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Potential Streamflow Changes from Forest Decline Due to Air Pollution

Mögliche Änderungen des Abflusses durch Waldsterben in Zusammenhang mit Luftverschmutzung

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SUMMARY

In recent years, serious die-back of forest trees has been reported in western Europe and eastern North America. One presumed cause of the forest decline is air pollution and acid deposition. Concern has been expressed that adverse hydrologic responses might occur in forested watersheds as the result of reduced evapotranspiration and increased discharge. Accor ding to one hypothesis, elevated soil-water storage might increase peak flows and cause stream channel damage or downstream flooding. This hypothesis is explored by reviewing the literature, recomputing published data, and simulating the effects of forest removal on streamflow. This study suggests that, although significant increases in water yield may result form a reduction in forest cover, hydrologic changes are unlikely to be large enough to cause downstream damage. This optimistic conclusion is based on the small increases that might be expected with even the most abrupt reduction in forest cover, and the likelihood that changes will be gradual and that pollution-intolerant trees will be replaced by more resistant plants through natural selection.

ZUSAMMENFASSUNG

In vergangenen Jahren wurde in Westeuropa and östlichen Nordamerika über schwerwiegendes Absterben der Waldbäume berichtet. Eine der Hauptursachen dieses Waldsterbens ist die Luftverschmutzung and sauereAblagerungen. Es ist der Befürchtunq Ausdruck gegeben worden, daβ sich die hydrologischen Verhältnisse in den bewaldeten Einzugsgebieten ändern werden. Dies ergibt sich aus der verminderten Evapotranspiration und dem anwachsenden Abfluβ. Ein Hypothese behauptet, daβ die erhöhte Boden-Wasser-Speicherung die Spitzenabflüsse anhebt und in den Gerinne Verwüstungen bzw. in den Unterläufen Oberschwemmungen verursacht wird. Die Hypothese ist untersucht worden durch Literaturüberblick, Wiederverwendung von publizierten Ergebnissen and der Simulation des Effektes der Entwaldung auf das Abfluβgeschehen. Diese Studie regt an, daβ, obgleich es zu einem signifikanten Ansteigen der Wassermenge durch die Verhinderung der Waldbedeckung kommt, die hydrologischen Veränderung jedoch wahrscheinlich groβ genug sind, um in den Unterläufen Verwüstungen zu verursachen. Dieses optimistische Ergebnis basiert auf dem geringen Anwachsen, das zu erwarten ist, wenn es zu einer plötzlichen Reduktion der Waldbedeckung kommt and daβ sich die Wahrscheinlichkeit des Wechsels im Abfluβgeschehen in Maβen halten wird and daβ auf die Luftverschmutzung ansprechende Bäume ersetzt werden durch resistenteres Pflanzenmaterial im Zuge einer natürlichen Selection.

2. INTRODUCTION

Evidence of forest dieback in Europe (PRINZ et al. 1982) and eastern North America (JOHNSON and SICCAMA 1983) continued to increase during the last decade. Although studies indicate multiple causes, atmospheric pollution is presumed to be a key factor (BACH 1985). Whatever the cause, the loss of timber stand vigor and the death of some trees may have hydrologic effects. Are these effects sufficiently important to require consideration when planning strategies to respond to dieback? They might be if the effects included substantial increases in flood runoff. We consider such increases unlikely. The discussion that follows will explain why we hold that opinion. Unfortunately, the data currently available concerning forest dieback are not sufficiently quantitative or extensive to permit a more definitive analysis.

When formulating policies to deal with the problem, at least five criteria must be met before the hydrologic effects of forest dieback should receive serious consideration:

[1] Major floods which threaten the values at risk must occur during the season of the year when the hydrologic effects of forest dieback are manifest.

[2] The dieback results in a substantial basin-wide reduction in evapotranspiration or ground cover.

[3] The magnitude of the change is great enough, relative to the pre-dieback condition, to make an important difference in flood volume or peak flows.

[4] The probability is high that potentially flood-producing precipitation will occur when soil-water deficits in dieback areas are significantly less than those in unaffected basins.

[5] Downstream values are at risk that justify attempts to reduce adverse hydrologic effects of forest dieback.

The first four of these criteria will be explored to better understand the hydrologic threat posed by current and projected levels of forest dieback. The fifth criterion is, of course, site-specific. In general, in North America, streams draining areas affected by dieback do not pose an immediate threat to life and property. On the other hand, settlements in many parts of Europe would be threatened if forest dieback led to flooding.

3. ANALYSIS OF PROBLEM

3.1 Flood Threat

Hydrologic effects of forest dieback would be manifest as decreased soil-water deficits resulting from reduced transpiration. In both Europe and in North America, the season of the year when the hydrologic effect of forest die-back would be expected to be at its maximum coincides fairly well with a period of high flood potential. In the southern Appalachians, for example, the maximum soil-moisture deficit occurs in late summer or early fall (HELVEY and HEWLETT 1962), and a high flood threat from hurricanes typically occurs in September or October. Throughout the east coast of the United States, most of the 24-hour maximum rainfalls are reported during that season of the year (TODD 1970). A similar circumstance prevails in Europe, although orographic summer precipitation rather than hurricanes is the origin of floods. Maximum 24-hour precipitation (MOLLER 1982, RUDLOFF 1981, WALLEN 1977) and maximum flood run-offs (VAN DER LEEDEN 1975, IMHOF et al. 1965) are typically found between May and September.

Floods in both Europe and North America may occur when reduction in transpiration results from forest dieback. It is important, therefore, that the magnitude of this potential threat be estimated as well as possible with existing data.

3.2 The Extent of Dieback

Forest dieback represents an alteration of a natural ecosystem. For a substantial reduction in evapotranspiration or ground cover, basin-wide dieback would have to be followed by a minimum response by successional vegetation. Such a sequence of events seems unlikely. In both Europe and North America, dieback affects tree species selectively. In Europe, at least 11 species are affected -- including 4 important conifers and 7 broad-leafed trees (HINRICHSEN 1987). On both continents the symptoms displayed and the intensity of damage differ widely among tree species (HINRICHSEN 1987, SCHÜTT and COWLING

1985). In West Germany, stands of white fir (Abies alba) were the most seriously affected: 87 percent of the forest area in that species showed symptoms in 1984. Two species of oaks (Quercus robur and Q. petraea) showed evidence of decline with 43 percent of their area displaying symptoms (SCHÜTT and COWLING 1985). It is unclear what proportion of the difference between species is due to genetic differences and what proportion is due to the sites which they characteristically occupy. BERRANG et al. (1986) suggest that genetic differences play a role in ozone tolerance. They subjected seedling-size clones of quaking aspen (Populus tremuloides) from five national parks to 180 ppb ozone for 6 hr and found "a high negative association between average injury and ambient ozone levels" in the parks of origin. These results are consistent with the hypothesis that polluted air is a powerful selective force (SINCLAIR 1969) and that ozone selects against sensitive genotypes of P. tremuloides (BERRANG et al. 1986).

In addition to the direct and indirect effects on trees, pollutants may affect soil chemistry and microbiology. In some cases these factors may hasten the senescence of an even-aged forest cohort (MUELLER-DOMBOIS 1987, ULRICH 1982). If the dieback is due to multiple stresses, it follows that the absence of one or more stress components should reduce stand damage. That phenomenon should promote a mosaic-like response rather than a basin-wide uniformity of response because many stress components will be confined to particular topographic facets. Forests do not seem to be uniformly vulnerable to dieback. Older trees are more likely to succumb than younger ones (SCHÜTT and COWLING 1985); stands at high elevations are more susceptible than those at low elevations (SCHÜTT and COWLING 1985); trees on exposed sites trees are more susceptible to dieback than those on sheltered sites (SCHÜTT and COWLING 1985, ULRICH 1982); trees exposed to wind, fog, and rime ice are reported to be more vulnerable (PRINZ et al. 1982, SCHÜTT and COWLING 1985, ULRICH 1982). Less vulnerable areas include "hollows, basins, and gorges" which are not exposed to prevailing winds (ULRICH 1982).

All of the foregoing considerations suggest that dieback will form a mosaic-on the landscape, being more intense in vulnerable sites, and less intense or absent in protected areas. Such a pattern is not a new phenomenon in European forests (MUELLER-DOMBOIS 1987). Forests throughout the world experience periodic diebacks from combinations of natural causes. However, forest ecosystems contain species adapted to the increased light, moisture, and nutrients made available by dieback. Since dieback is not an abrupt change such as a forest fire, plant succession can proceed with little alteration of the hydrologic properties of the ecosystem. In the Ohia decline in Hawaii between 1954 and 1972, HODGES et al (1986) reported that "In areas of severe decline, ninety percent or more of the Ohia canopy may be dead. Such areas are not denuded of vegetation however. Sub-canopy species and litter provide ground cover for perhaps ninety-five percent of the area." Unless air pollution becomes so severe as to cause dieback of almost all plant species in the ecosystem, it seems unlikely that basin-wide reductions in transpiration or ground cover will occur. To sum up, forest dieback occurs in heterogeneous, dynamic ecosystems composed of sites of varying stress and species with varying susceptibility to the agents causing dieback. Extensive uniform dieback would, therefore, require a highly improbable set of circumstances.

3.3 Magnitude of Hydrologic Effects

The maximum possible effect from forest dieback would occur with complete basin-wide dieback and no regrowth of any type. Two American paired-watershed experiments have reproduced this condition (HORNBECK 1973, LYNCH and CORBETT 1982). In both studies, virtually all of the treated watershed was clear-felled and regrowth was prevented with herbicides. Substantial streamflow increases were reported. The maximum post-treatment peaks in the two studies were 200% and 300% of their predicted values, respectively. In the Hubbard Brook experiment (HORNBECK 1973) storm run-off volumes were also reported. The maximum summer quick flow increase was about 160%; the maximum summer peak flow increase was about 250%. If these two experiments reflect what may occur as the result of forest dieback, then increased flooding would likely result, at least in small basins of 40-50 ha.

The preceding studies suggested the potential for significant hydrologic effects. Are the necessary drastic reductions in transpiration likely to occur as the result of dieback? We think not. In Section 3.2 of this paper, we reported evidence against substantial basin-wide dieback. ULRICH (1982) contrasted basal-area growth of beech and spruce during the period 1969-1973 with the period 1973-1977. His data suggest approximately a 60 percent reduction in growth. Conceivably, this growth translates to a comparable reduction in water use. Estimates of hydrologic effect based on such a reduction are probably closer to what may be experienced as the result of forest dieback. The killing of Japanese black pine (*Pinus thunbergii*) in the 22.6-ha Minamitani Watershed on the Tatsunokuchiyama Experimental Forest near Kyoto, Japan is probably a close analog to the dieback effect (ABE and TANI 1985). Pine forests covering 69% of the watershed were completely killed by the pine-wood nematode. No difference in peak flows which were larger than 4 mm/hr were found, even though there were both winter and summer increases in base flow. We digitized ABE and TANI'S (1985) data for the months of June through August and recomputed the "before" and "after" treatment regressions. The two regressions were not statistically significantly different (P=0.37) based on CHOW'S (1960) test. Presumably competing vegetation quickly invaded the sites made available by the death of the forest cover and negated any possible soil-moisture losses.

For the hydrologic effects of dieback to be important, they must be evident during potentially large floods. The data cited above strongly suggest that they will not be. That conclusion conforms to conventional hydrologic thinking that the effect of watershed condition diminishes as flood size increases.

3.4 The Probability of Significant Soil-Water Deficits Coinciding With Large Summer Storms

We could find no research addressing the issue of significant soil-water deficits coinciding with large summer storms. Our analysis of data taken from ABE and TANI (1985) suggests that the probability of the joint occurrence of large soil-water deficits and large storms is low. Further investigation did, however, seem warranted.

To estimate the likelihood of large storms occurring when there were large soil-water deficits we developed a simple Markov computer model based on data that were readily available to us and that approximated the conditions where the dieback threat is greatest. Precipitation data came from weather stations in Austria (MÜLLER 1982). Conceptually, the computer simulation reproduced sets of the two summer months in which serious flood threats exist. The simulation included a total of 10,000 summer days, about 160 years. We created a hypothetical site at which the probability of rainfall on any day during the two rainiest summer months was 0.55. The mean rainfall was 8mm on rainy days. Daily precipitation amounts were log-normally distributed with a 75mm daily rainfall amount having a return period of 1000 summer days. The maximum daily precipitation in the simulation was 150mm. A set of conditional probabilities was used to simulate the clustering of dry and rainy days typical of summer weather. The best data available to us for those probabilities were precipitation records of four sites on the east slopes of the Sierra Nevada in California (NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION 1985a, 1985b, 1986).

Evapotranspiration (ET) was modeled to produce a 400-mm mean annual difference between dieback and non-dieback sites, with 37% (150mm) occurring in June and July. The annual figure is based on typical water yield increases from worldwide catchment studies (BOSCH and HEWLETT 1982) in the first 5 years after clearcutting coniferous forests. The annual distribution was inferred from potential evaporation data from the Austrian weather stations (MOLLER 1982). To produce the 150-mm target, the average daily difference in evapotranspiration between a dieback site and a non-dieback site on dry days was set at 4mm, while on rainy days the evapotranspiration difference was an inverse function of the daily precipitation. (ET was distributed normally with a mean of 4/ppt mm and a standard deviation of 2/ppt mm.)

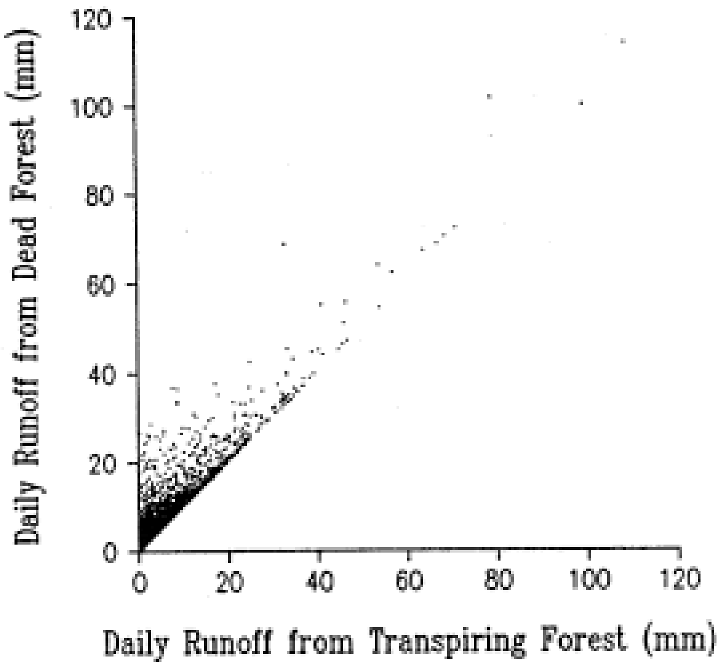

Figure 1. Simulated effect of forest dieback on daily summer runoff.
Abb. 1: Simulation des Waldsterbens auf den täglichen Abfluβ im Sommer

The model allowed 75% of any surplus water to run off the same day it was generated. This high value was chosen to avoid diminishing the flashy effects of intense storms in small basins. In most cases, we believe detention due to flow routing would be much greater, thereby reducing the effects of dieback on runoff.

As noted in Section 3.2, dieback is more likely to occur on ridges and exposed areas and less likely to occur in swales. This topographic arrangement would mean that the run-off increases from affected areas would tend to be upslope and tributary to unaffected areas. A likely ecological response to this circumstance is increased water use by the vegetation in the unaffected areas. However, this model simulates 100% dieback, as in clear-felling, thus creating the optimal scenario for increasing flood peaks.

On 6.8% of the rainy days, the dieback area produced an additional l0mm or more of simulated runoff. Increases of more than 20mm occurred only about 1% of the time. The maximum increase was 40mm. In only three cases did increases of 20mm or more result in total runoff greater than 40mm (Fig. 1). The number of runoff days with 40mm or more runoff increased from 18 to 27, but the number of days with 75mm or more remained constant at 3. Generally as the size of the runoff event increased, the additional contribution due to dieback decreased.

To the extent that the simulation is a satisfactory approximation to reality, it suggests that most of the on-site run-off increases would be minor. Large increases during large events apparently would be rare, even with 100% permanent dieback in the flashiest of basins, such as that modeled here. Where dieback is temporary or incomplete, and in catchments of more than a few square kilometers, the expectation of large increases would be diminished further.

4. CONCLUSIONS

This review of the literature and computer simulation suggests that important hydrologic effects as the result of forest dieback are very unlikely, although weather patterns favor the occurrence of serious dieback effects. In both Europe and eastern North America, major flood threats coincide with the season when dieback effects on hydrology are likely to be greatest. Our computer simulation suggests that the probability of a large storm runoff increases resulting from dieback-caused differences in evapotranspiration is insufficient to warrant much concern. However, our conclusion is based primarily on the expected responses of the affected forests. It is unlikely that there will be substantial basin-wide dieback because the magnitude of effects varies with elevation, topographic position, resistance of tree species, and genotypes within tree species. A mosaic of dieback patches seems more probable. Patterns of dieback observed to date suggest that affected elements of the mosaic will often be tributary to unaffected elements. This condition will tend to cause dieback-related increased runoff to replenish soil-water deficits downslope, diminishing any contribution to increased streamflow. Given that dieback occurs as a mosaic, its hydrologic effects will be similar to those observed as a result of logging. Consequently, the conclusions of LULL and REINHART (1972) and HEWLETT (1982) that "forest operations do not seriously increase flood flows in major streams" can be applied to dieback effects.

All of the above does not mean that hydrologic effects of forest dieback can be completely ignored. Rather it argues that such effects should not figure prominently when planning strategies to combat forest dieback. Only in circumstances of nearly basin-wide dieback which pose an immediate threat to human life and property should careful analysis of the hydrologic effects of dieback be required.

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