slope of the line for pH versus pAl^{3+} is significantly different from zero in all periods except late melt (*10*).

When the data for all sites are separated temporally in a similar manner (Table 2), there is a significant decrease in the slope during late melt, although the change is not so dramatic as when the site A data are considered alone. The Falls Brook data (Fig. 2) also exhibit a temporal variation in the pH versus pAl^{3+} relation. The slope of the best-fit line for the spring samples is 4.40 ± 0.76, and that for the autumn samples is 2.74 ± 0.59.

This temporal variation in the aluminum response to pH depressions also indicates a more complicated aluminum mobilization mechanism than a mineral dissolution equilibrium. One explanation for this phenomenon is that aluminum is slowly converted into a labile form from the weathering of primary minerals and is accumulated in the soil. The first major flush (the midwinter thaw, in this case) following an extended period of low flow would mobilize this more soluble form of aluminum. If this labile pool is leached out of the soil in the early stages of the melt by a large volume of water flowing through the watershed over a short period, there would be no elevation in aluminum above baseline levels during later acidic events. In watershed 3, especially at site A, the aluminum concentration did not increase as much in response to lower pH in the late melt period (following the large melt and rain event of 5 April) as it did in earlier events. The interval between the disappearance of the snowpack and the storms may have permitted the formation of labile aluminum, thereby accounting for the increase in the slope during the spring period. Laboratory studies of aluminum mobilization kinetics have found that exchangeable aluminum is depleted with increased leaching (*11*).

These findings are important to much of the ongoing acid rain research, especially that focusing on predictive mathematical models or biological effects. The observed disequilibrium between aluminum concentrations in stream water and a readily formed $Al(OH)_3$ mineral phase reduce our confidence in predictions of short-term temporal changes in stream chemistry made by investigators using models based on an equilibrium.

Our findings also indicate that the temporal pattern of the snowmelt is important in the mobilization of aluminum. We observed the highest aluminum concentrations in the midwinter thaw, not during the main spring melt. Because sensitive life stages of fish species are present only at certain times of the year, such patterns are important in the assessment of the biological impacts of acid precipitation.

In a broader context, these results emphasize the importance of temporally intensive event sampling to identify the mechanisms controlling stream water chemistry and hence to establish the relationship between the acidity of precipitation and the resultant surface water chemistry.

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Smoke Production from Multiple Nuclear Explosions in Nonurban Areas

Abstract. *The amount of smoke that may be produced by wildland or rural fires as a consequence of a large-scale nuclear exchange is estimated. The calculation is based on a compilation of rural military facilities, identified from a wide variety of unclassified sources, together with data on their geographic positions, surrounding vegetation (fuel), and weather conditions. The ignition area (corrected for fuel moisture) and the amount of fire spread are used to calculate the smoke production. The results show a substantially lower estimated smoke production (from wildland fires) than in earlier "nuclear winter" studies. The amount varies seasonally and at its peak is less by an order of magnitude than the estimated threshold level necessary for a major attenuation of solar radiation.*

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Several estimates in scientific journals (*1–3*) have attributed approximately half the global smoke production resulting from a general nuclear exchange to wildland fires; a National Academy of Sciences (NAS) study (*4*) estimated a smaller fraction from wildland fires. The estimates of the smoke fraction due to nonurban fires are scenario-dependent and vary from nil for city-only exchanges to 100 percent for city-avoidance attacks. In general, the baseline scenarios of these earlier studies have projected a wildland smoke production of roughly 10^{14} g—an amount sufficient to initiate a prolonged and possibly catastrophic cooling of the earth's surface.

Although many facets of these estimates warrant attention, we focus here on the source function—the nonurban area burned and the amount of smoke produced. We do not consider the mechanics of smoke injection, the scavenging of smoke particles, the transport and distribution of smoke, the composition and optics of the particulate cloud, or the earth energy balance. Our calculation of the global smoke production suggests a much smaller atmospheric loading than that estimated previously.

For this report, "wildland" targets are defined as those major military installations located far enough from urban concentrations that attack on them is unlikely to result in urban fires. Although generic military targets have been selected, they tend to be missile silos and air bases, radar sites, weapon storage centers, C^3 (command, control, and communications) sites, and some tactical weapon–launch concentrations. The list is not intended to be complete but may represent nearly all missile-launch facilities and major air bases remote from cities.

Crutzen and co-workers (*1, 3*) and Turco *et al.* (*2*) assumed that such wildland targets are more or less uniformly distributed in the Northern Hemisphere. In effect, they assigned more targets to areas of high fuel density such as forests than to low density or low flammability areas such as grass and croplands. As a consequence, both the ignition area and the amount of fuel burned may have been greatly overestimated. It is apparent to us that most military targets (especially those located in the United States and the Soviet Union) are not distributed uniformly but are either concentrated in a relatively few missile fields or collocated along major transportation arteries. Such concentrations imply that hemispheric averages of fuel loadings and weather conditions may be inappropriate. Since the amount of smoke produced depends in large part on the amount of fuel consumed, hemispheric biomass averages may be misleading and incorrect, and a more careful accounting of target locations, surrounding fuels, and local weather is needed.

Fig. 1. Unclassified global distribution of wildland military facilities.

Fig. 2. Climate stations used in defining local weather conditions for identified (unclassified) wildland-military targets.

Rather than adopt a specific scenario and then bound the result by considering larger or smaller nuclear exchanges, we consider an attack against all the wildland (military) targets in our compiled list. For this target set, the maximum area that could be ignited and the maximum amount of smoke that could be produced in a general exchange are calculated. The use of additional weapons against these targets would not appreciably change the total area burned or the mass of smoke generated.

Many open literature sources were used in compiling the potential target list (*5–9*). We have made no attempt to make our target list coincide with any official list. However, we believe that the total number and variety of targets and their geographic diversity is sufficiently representative for this study. Descriptions of North American and West European facilities in these sources were more explicit and complete than documentation of Soviet and East European facilities. Nevertheless, we found sufficient information about the latter to compile a reasonable list of targets. Our list included approximately 3500 military facilities, including intercontinental ballistic missile silos and control centers, airfields, radar stations, command centers, intermediate-range and medium-range ballistic missile launchers, and tactical weapon storage sites. Most are located in the United States and the Soviet Union. There are an appreciable number in Europe and a lesser number in East Asia. We have neglected potential targets in the Southern Hemisphere, North Africa, the Middle East, and the Indian subcontinent. These omissions are not expected to substantially modify the estimates of total area burned or smoke produced.

We have taken as estimates of strategic arsenals the work by Forsberg and Barnaby (*10, 11*). According to these estimates, sufficient warheads are available such that multiple weapons can be allocated against each rural target. We have assumed two warheads per target and estimate an exchange of roughly 4100 megatons (Mt) [about half the 1982 total deliverable strategic weapon yield (*11*)]. All weapons were assumed to be reliable. For comparison, the generic baseline scenarios used by Crutzen *et al.* and Turco *et al.* (*1–3*) assumed an attack of 4000 Mt against wildland targets; the NAS study (*4*) assumed 5000 Mt.

Most of the identified targets could be located geographically with sufficient accuracy to define both the local vegetation and the weather. Land-use maps and regional atlases (*12–14*) were used to define the type of fuel and its properties (loading, ignition threshold, and burning characteristics) surrounding each target. The classification was limited to 12 fuel types ranging from swampland to forests, although in many cases greater detail was possible. In many target areas, several classes of fuel were present and noted. The results of the data classification are summarized in Table 1.

The greatest number of targets are located not in wildlands but in croplands or grasslands. Only 14 percent are located in forested areas, and, of these, most are in the Soviet Union. In general, the targets are located in regions characterized by small fuel loadings or by fuels (crops) not likely to support major fires. The target locations are indicated on the polar projection shown in Fig. 1. They are concentrated in missile fields and are far from uniformly distributed.

The fuel loadings (the probable amount of burnable biomass assigned to each target area) are based on measured fire data as used in the U.S. Forest Service National Fire Danger Rating System (NFDRS) (*15, 16*). Grasslands can have burnable fuel loadings of from 0.01 to 0.06 g/cm^2. A coniferous forest with normal litter has a burnable fuel loading of about 0.17 g/cm^2; higher values are characteristic of logged forests with extensive slash. Heavily cultivated (ripening) croplands may have a fuel loading of 0.2 g/cm^2. In all cases, we assume that the entire burnable loading is consumed. Since the amount of smoke depends directly on the type and quantity of material burned (and the fire intensity), the loading variation for each different target area is important.

Most of the time, the croplands will not be capable of burning (*17, 18*). Accordingly, even though only 14 percent of the targets are in forests, those fires account for 35 percent of the total area burned. Portions of the croplands can be ignited when grains have ripened but have not yet been harvested (*19*), a period of ~2 weeks (*20*). In general, planting and harvesting times are staggered. Thus at any one time, only a fraction of the total acreage is ripe (and unharvested) and available to burn. The maximum threat is in July and August. Smaller cropland acreages are likely to burn in June and September, and negligible amounts during the rest of the year.

Table 1. Wildland target distribution.

Area	Number	Fraction (%)
Wasteland	204	6
Forest	481	14
Grassland	702	20
Cropland	2072	60
Total	3459	100

Weather is also a major influence on the possible extent of wildland fires. The consequent variation in fire area is both geographic and seasonal. In winter, snow cover and heavy rainfall limit the area that will burn. Ignitions and fire spread are more likely to occur in summer, but not in all regions of the Northern Hemisphere at all times.

Keeping in mind the identified target locations, we defined 72 climate stations (Fig. 2) across the Northern Hemisphere for use in this exercise. Most are located so as to accurately represent the weather at nearby target sites; some, however, represent only the closest possible reporting weather station for some remote targets. For each climate station, data necessary for calculation of both the weapon ignition radius (visibility and fuel moisture) and the probability for fire spread (temperature, fuel moisture, and wind) are catalogued. The weather data include maximum and minimum daily temperatures and humidities, rainfall, snow cover, cloud cover, fog conditions, and average wind speeds (*21, 22*).

Earlier estimates of the wildland area ignited in a nuclear exchange were based on assumed average fire areas per yield expended. Turco *et al.* (*2*), for example, used 500 km^2/Mt. Thus, the total area burned and the smoke production (for a given fuel loading and smoke emission factor) is determined by the assumed total yield of weapon exchange.

Many factors influence the ignition area and subsequent fire spread, none of which are explicitly included in an "area per yield" estimate. Fuel type, level of fuel moisture, local visibility conditions, snow cover, and target spacings are all important variables. The data compilation described above allows the evaluation of these effects and the determination of the likely area to be burned as a function of location, weather, fuel, and time of year.

Since most targets are considered "hard," surface or near-surface bursts were assumed. The thermal radiation fluxes (calories per square centimeter) were calculated for the local visibility conditions. If no visibility information was available, clear conditions (20-km visibility) were assumed. Ignition radii were determined as a function of the fuel ignition threshold (*18, 23*) and were corrected for moisture content. The fuel

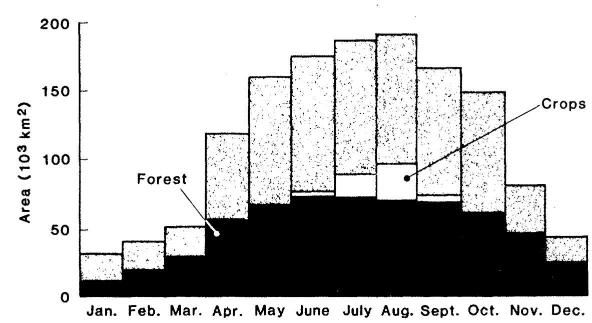

Fig. 3. Monthly variation of ignited area; the lightest shading indicates the low fuel loading areas.

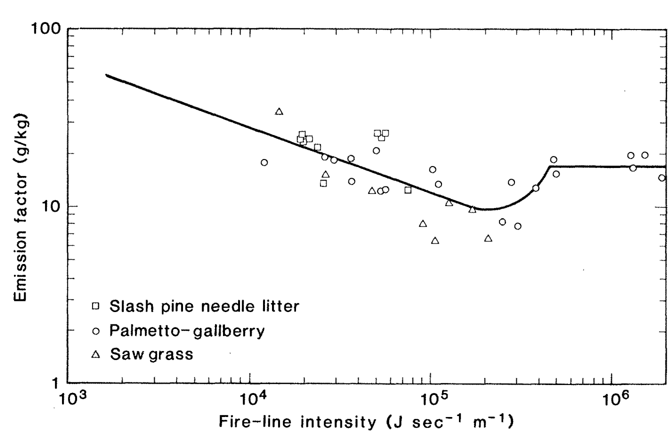

Fig. 4. Relation between fire-line intensity and smoke emission for low intensity fires (*29*).

Table 2. Results and comparison.

Study	Yield (Mt)	Area (10^3 km^2)	Loading (g/cm^2)	Emission (g/g)	Smoke (10^{12} g)
Crutzen and Birks (*1*)	3800	1000	0.3 to 0.55	0.067 to 0.073	200 to 400
Turco *et al.* (*2*)	4000	500	0.5	0.032	80
Crutzen *et al.* (*3*)	3800	250 to 1000	0.4	0.06	60 to 240
NAS (*4*)	5000	250	0.4	0.03	30
Bush and Small (*31*)	4100	30 to 190	0.01 to 0.20	~0.03	0.3 to 3.0

moisture was related to the catalogued meteorological data on the basis of the NFDRS (*24*). Threshold levels were increased by the amount of thermal energy necessary to dry the fuel. Even though there may be sufficient thermal energy to start fires in wet fuels, the energy used to dry the fuels can significantly reduce the ignition radii. For most sites the correction for wet fuel ranged from +1 to +3 cal/cm^2 (about a 3 to 9 percent reduction in radius for a 500-kiloton burst).

We assumed no ignitions in snow-covered areas. Additional corrections were made to allow for the use of multiple weapons against single targets and the overlap of ignition areas for closely spaced targets such as missile silos.

The total area ignited in the assumed exchange is shown in Fig. 3. The seasonal variation is quite pronounced. During the winter months, snow cover and increased moisture levels reduce the fire area. Some variation—due mostly to the

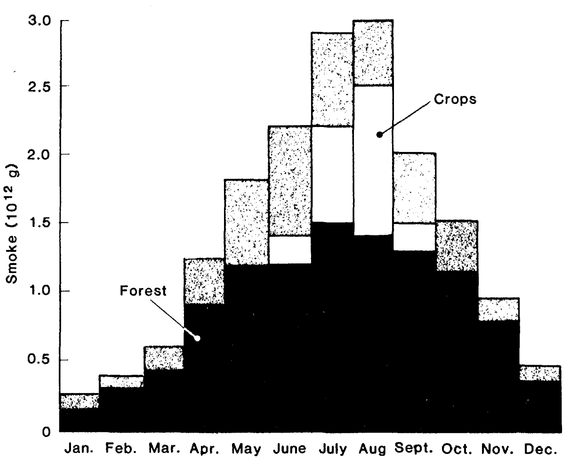

Fig. 5. Monthly variation of smoke production; the lightest shading indicates low fuel loading areas.

Fig. 6. Polar projection indicating summer global smoke distribution prior to spread from the source areas (5° × 5° bins).

greening and curing of vegetation—is present in the summer months. The burning of ripe, unharvested crops accounts for 5000 km^2 in June and September, 17,000 km^2 in July, and 27,000 km^2 in August. The maximum area burned is 191,000 km^2.

The amount of fire spread beyond the initially ignited areas depends on the fuel (type, size, loading, and moisture), topography and meteorological conditions. On the basis of the NFDRS (*16, 25, 26*) and "fire out" criteria devised by Chandler *et al.* (*27*), we have estimated the additional area burned as a result of fire spread (assuming no firefighting). Surprisingly, fire spread does not appreciably add to the area burned either in winter (1 to 2 percent) or in summer (4 to 9 percent). As demonstrated by the Forest Service models and experience, weather conditions do not often favor large amounts of fire spread in the Northern Hemisphere at any one time.

There is considerable uncertainty about the amount, composition, and size distribution of the fire emissions. Similarly, it is not clear whether the "smoke" produced by wildland fires is injected to altitudes high enough to remain in the atmosphere for an appreciable period. These issues notwithstanding, Crutzen *et al.* and Turco *et al.* (*1–3*) considered the quantity of smoke produced by the fires to be the principal parameter. Their estimates were based on a fixed smoke emission factor (≈3 to 6 percent), independent of the fuel or fire intensity.

Rather than assume a fixed smoke emission factor, we allow a variation proportional to the fire intensity. Since the fire intensity depends on the fuel and weather, the smoke production similarly can be related to those variables, with fire intensity based on the NFDRS estimation. Although only limited field data (*28, 29*) are available, correlations between the smoke emission factor and the fire characteristics have been developed (*30*). The correlation we use in our calculation is shown in Fig. 4. Despite the uncertainties, we expect that a more accurate estimate of the seasonal and geographic distribution of smoke results when these relations are used.

Figure 5 summarizes the amounts of smoke produced for each month of the year. The heavily shaded area represents the fraction attributed to forest fires. Although only 14 percent of the targets are in forests, these areas account for 35 percent of the area burned and for ~50 percent of the smoke produced. This is the result of heavier fuel loadings. As expected, smoke production is heaviest in the summer (varying somewhat from May to October as annual and perennial grasses cure) and is greatly reduced in the winter.

Our results are compared to those of earlier studies in Table 2. All the studies have assumed nuclear attacks of similar total megatonnage. The area burned, however, varies widely. Our value is roughly one-third the value of Turco *et al.*, and that is a seasonal high. In the winter months, the area burned is further reduced by a factor of 6.

A major difference in these studies is the fuel loadings assumed to be available for burning. Most of the targets we have identified are located in areas of low fuel density such as grasslands or croplands. Although the loading factors used by Crutzen and Birks (*1*) and by Turco *et al.* (*2*) are only a fraction of the available biomass, they are more appropriate for logged forests with extensive ground litter ("slash") than for naturally occurring vegetation (*26*). Such values greatly overestimate the amounts of fuel that can be burned in a nuclear exchange.

Our smoke emission–fire intensity formulation allows a range of emission factors of 0.01 to 0.06 g/g. This corresponds to a weighted emission factor of roughly 0.03 g/g, similar to mean values used by Crutzen *et al.* and Turco *et al.* (*1–3*). The bulk of the emissions are from the forested areas (Fig. 5). Since more of the Soviet targets are located in forests (most U.S. targets are surrounded by grass or croplands), hemispherically nonuniform smoke concentrations are likely. This is suggested in Fig. 6 by the coarse-grid shadings that represent the initial smoke distribution prior to any diffusion or transport in the atmosphere. Because of the limited global coverage and variation in concentration, it is not clear that a uniform smoke layer will develop across the Northern Hemisphere.

For a general nuclear exchange involving nonurban military facilities, we predict a maximum (July) smoke production of 3.0×10^{12} g. This is very much lower (by about a factor of 10 to 100) than earlier estimates, principally because of lower fuel loadings and total area burned. Other factors, such as weapon overlap, smaller fuel moisture, and snow cover, also contribute to the lower smoke production. Sensitivity tests in which we varied separately the yields and number of weapons, heights of burst, threshold limits, and moisture conditions result in upper estimates of about 10^{13} g of smoke production.

Our estimates of smoke production imply much smaller optical depths for solar light occlusion than estimated earlier. Even if all the smoke were distributed uniformly between 30°N and 60°N, the resulting optical depth would be 0.18, a value much smaller than that required to produce a "nuclear winter." If we take into account the low stabilization altitude of wildland smoke plumes (wildland fires seldom produce plumes that reach or penetrate the tropopause) and the consequently enhanced scavenging and rainout of smoke particles, the optical depth would be even smaller. Similarly, accounting for the fraction of smoke particles that are optically active (those with a radius less than 0.5 μm) would further reduce the optical depth. If these factors were included, optical depths of 10^{-2} or smaller could result. The possible ecological and biological consequences of such small amounts of solar absorption are not known, but they are not likely to be of the serious proportions hypothesized earlier (*1–4*), particularly in light of the vast destruction and intense radioactive fallout that would be created by such nuclear attacks.

Not only is our estimate of the smoke that would be produced from rural fires significantly smaller than earlier estimates, but the smoke layer developed is not likely to be uniform over the Northern Hemisphere. The geographical concentration of many wildland military facilities suggests that abnormal gradients may develop that could encourage violent meteorological activity with consequent enhanced scavenging and self-cleansing of the atmosphere. Even if we were to use values of parameters somewhat higher than justified by the data available to us, the smoke production is substantially less than the threshold (10^{14} g) for the onset of a "nuclear winter" (*32*).

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