that the bog's mesotopography has not changed since the 1980s, it would have been fed by surface runoff and interflow from the hillside to the east before a substantial fraction (4.85 ha) of its catchment was cut off by the road. The resulting shortening of flow lines to about half of their original length is likely to have reduced the potential for natural bog growth (van der Schaaf 2012).

It is also possible that the bog was domed before road construction, as suggested by Dierssen & Dierssen (1984), and then lost its dome by subsidence or peat decomposition due to the reduction in water supply. Subsidence is a common phenomenon in the Black Forest, but is usually observed only adjacent to drainage ditches in mire sites without peat growth and with highly decomposed peat below the surface. The eastern lagg of the Ennersbacher Moor has subsided due to the direct hydrological impact of the road. Here, the root collars of most spruce trees are above the surface, and hollows and sub-surface soil pipes can be found. In Plot E1 at the centre of the site the peat at 70–300 mm depth is more humified (H5–H8) than one would expect in a growing bog, but the overgrowth of the root collars of young pines by *Sphagnum* and peat suggests that the bog may still be actively growing. On the other hand, Ise *et al*. (2008) report that the feedback loop between water table and peat depth increases the sensitivity of peat decomposition to temperature, and stress the lability of the carbon sequestrated by peat growth. In view of the rather high decomposition of the acrotelm peat in the Ennersbacher Moor, some loss of peat since 1983 thus seems likely. Overall, the evidence for loss of a former dome is equivocal and now impossible to test.

Whether or not a dome was present in the 1980s would, in any case, make little difference to the conclusion that impairment of the hydrological equilibrium of the peatland system by construction of the road remains the only candidate cause for the change in bog pine growth at the Ennersbacher Moor. If the bog centre was previously domed, the lagg might both define a hydrological boundary for the dome during times of water surplus and directly buffer the water table within the bog if it were drawn down sufficiently to create an appropriate hydraulic gradient under drought conditions. Its effectiveness in performing both of these functions would depend directly on maintenance of the water supply from the upslope catchment. It is clear that this supply is now curtailed by the presence of the Dachsberg road, which must be regarded as a source of human disturbance to this mountain bog even though the road does not physically encroach on the peatland itself.

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