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Satellite-based estimations of coniferous forest cover changes

Krusne Hory, Czech Republic 1972-1989

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Satellite-based Estimations of Coniferous Forest Cover Changes: Krušné Hory, Czech Republic 1972–1989

The extent and rate of deforestation from 1972 to 1989, including some spatial properties in the heavily polluted mountains of Krušné Hory, on the border between the Czech Republic and Germany were studied. Deforestation was assessed using satellite remote sensing integrated with digital elevation data. The results show that over 50% of the coniferous forest disappeared during this period. Especially affected areas were between 600 and 1000 m a. s. l. and slopes facing south and southeast. The sector downwind of a large point source of SO₂ and NO_x was strongly deforested. The relation between deforestation and distance to the point source is unclear. A satellite estimation of forest damage in 1989, based on needle loss, resulted in 79%, 17% and 4% of the remaining 308 km² conifers being classified as lightly, moderately and heavily damaged forest, respectively.

INTRODUCTION

Background

Increasing areas of the coniferous and deciduous forest in Europe and in northeastern America are affected by air pollution, causing deterioration of areas of large economic value. Extensive areas are at risk of damage (1–3) and are receiving acidic deposition in excess of critical loads (4). Air pollution has changed ecosystems in Europe and North America (5) and has resulted in soil acidification, loss of base cations, changes in plant community composition (6–8) and forest damage (2, 5, 9, 10). In Europe, forest damage and deforestation negatively influence forestry, forest industry (11), availability and quality of water (12), and soil erosion. In addition, these effects lead to negative social consequences (13).

Despite prodigious amounts of research, questions are still raised about the widespread forest decline in temperate regions. Kandler (14) concluded that “a decade of research on novel forest damage in western Germany has shown that: no spatial and tem-

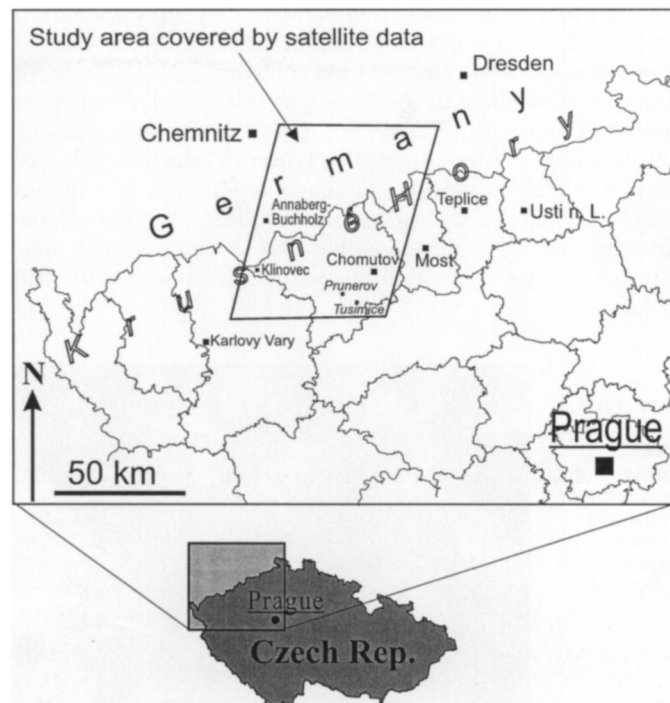


Figure 1. Overview of North Bohemia and the study area covered by satellite data.

poral correlation between novel forest damage and air pollution could be shown” and “that similar levels of crown transparency were found in Norway spruce at the beginning of this century”.

By investigating the spatial and temporal distribution of deforestation and forest decline in relation to abiotic factors such as air pollutants, climate, topography, critical loads (15) and critical levels we may obtain indications about the causes of forest decline. Satellite data could provide a means of assessing and mapping forest damage on a regional scale (16–18) and, thus,

Table 1. Air pollution characteristics in the Krušné Hory area, Czech Republic.

Type of measurement, period, (unit)	S	SO ₂	N	NO ₂	NO _x	Ref.
Emission in N. Bohemia 1988, (t yr ⁻¹)		964 000			330 000	[21]
Emission by Prunéřov I & II and Tusiřice I & II 1988, (t yr ⁻¹)		469 800			98 916	[21]
Deposition 1880–1991, (kg ha ⁻¹)	6000					[25]
Deposition 1988–1989, (kg ha ⁻¹ yr ⁻¹)	150		46			[51]
Ann. air conc., 1978–1990, (µg m ⁻³ yr ⁻¹)		78				[51]
Ann. air conc., 1981–1987, (µg m ⁻³ yr ⁻¹)		82				(Lesprojekt, unpublished)
Ann. air conc., 3 year mean value, (µg m ⁻³ yr ⁻¹)		112			33	[30]
Ann. air conc., 1993, (µg m ⁻³ yr ⁻¹) one station		117			64	[40]
Peak conc. 1993, (µg m ⁻³ day ⁻¹) one station		1276			504	[40]
Peak conc. 1993, (µg m ⁻³ day ⁻¹) one station		2400				(Lesprojekt, unpublished)
Critical level, (µg m ⁻³ yr ⁻¹)		20		30		[5]
Critical level, (µg m ⁻³ yr ⁻¹)		10–15		30		[36]
Critical level, (µg m ⁻³ day ⁻¹)		70				[5]
Critical level, (µg m ⁻³ 4h ⁻¹)				95		[5]

Ann. air conc. = annual air concentration

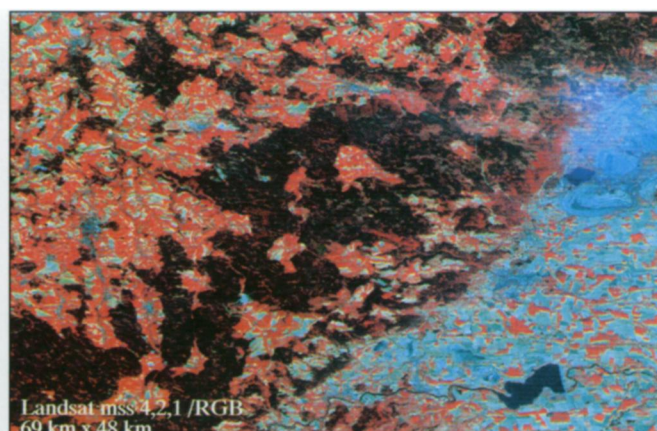
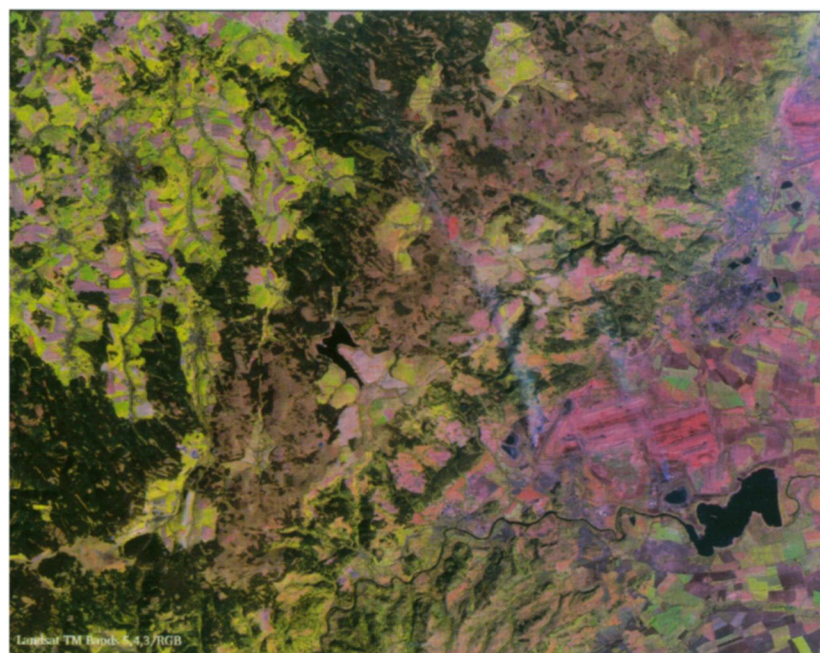


Figure 2a. Landsat Thematic Mapper data from 30 September 1985, covering the study area. False color composite (RGB) of band 5 (mid-infrared), 4 (near infrared), and 3 (red). Dark areas extending from the lower left to the upper right corner are coniferous forest of the Krušné Hory, black represents water, deciduous forests are green, and large clearcuts, now covered by grass appear red. Agricultural areas are characterized by the field patterns. In the lower right part are the power plants Tusimice and Prunerov visible and the neighboring large open-cast coal mine. 2b Landsat Multispectral Scanner data from 13 August 1972, covering the same areas as Figure 2a. False color composite (RGB) of band 4 (near infrared), 2 (red) and 1 (blue).

complement ground-based assessments (2), pollution impact models (5), and damage assessment by aerial photography (19).

The Krušné Hory (Ore mountains) mountains in northern Bohemia (Fig. 1) are the most heavily polluted area in the Czech Republic (20, 21). This area stretches 130 km from SW to NE along the German border. The forests of the Krušné Hory have been heavily impacted by local air pollutants (mainly SO_2 , NO_x) since the 1960s, with the first major damage occurring in 1947 (12). Extensive clearcutting of damaged and dead areas resulted in a sharp decrease of the forested area. A severe decline in the health status of the forests has also occurred over the past three decades (8, 12, 22). All of the forests in northern Bohemia (approx. 250 000 ha) are now classified as damaged (8, 23). Kubelka et al. (22) report that 56% of the spruce stands in the Krušné Hory mountains were cut between 1970 and 1990 and that the rest were damaged.

Local Air Pollution

North Bohemia, especially the basin on the southeastern edge of the Krušné Hory fault (Fig. 2) is an important area for energy production and chemical industry (24). Over 75% of the former Czechoslovakia's brown coal was mined here and > 50% was burned locally (20). In 1988, 48% of the SO_2 and 30% of the NO_x emissions in northern Bohemia were emitted by four power plants, all located in the study area (Figs 1 and 2; Table 1). Burning of brown coal with high sulfur content in these plants started in the mid-1960s, with maximum activity around 1979. SO_2 emissions strongly increased from 1963 to 1977, decreased after 1984, and in 1991 were reduced to 715 Kton year⁻¹ (Fig. 3b) (22).

The annual deposition of total S and NO_x rapidly increased from 1960 to 1974 with smaller variations after 1974 (Fig. 3a). The 5th percentile critical load was exceeded more than 100 years ago, with the area receiving > 600 g S m⁻² since 1880 (25). The area is characterized by high depositions of sulfur and nitrogen, and concentrations of SO_2 and NO_x in the air exceed critical levels (5) (Table 1).

Forest Impact

Due to their high filtering effect, spruce stands can capture almost twice the concentrations of sulfates as do deciduous stands

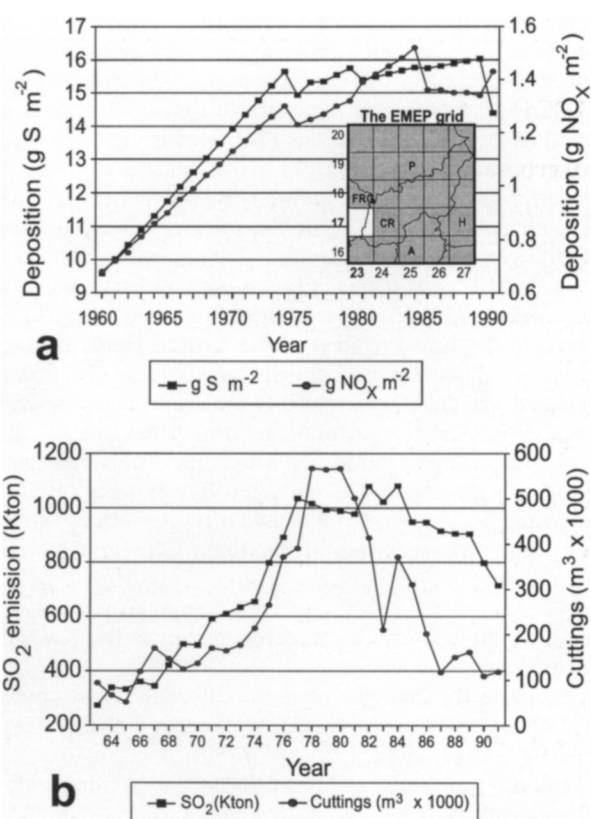


Figure 3. (a) Total S and total N annual deposition for EMEP (55) grid no 23, 17, (covering the study area) from 1960–1990 according to the Regional Acidification Information and Simulation model (RAINS) (56). (b) Annual emissions of SO_2 and cuttings in the NE Krušné Hory Mountains from 1963 to 1991 (22).

(26), significantly increasing the amount of sulfur received by spruce stands (22). Harmful effects of air pollutants on trees and forest ecosystems include direct effects on leaves and indirect effects via soil. Soil acidification causes depletion of cations, decreases base saturation and increases the molar ratio of aluminum to base cations (10), which has been related to forest damage (27). In addition to soil acidification, nitrogen deposition disturbs the nutrient balance causing reduced winter hardiness (28) and reduced occurrence of mycorrhizae (29). Droughts, insects and damage caused by heavy metals, which often become more soluble at lower pH, are other mechanisms believed to play a role in forest damage and decline.

In Czech Norway spruce (*Picea abies*) forests, increased air concentrations of SO₂ have been associated with increases in the extent of forest damage (12, 30), decreased life expectancy (31), reductions in increment growth (32) and stand density (31). In Sweden, reduced forest growth has been found close to point sources of sulfur (33). Söderberg (unpubl. data) found decreasing annual increment with increased defoliation. In 1972, growth reductions were already suspected to be caused by acidification in sensitive regions (34). Björkdahl and Eriksson (35) reported increment losses ranging from 0% to 36% for Norway spruce stands with a defoliation of 31–60%.

Climate, soil conditions, exposure to local air movement and elevation are important factors modifying the forests reaction to SO₂ concentration in air (23, 36). Forests at high elevations are more sensitive to SO₂ than low elevation forests due to harsher climate conditions and shorter vegetation periods (37). This has resulted in an increased sensitivity of Norway spruce to insect damage, especially from the bark beetle (*Ips typographus*) and to pathogens. Long-term exposure to SO₂ is of greater importance than peak concentrations (36). However, there is no correlation between SO₂ and injury to the forest if a broader region with different ecological conditions is considered (14, 36).

The air pollution load in the Krušné Hory area has exceeded, and still exceeds, levels at which damage to vegetation occurs (Table 1) (5, 22, 38). This is true for instantaneous rates and long time averages (39, 40). The factors mentioned above have contributed to the forest decline in the Krušné Hory, although the physiological decline mechanisms are not clear (14, 36). Figure 3b presents the development of SO₂ emissions and forest removal in the NE Krušné Hory Mountains from 1963 to 1991 illustrating the rapid forest removal, which has been dominated by “emergency cuttings”. The damaged forests were often cut before dying (8, 23), to avoid reduced timber prices due to low quality and, thus, securing the maximum economic benefit.

Aim

This descriptive study of the deforestation in the Krušné Hory area aims to:

- (i) estimate the changes of the coniferous forest cover from 1972 to 1989 using satellite data from five different years (1972, 1979, 1982, 1985 and 1989);
- (ii) examine the relationship of deforestation versus elevation and aspect;
- (iii) examine the relationship of deforestation versus the distance and direction of forest areas to a point pollution source; and
- (iv) perform a satellite-based estimate of needle loss of the conifers in the area in 1989.

MATERIAL AND METHODS

Study Area

Approximately 2600 km² of the Krušné Hory were studied (Figs 1 and 2). In addition to the forested mountain areas, the lowlands and the coal basins near Prunerov, Chomutov and Most

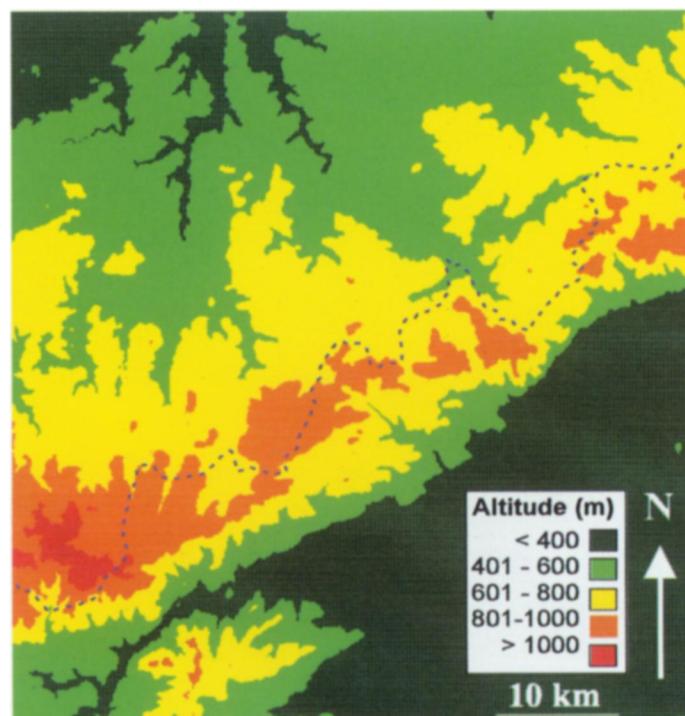


Figure 4. Elevation of the study area, Krušné Hory, Czech Republic. The blue line is the Czech/German border.

are included, as are parts of the agricultural areas on the German side. The Krušné Hory mountains are formed by a plateau, gradually sloping towards the German side with steeper slopes towards the north Bohemian basin on the Czech side. The elevation difference between foot and summit ranges from 500–700 m (41) with the highest peak in the western part (Klinovec, 1244 m) (Fig. 4). The area is primarily comprised of schists and granitoids which are mostly covered by mineral soils of local origin (41). Peat bogs and peat soils, of importance for local water management, are also present (22). The surface horizons of the mineral soil are strongly to extremely acid and very poor in Mg, Ca, K (42). In general, soil pH in the area is lower than 3.5–4.0 with extremes reaching 2.2 (8). Enrichment of heavy metals in the soil occurs as a result of fallout from solid particles of local origin (22).

Average annual rainfall in the area is 840 mm, higher elevations receiving up to 1100 mm (22, 43). Prevailing winds blow from west or southwest (20, 24). Average annual temperature is 5.4°C, higher elevations have lower temperatures and shorter growing periods. Inversions preventing air pollution dispersal often occur during the winter, causing accumulations and high concentrations of air pollutants (20).

According to Kubelka (23), the most serious emission-induced damage to forests occurs at 600–800 m elevation where a zone of fog significantly enriched with pollutants forms. The fog forms due to the merging of warmer, pollution-rich air masses from the south and southwest with cooler air from the northwest. This formation is facilitated by abundant condensation nuclei in the air, probably originating from local power plants.

The dominating forest type is even-aged monocultures of Norway spruce, but a significant transition to other conifers such as the Colorado blue spruce, (*Picea pungens*), European larch (*Larix decidua*) and broadleaf species such as birch (*Betula sp.*) and mountain ash (*Sorbus acuparia*) has occurred over the last 35 years due to changed reforestation practices (22). Beech (*Fagus sylvatica*) and oak (*Quercus sp.*) are present at lower elevations. Figure 5 summarizes the forest types in the area.

In addition to air pollution related damage, the reed grass (*Calamagrostis villosa*) strongly increases in cover and biomass

in areas of spruce decline (6–8) preventing establishment of young spruce seedlings. Heather (*Calluna vulgaris*) and blueberries (*Vaccinium myrtillus*) have declined in spruce forests (8). A more detailed description of the environment and the forestry of the Krušné Hory can be found in Kubelka et al. (22).

Field Data and Forest Statistics

Digitized forest maps (scale 1:10 000), were used for calibration and evaluation of the remotely sensed estimates of deforestation and forest damage. These maps delineate homogenous forest stands, describing the species composition, age and forest damage of each stand. The degree of forest damage, defined as percent needle loss using six damage classes, was assessed by subjective visual methods in 1988/1989 (44). The assessment error connected with the method used is $\pm 6\%$.

As an independent estimate of the forest health status in the area, forest damage statistics are provided. All field data and statistics used originate from fieldwork performed in two forest enterprises within the study area. In 1988/1989, these two enterprises consisted of > 40 000 ha of forest land with 22 400 ha conifers (Fig. 5).

Satellite Data

Landsat satellite data from the Multispectral Scanner (MSS) in 1972 (August 13), 1979 (October 24) and 1982 (September 14) and from the Thematic Mapper (TM) in 1985 (September 30) and 1989 (July 7) were used. All satellite data were geometrically corrected to 25 m pixel size and identical geometric projection properties, the aim being to make them comparable to each other and to the digital forest maps.

Satellite-based Estimates of Coniferous Forest

A supervised maximum likelihood classification (45), based on the spectral differences between coniferous vegetation and nonconiferous areas, was used to classify the amount of coniferous forest cover for each date. Only areas classified as coniferous forest in 1972 were used for classification of conifers and deforested areas in the later data sets.

Evaluation of Satellite-based Estimations

The classification results were evaluated using the digitized forest polygons with known location, stand age and forest composition, i.e. a coniferous area or a nonconiferous area (including clearcuts, open areas, deciduous forest and other land-cover classes). Evaluation areas used were independent of the areas used for supervision of the classification. The overall classification accuracy (%) for each date (Table 2) was calculated as the ratio of all correctly classified polygons to all polygons (46).

Satellite-based Estimates of Forest Damage

Logit regressions, using satellite recorded spectral reflectance data from 1989 to predict each pixel's probability of belonging to one of three forest damage categories—light, moderate and heavy damage—were performed for all coniferous forests. The categories used result from a merging of the original six damage classes (44). The methodology is supervised, based on the spectral differences among spruce stands with different degree of needle loss and described in Lambert et al. 1995 (18).

Digital Elevation Data

Digital elevation data were resampled to give identical geometric properties as the satellite data. The information content of the original data are equivalent to a 1:250 000 scale resolution. The horizontal error is ± 130 m and the vertical ± 30 m (90%

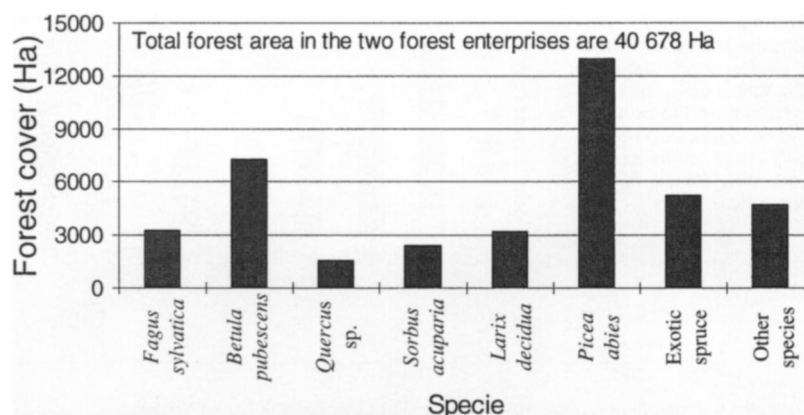


Figure 5. Dominating tree species in two forest enterprises (Janov and Klasterec) in the Krušné Hory 1988/1989. Exotic spruce includes blue spruce, (*Picea pungens*), white spruce (*Picea glauca*) and black spruce (*Picea mariana*).

confidence interval). The aspect of each pixel was calculated. The elevation data were stratified into five strata and the aspect data were stratified into nine strata, eight of them 45° wide plus one stratum for horizontal areas. The forest cover for each date and each stratum was then calculated in order to compare changes in forest cover over time among the strata. The χ^2 test was used to test for differences among strata.

Deforestation Rate

Conifer forest cover was calculated by summing all the areas classified as forest for each date. Annual deforestation was calculated as:

$$\% \Delta_{\text{annual}} = \frac{\% \Delta_{t_1, t_2}}{t_2 - t_1} \quad \text{and} \quad \% \Delta_{t_1, t_2} = \frac{fc_{t_1} - fc_{t_2}}{fc_{t_1}}$$

Where

t_x = time (years)

fc_{tx} = conifer forest cover (ha)

$\% \Delta_{t_1, t_2}$ = Deforestation from time₁ to time₂

$\% \Delta_{\text{annual}}$ = Annual deforestation ($\% \text{ yr}^{-1}$)

Forest Cover in Relation to Distance and Direction to Point Sources

To investigate the spatial relation between vegetation changes and major pollution sources in the area (Table 1), deforestation was compared to the distance and the direction to two large air pollution point sources in the area. These sources are located approximately six km apart, but treated as one point, located in between the two sources. In what follows these two point sources are referred to as the pollution source. Distance in km and direction in degrees of all locations, relative to the pollution source, were calculated.

RESULTS

Coniferous Forest Cover

The coniferous forest cover in the area decreases with 52% or 337 km² from 1972 to 1989 (Fig. 6; Table 2). The annual deforestation rate was high from 1972 to 1985, with a peak during 1979–1982 and a decrease after 1985 (Fig. 6; Table 2). A normal annual cutting rate in managed forest areas is approximately 1%, assuming a rotation period of 100 years (47).

Elevation

The majority of the forests are between 400–1000 m elevation. Below 1000 m, > 25% of the forest cover was lost from 1972

Figure 6. Satellite-based estimates of coniferous forest cover (the forest cover in 1972 is considered to be 100%) and deforestation rate 1972–1989, in the Krušné Hory area, Czech Republic.

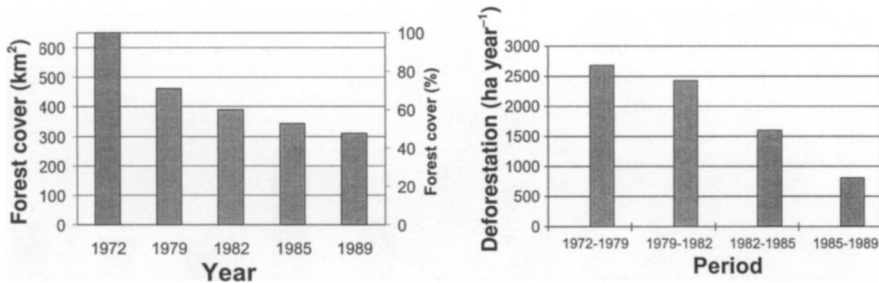


Table 2. Classification results and accuracy of the satellite based estimates of coniferous forests in the Krušné Hory area 1972–1989.

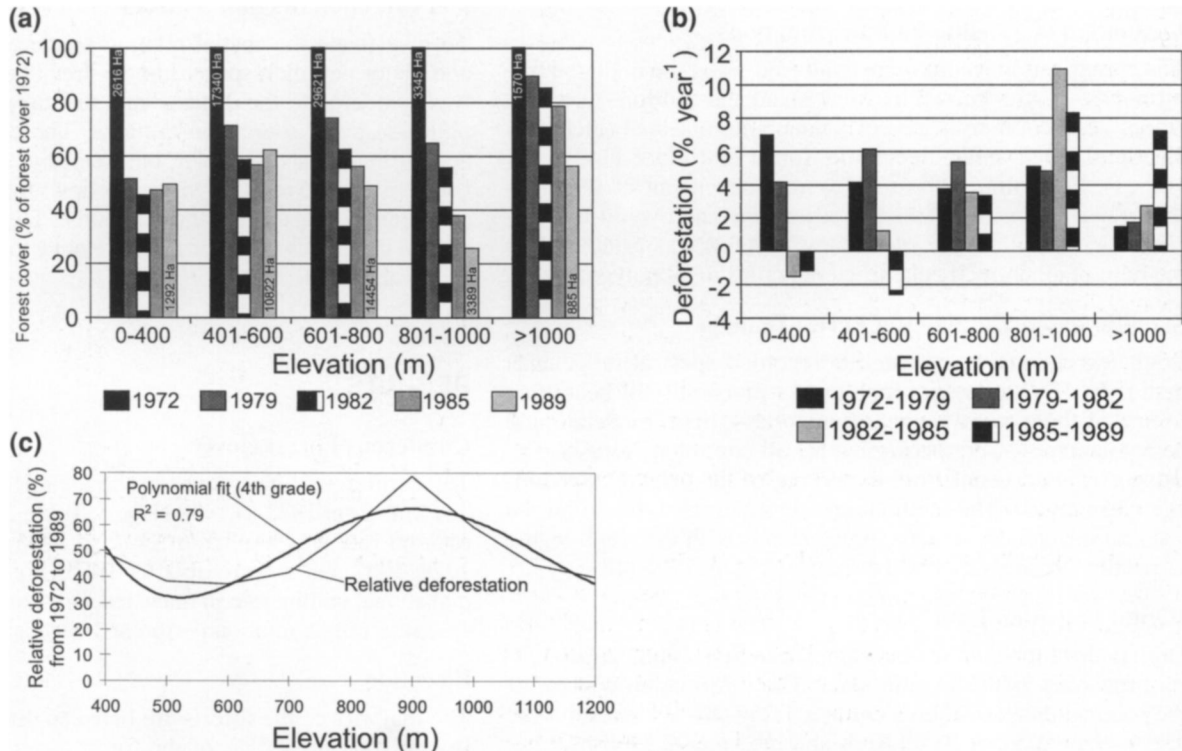
Year	Forest area		Deforestation rate		n polygons for evaluation	Forest accuracy	Nonforest accuracy	Overall accuracy
	(km²)	(%)	(km² yr ⁻¹)	(% yr ⁻¹)				
1972	645	100			233	92	82	89
1979	459	71	26.7 ¹	4.1 ¹	258	96	94	95
1982	387	60	24.1 ²	5.2 ²	300	91	90	91
1985	340	53	15.8 ³	4.1 ³	377	98	88	92
1989	308	48	7.8 ⁴	2.3 ⁴	411	83	100	90

¹1972–1979, ²1979–1982, ³1982–1985, ⁴1985–1989

Table 3. Satellite based estimates of forest cover at different elevations in the Krušné Hory area, Czech Republic, 1972–1989. The forest cover in 1972 is considered to be 100% for each stratum.

Elevation (m)	Forest cover (km² and %) at different elevations									
	0–400		401–600		601–800		801–1000		> 1000	
	(km²)	(%)	(km²)	(%)	(ha)	(%)	(km²)	(%)	(km²)	(%)
1972	26.17	100	173.40	100	296.22	100	134.45	100	15.70	100
1979	13.49	51.5	124.10	71.6	220.22	74.3	87.30	64.9	14.19	90
1982	11.84	45.2	101.60	58.6	185.31	62.5	74.91	55.7	13.48	85.6
1985	12.35	47.2	98.19	56.6	166.17	56.1	50.52	37.6	12.42	78.8
1989	12.92	49.4	108.22	62.2	144.54	48.8	33.90	25.2	8.85	56.2

Figure 7. (a) Satellite-based estimates of coniferous forest cover in five elevation strata. The forest cover in 1972 is considered to be 100% for each stratum. (b) Deforestation in five elevation strata (negative values indicates afforestation). (c) Relative deforestation versus elevation including a polynomial fitted regression model based on data from 400 to 1200 m.



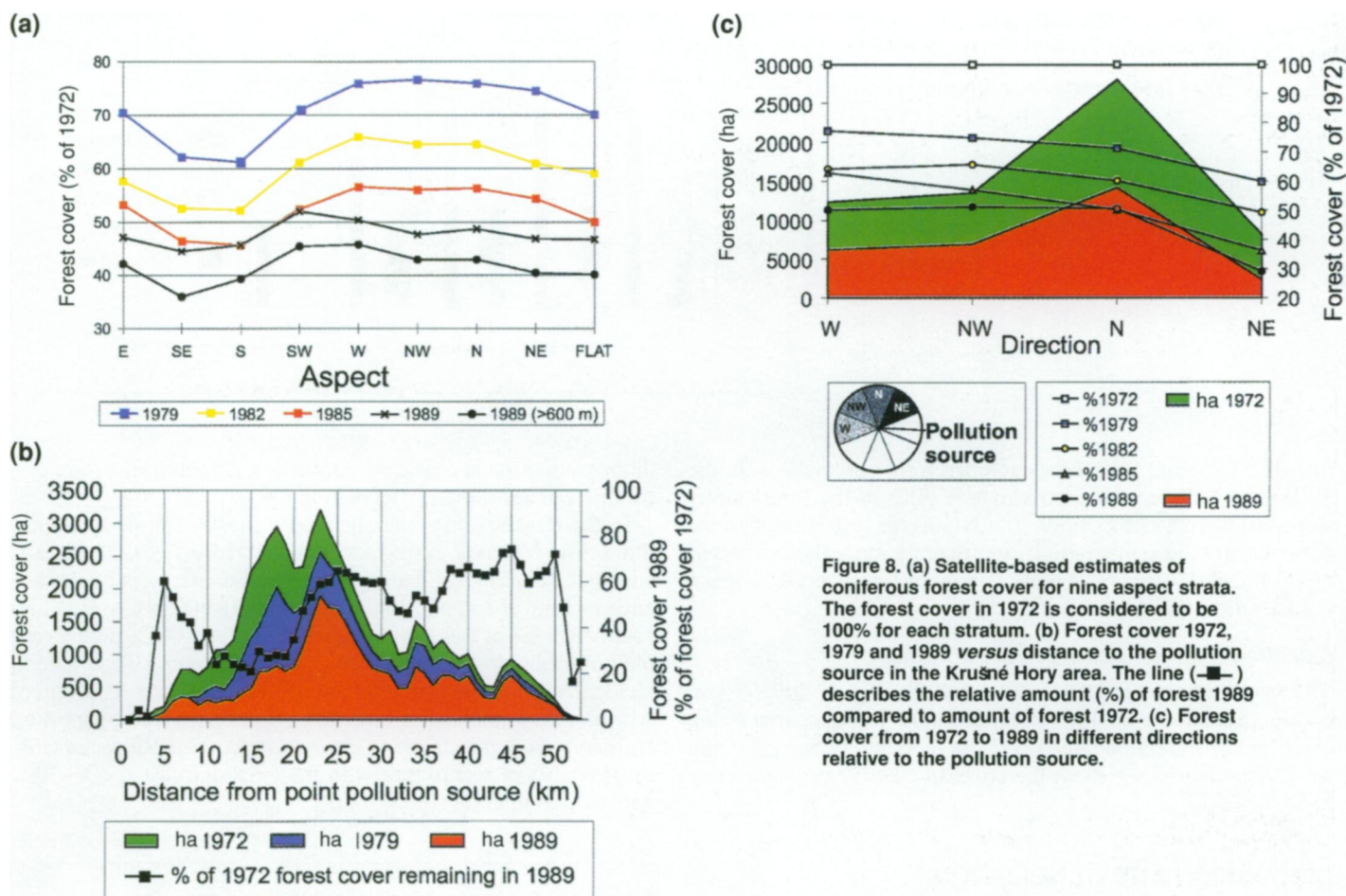


Figure 8. (a) Satellite-based estimates of coniferous forest cover for nine aspect strata. The forest cover in 1972 is considered to be 100% for each stratum. (b) Forest cover 1972, 1979 and 1989 versus distance to the pollution source in the Krušné Hory area. The line (—■—) describes the relative amount (%) of forest 1989 compared to amount of forest 1972. (c) Forest cover from 1972 to 1989 in different directions relative to the pollution source.

to 1979. Most affected was the 801–1000 m stratum where > 75%, significantly more than expected (χ^2 , $p < 0.001$), was lost, and the 601–800 m stratum where > 50% was lost from 1972–1989 (Fig. 7; Table 3). A regression of relative deforestation vs. elevation illustrates the large deforestation occurring between 800 and 1000 m (Fig. 7).

The relative annual deforestation between 801 and 1000 m exceeds 10% yr^{-1} from 1982 to 1985 and 8% yr^{-1} from 1985 to 1989. Lower elevations (< 600 m) shifted from a deforestation of approximately 4% to 6% yr^{-1} to a reforestation of 2.5% yr^{-1} during the study period. Elevations between 600 and 800 m have a more uniform deforestation and areas above 1000 m an increasing trend of annual deforestation (Fig. 7).

Aspect

The forest cover on all slopes was reduced by $\geq 25\%$ from 1972 to 1979 (Fig. 8). Slopes with a S-SE aspect were significantly more deforested than expected (χ^2 , $p \leq 0.001$). The range among the aspect strata is larger in 1979 and 1982 than in 1985 and 1989, indicating a faster initial forest-cover reduction on slopes with SE and S aspects compared to slopes with other aspects. Horizontal areas experience a median decrease in forest cover. When excluding low elevation areas (< 600), outside the Krušné Hory, the amount of forest decreases, but the pattern among the different strata is stable.

Distance and Direction to the Pollution Source

Deforestation appears to have no clear relation with the distance to the point pollution source (Fig. 8). The area between 11 and 19 km from the source, where > 70% of the forest cover were lost from 1972 to 1989, has suffered the largest deforestation.

Seen from the pollution source, 620 of the 645 km^2 of forest are located to the W, NW, N and NE, and hence remaining sec-

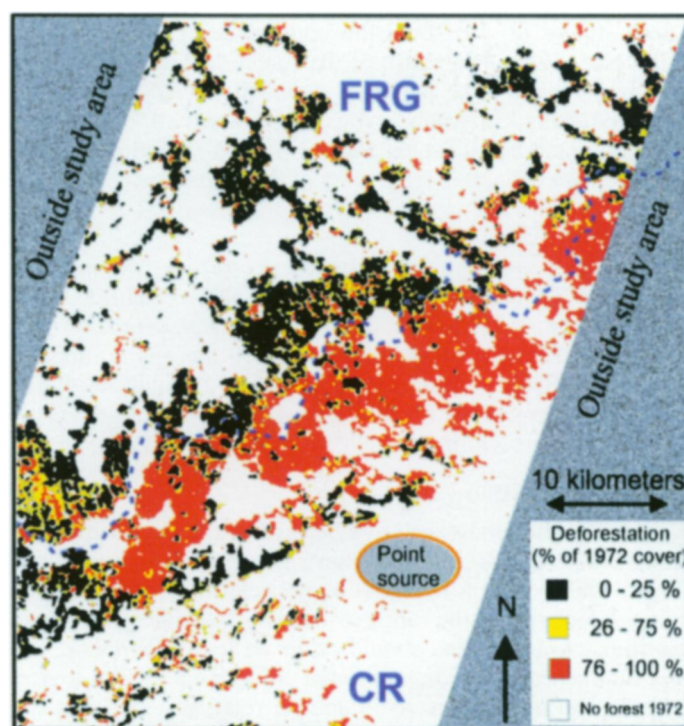
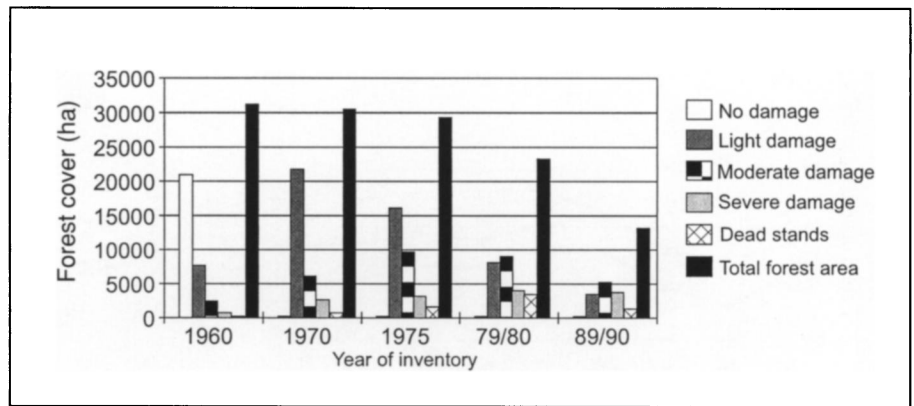


Figure 9. Relative amount of forest (%) ha^{-1} remaining in 1989 compared to 1972. The blue line is the Czech/German border.

Figure 10. Total forest area and forest health status of Norway spruce in two forest districts in the Krušné Hory 1960–1989/1990 (Lesprojekt).



tors (E, SE, S, and SW) were excluded from our analysis. In the N, W and NW sectors approximately 50% of the forest cover were lost from 1972 to 1989. The NE sector lost 70% of forest cover during the same period, significantly more than expected (χ^2 , $p \leq 0.001$) (Fig. 8). Figure 9 provides an overview of the deforestation pattern.

Satellite-based Estimates of Forest Damage

The satellite-based estimation of forest damage of the 308 km² conifers remaining in 1989 resulted in 79% of the area being classified as lightly damaged, 17% as moderately damaged and 4% as heavily damaged, with an overall classification accuracy of 71%.

DISCUSSION AND CONCLUSION

Severe deforestation has occurred in the Krušné Hory over the last two to three decades. This is strongly supported by our study, by forest statistics (Fig. 10) and by other studies (8, 12, 22, 36). Czech studies (8, 12) stress the importance of the large local emissions of SO₂ as a cause of the forest decline, which initiated the felling of large areas (22), probably in combination with climatic factors and secondary agents such as bark beetles. Results presented here (Tables 2 and 3, Figs 6–9) add new information about certain affected parts of the landscape.

Forest Statistics

According to local forest statistics (Lesprojekt, unpubl.), a decrease of Norway spruce forest from approx. 31 000 ha to 13 000 ha occurred from 1960 to 1990. In 1960, over 20 000 ha were classified as healthy, but since 1970 there is no undamaged forest. These statistics (Fig. 10), with a spatial resolution at the “forest enterprise level”, agree with the satellite-based estimates of deforestation.

Spatial Information

All parts of the landscape have been affected. High elevations (> 600 m) with SE–S aspects have been particularly affected (Figs 7 and 8). The lowest and highest elevation strata contain only a minor part of the forest (6% in 1972), resulting in higher sensitivity to errors and should be given less importance. Except for the heavily deforested sector NE of the pollution source, distance and direction have an unclear relation with deforestation (Fig. 8).

High elevation sites have lower mean temperatures, shorter vegetation periods and receive more precipitation than do low elevation sites (43). Slope and aspect of an area partly determine the amount of incoming radiation, influence temperature, evaporation, and growth conditions. In addition to elevation, direction and distance, slope and aspect determine the position of an area relative to pollution sources and the prevailing wind direction. This relative position, in combination with meteorological con-

ditions, emission and receptor properties, determine the local distribution of atmospheric deposition (48).

In the Krušné Hory, the air masses mostly follow a longitudinal SW–NE axis, along the Krušné Hory fault. These air-streams, including solid and gaseous pollutants, meet cooler air-streams from N and NE. In the zone of 600–800 m a. s. l. a characteristic zone of fog, enriched with SO₂, forms (22). In the case of sulfur dioxide, the major pollutant in the area, effects tend to be local and spatially related to the emission source. This agrees with the dominant wind direction (from W–SW) transporting emissions from the source to the most deforested NE sector (Fig. 8). It is also in accordance with the most deforested 600–1000 m elevation interval (Fig. 7).



Erosion of a former forest road. 20 years ago the forester on the picture drove his car up this road, in 1993 we had to walk. Krkonose mountains, Czech Republic. Photo: J. Ardö.



Factors determining the amount of stress and the predisposition of trees to disease vary with location (49), and influence the pattern of forest decline and deforestation. These factors are different and of varying magnitude in different regions. Forest decline could be assumed to be caused by a combination of many factors, summarized as multiple stress. Areas characterized by a large stress sum, i.e. with low buffering capacity, high acidic deposition, low natural weathering rate, harsh climate, unsuitable tree species and genetic material, improper management, etc. would be severely affected. Areas characterized by a smaller stress sum, i.e. with low acidic deposition, high buffering capacity, suitable climate, suitable genetic material, proper management, etc. would be less affected.

The coniferous forest in Krušné Hory is characterized by high relative sensitivity to acidic depositions (50)), harsh climate (43), high acidic depositions (21, 25, 51) and in some parts high deposition of arsenic, cadmium, copper, lead, nickel and vanadium occur (52). The origin of the Norway spruce genetic material is uncertain and only limited areas are of local origin (22). In addition to insect infestations, all these factors are possible, and probable, contributors to the Krušné Hory deforestation.

Satellite-based Estimates of Forest Damage, Advantages and Limitations

The logit regression used for estimation of forest damage utilizes the spectral, morphological and physiological changes occurring in the canopy during the decline process. These include alterations of moisture and light-absorbing pigment concentrations in the needles and changed exposure of trunks, branches and stand of understory vegetation such as herbs and grasses. The spectral variation caused by decline related phenomena strongly overlaps the spectral variation caused by topography, species composition, stand age and biomass (17). This partly restricts successful mapping of forest damage in Norway spruce using Landsat TM data. Still, some stress agents affecting conifers (water deficit, ozone, heavy metals, etc.) produce characteristic physiological, anatomical or morphological symptoms with unique spectral responses (3). Future high resolution airborne scanners may detect these responses and, hence, indirectly

identify the stress agent involved, hopefully improving mapping capabilities.

Satellite remote sensing is a good technique for detection and quantification of vegetation and forest change (53). Advantages include access to historical data and easy integration with other data. Remotely sensed data are the only available data providing complete areal coverage, even on a global scale. Limitations of using such data are the small spectral separability among damage classes with minor differences in defoliation (18) and the large need of ancillary calibration data (17). The unique, scene-dependent, relationship between satellite data and field measurements exclude using a single sensor-target relation that is stable over time and space. Compared to information derived from aerial photography (19), satellite-based estimates of forest decline are rough, but relatively fast and cheap to achieve.

The reliability of the results depends on the errors of the classification (Table 2), the field data, the nonperfect geometric properties and of the error propagation occurring when integrating the classification results with the topographic data. Calculation of aspect from nonperfect digital elevation data introduces errors (54). The different spatial measurements are not independent of each other, which should be recognized when interpreting the spatial descriptive results (Figs 7 and 8; Table 3). All these error properties have not been calculated in this study.

Conclusion

Information regarding the relation of deforestation and abiotic factors has been gained through integrating remotely sensed data with spatially distributed topographic data. Areas with significant changes have been localized and quantified. These spatial investigations should be extended to admit testing of different hypotheses regarding possible explanations of forest decline. This requires high quality, spatial distributed data, both about forest conditions and about the environment.

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- | Damage Class | Description |
|--------------|--|
| 1. | More than 20% of trees slightly* damaged but no more than 5% of trees heavily* damaged and no more than 32% of trees have medium* or greater damage. |
| 2. | 6–30% of trees heavily damaged or 33–84% of trees with medium damage. |
| 3. | 31–50% of trees heavily damaged or 84–100% of trees with medium damage. |
| 4. | 51–81% of trees heavily damaged. |
| 5. | > 81% of trees heavily damaged. |
| 6. | > 70% of trees "depreciated or destroyed". |
- *slight damage = 5–25% defoliation
 *medium damage = 25–50% defoliation
 *heavy damage = > 50% defoliation
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