Soil Drainage and Its Potential for Influencing Wildfires in Alaska

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Abstract

Soil drainage, as defined by water-holding capacity, hydraulic conductivity, and position of seasonal water table, is closely associated with soil C storage because of controls on plant production, decomposition, fire severity, and fire frequency. As an initial regional assessment, we have used the U.S. Department of Agriculture's Natural Resource Conservation Service (NRCS) map (scale 1:1,000,000) to categorize areas in Alaska according to seven soil-drainage classes, using a simple numeric scale and an area weighting of mapped polygons. The seven NRCS soil-drainage classes were ranked numerically, from 1 (excessively drained: very high hydraulic conductivity and low water-holding capacity, water table >2 m deep) to 7 (very poorly drained: low hydraulic conductivity, water table <30 cm deep throughout the year). Area-weighted scores for each polygon were computed and plotted. About 50 percent of Alaskan landscapes have low hydraulic conductivity and high (<1-m depth) water table, which in many areas are related to shallow permafrost. Less than a third of the landscape (~26 percent) is moderately to excessively drained, and ~4 percent qualifies as very poorly drained wetlands. A statistical correlation exists between more poorly drained wet areas (drainage class, >5) and historical burning (since 1950), which we hypothesize to be related to high soil C storage and continuous cover of fuels typical of black spruce/feathermoss systems underlain by shallow permafrost.

Introduction

The spatial occurrence of boreal forests currently coincides largely with the zone of discontinuous permafrost (Brown and others, 1997), very large wildfires (Stocks, 1991, 1993; Kasischke and others, 1995) and very large carbon stocks (Eswaran and others, 1993; Tarnocai, 1998). Much of the terrestrial C of these regions is stored in soils, particularly in areas underlain by wetlands or permafrost (Gorham, 1991).

A closer examination of boreal forest systems reveals a hundredfold variation in soil C storage, ranging from about 3 to 5 kg C/m^2 in sandy, permeable soils to as much as 120 kg C/m^2 in well-established wetland peats (fig. 1). A recent evaluation of the long-term C accumulation on land (Harden and others, 2000) suggests that although net primary production varies threefold among these systems (Trumbore and Harden, 1997), C losses vary tenfold to a hundredfold, resulting in large variations in net C accumulation and storage. Variations in decomposition rates have been evaluated for temperature (Trumbore and others, 1996) and nutrient gradients (Bubier, 1995) within boreal systems. However, a recent evaluation of fire and decomposition along a soil-drainage gradient emphasized the role that wetness plays in protecting C stocks from fire (Harden and others, 2000). In general, northern soils are accumulating carbon (net ecosystem production is positive) and fall below the "steady state" line (fig. 2). Soils that are well drained, with rapid decomposition rates (turnover, <10 years; Trumbore and Harden, 1997), have relatively low ground fuels and burn emissions (fig. 2). In wetland soils that are very poorly drained, not only are decomposition losses low, but also average burn emissions are low because of sustained, high water tables. Between these two extremes, soils that are intermediate in drainage have the potential for large amounts of ground fuels and high fire emissions. During normal fire years, these systems may lose significant amounts of C to fire relative to their drier or wetter counterparts.

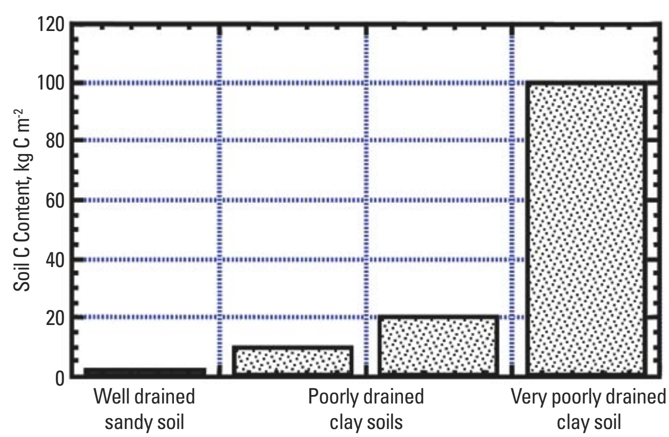

Figure 1. Soil C storage in soils of different drainage classes (Harden and others, 1997), based on data from soils of northern Manitoba, Canada. Well-drained soils are covered by jack pine and lichen, poorly drained soils covered by black spruce/feathermosses and black spruce/sphagnum mosses, and very poorly drained soils are covered by brown mosses and sedges.

Because significant amounts of C are stored in deep organic layers, unusually dry periods have the potential to expose very large C stocks to severe fires. In contrast, periods of wet summers could result in higher C storage and low emissions.

We hypothesize that large-scale patterns of fire are partly controlled by soil drainage and that permafrost-laden systems are particularly “elastic” in their ability to store, release, and sequester carbon onto land (fig. 2). This elasticity is derived from the unique thermal-moisture relations that govern peatland and wetland occurrence (Halsey and others, 1997). This hypothesis motivated us to extract spatial information on soil drainage in Alaska. For evaluation purposes, we compared a spatial overlay of fire history as a first test of our hypotheses.

Methods

Analysis of soil drainage is based directly on the U.S. Department of Agriculture’s Natural Resource Conservation Service (NRCS) 1:1,000,000-scale soil map of Alaska (Rieger and others, 1979), available through the State Soil Geographic (STATSGO) Alaska data base (Natural Resource Conservation Service, 1991). Soil-drainage classes were assigned by NRCS soil scientists to subunits within each soil-mapping unit on the basis of field observations during the soil survey. Field observations included both soil-wetness state or depth to water table in soil pits and soil-morphologic properties that are associated with dry or wet soils. Wetness must be inferred from soil morphology because soil wetness can vary greatly over time, such that one-time observation of wetness may not be representative. The main soil morphologic properties used to infer wetness conditions include the presence or absence of features that are produced by biochemical reduction of Fe and other elements; accumulation of organic matter at the surface due to restricted decomposition under water-saturated conditions; and the permeability of soil layers, which indirectly indicates water retention. Although landscape properties, such as vegetation and topography, aid the soil scientist in delineating the extent of a given soil, the decisive criteria in assigning drainage classes are soil morphology and observations of the soil-wetness state. In the STATSGO Alaska data base, the properties of soil-drainage classes can be summarized as follows; the sources used include unpublished NRCS guidelines and the STATSGO data base itself.

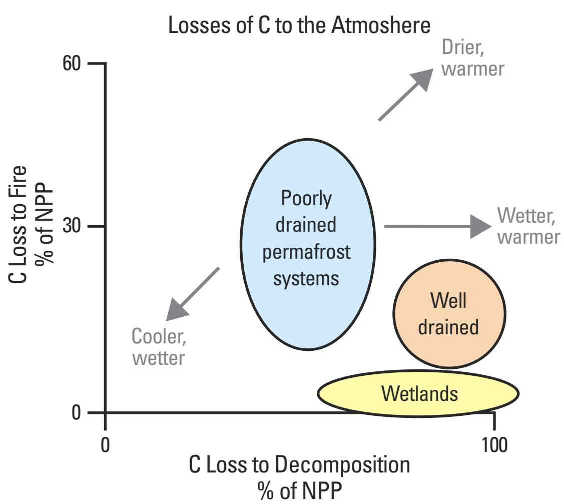

Figure 2. C losses to fire and decomposition for soils of different drainage classes, and conceptualizations of sensitivity to climate change, based on data and models of Harden and others (2000). Climate-change sensitivity is based on the logic that wet periods would favor suppression of fire and cold periods would favor suppression of decomposition. Poorly drained soils, particularly those with shallow permafrost, are conceived as most “elastic” or sensitive to climate change because of changes in active-layer thickness, perched water table, and sensitivity of fire severity to permafrost depth.

Excessively drained.—Excessively drained soils are almost exclusively coarse-grained Entisols, with very high permeability, little horizon development, and no redoximorphic features (reduced colors).

Somewhat excessively drained.—Somewhat excessively drained soils are mostly not represented in the STATSGO data base (2 out of 1,664 records).

Well drained.—Well-drained soils include a wide variety of morphologies (Inceptisols, Andisols, Spodosols, Entisols), but their common property is no to very weak redoximorphic features within 75 cm of the surface and a thin (<20 cm thick) surface organic layer. Saturation of the soil above 75-cm depth can occur, but it must be brief (<2 weeks per year). Some of these soils have permafrost, but it does not result in a wet soil for various reasons: the soils thaw deeply (generally >1 m deep), are generally coarse grained or shallow over bedrock, and are mostly on steep slopes.

Moderately well drained.—Moderately well drained soils are mostly not represented in the STATSGO data base (2 out of 1,664 records; some mixed moderately well drained and other soils are listed, but only a few).

Somewhat poorly drained.—Somewhat poorly drained soils generally show some morphologic effects of wetness in the form of reduced colors above 75-cm depth, and saturation at 50- to 75-cm depth can be prolonged. However, the surface organic layer is still thin (<20 cm thick), and any saturation above 50-cm depth should be brief (<2 weeks), including soils with and without permafrost. In soils with permafrost, some factor, such as coarse texture or slope, prevents continuous perching of water high in the profile; in the soils without permafrost, fine texture and (or) landscape position causes the soil to be wet part of the year.

Poorly drained.—Poorly drained soils generally show strong morphologic signs of wetness—dominantly, reduced colors above 50-cm depth, and in some soils a thick (max 40 cm) surface organic layer. Saturation is prolonged at 25- to 50-cm depth but brief (<2 weeks) above this depth. In northern and central Alaska, these soils generally have permafrost that thaws to about 50-cm depth in the summer; in areas that lack permafrost, other factors, such as fine texture, flat slope, and high regional ground-water table, keep the soils wet.

Table 1. Numerical-value assignments to Natural Resource Conservation Service soil-drainage classes.

[From Rieger and others (1979)]

Value	Soil-drainage class	Description
1	Excessively drained----------------	Very high hydraulic conductivity and low water-holding capacity, water table >2.0 m deep.
2	Somewhat excessively drained---	High hydraulic conductivity and low water-holding capacity, water table >2.0 m deep.
3	Well drained------------------------	Intermediate water-holding capacity, water table >2.0 m deep.
4	Moderately well drained----------	Low hydraulic conductivity, wet state high in profile, water table 1.0–2.0 m deep.
5	Somewhat poorly drained---------	Low hydraulic conductivity, wet state high in profile, water table 0.3–1.0 m deep.
6	Poorly drained----------------------	Saturated zone or layer of low hydraulic conductivity, water table <25 cm deep.
7	Very poorly drained---------------	Saturated, water table <30 cm deep throughout the year.

Very poorly drained.—Very poorly drained soils are saturated with water below 25-cm depth for at least 2 weeks per year and commonly longer—most of the growing season for many such soils. In Alaska, these surface soils have a surface organic layer that is at least 20 cm (commonly >40 cm) thick. Mineral soil, if present, is generally reduced. In northern and central Alaska, these soils commonly have permafrost and thaw 0.5 m or less each summer. In southern Alaska, the soils lack permafrost but are still organic and continuously saturated near the surface.

Data are organized by map unit in the STATSGO data base. A map unit is represented by one or more polygons on the map (Rieger and others, 1979) and has a single data set with many attributes. We selected the attributes rock, open water, and soil-drainage class to portray soil-drainage conditions, and converted the qualitative soil-drainage classes to numerical soil-drainage classes from 1 (excessively drained) to 7 (very poorly drained) (table 1).

A map unit may have as many as seven components or subunits, corresponding to spatially distinct areas with different soils. Although the locations of these subunits are not shown on the map (Rieger and others, 1979), the areal percentage of the component is represented along with its associated soil-drainage class. To quantify the composite drainage class of each map unit, we first subtracted the percentage of area represented by rock, ice, or open water, and then recalculated the proportional areas representing soil-drainage classes 1 through 7. To assign a single drainage value to each map unit, we multiplied each drainage rank by its proportional area and summed the products to represent the drainage in each polygon, according to the strategy of Rapalee and others (1999). The resulting soil-drainage map (fig. 3) displays only six broad soil-drainage classes, calculated from the relation

$$A = \frac{\sum (R * P)_{1 \ldots n}}{n}, \tag{1}$$

where A is the area-weighted soil-drainage class for each map unit, R is the soil-drainage class for each subunit within the polygon, P is the areal percentage of each subunit, and n is the total number of subunits.

Fire-History Maps

A data base for historical fire occurrence was developed from data of the Alaska Fire Service (Kasischke and Stocks, 2000; Murphy and others, 2000). The polygons of fire scars were digitized and registered, and the resulting file was converted to a grid format, using ArcInfo software, with 1-km grid-cell spatial resolution. The associated files (fire, drainage) were projected together, coregistered, and then reclassified according to burning (burned, unburned) and drainage (wet, dry).

Statistical Analysis

The size of soil-drainage polygons and the size of historical burns are generally quite large; for example, three or four burns account for most of the area burned in any given year. The average polygon size of fires, about 10,000 ha, is about one-sixth the size of the average polygon (~65,000 ha) of the soil map unit. As a result, the utility of comparing fire history and soil drainage on a detailed spatial or historical scale is limited to more general parametric approaches. To test whether fire and soil drainage are associated or collocated, we distinguished 1-km^2-area cells with soil-drainage values >5 (“wet”) from those with soil-drainage values <5 (“dry”), and distinguished cells that had burned since about 1950 from those that had not. Using a chi-square statistic, we tested for the null hypothesis of no correlation between burning and drainage class as follows. For the entire population of 1-km^2-area cells, we generated the observed frequency

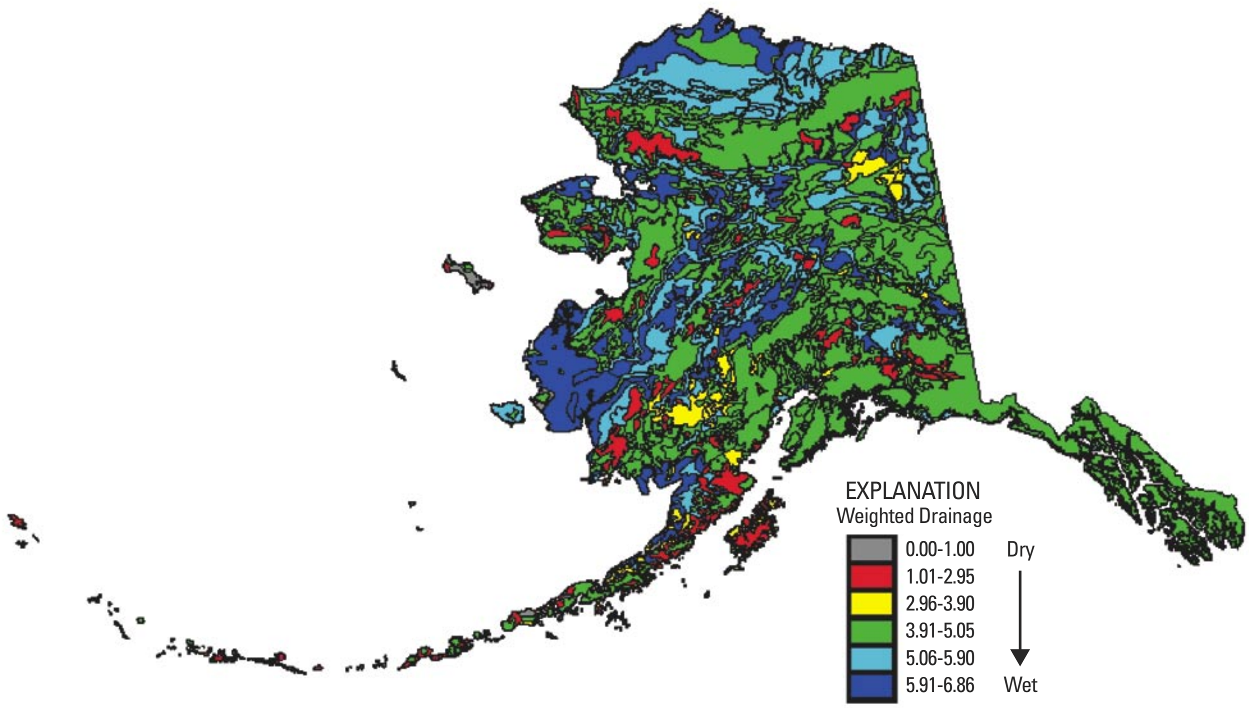

Figure 3. Soil-drainage map of Alaska (from Rieger and others, 1979).

of each unburned, burned, wet, and dry populations of cells. Then, for cells that burned, we generated a similar (expected) frequency of wet and dry populations as was found for the entire population. If a significant difference exists between the expected and actual populations, then the null hypothesis is rejected.

Results

About 40 percent of Alaska is composed of soils that are "wet" (soil-drainage class >5, figs. 3, 4). Many of these soils are likely to be underlain by shallow permafrost, as indicated by a wet state high in the soil profile (table 1). Wetlands (very poorly drained soils) represent about 10 percent of the nonrock, non-open-water cells (soil-drainage class 7, fig. 3). About 15 percent of Alaska is well drained, typically south-facing slopes or steep uplands or coarse-grained deposits with deep water tables. Much (~40 percent) of Alaska is "moderately well drained" (soil-drainage class 4–5). As noted above, few soils are actually rated as 4 (moderately well drained), and so a soil-drainage class of 4 for a polygon is obtained from a mixture of wetter and drier soil-drainage classes—mostly hilly or mountainous regions where soil drainage varies greatly with slope position (see fig. 1, where soil-drainage-class 4 areas occur in and near mountain ranges).

The statistical approach rejected the null hypotheses for the combination of drainage and burning (table 2), indicating a significant positive association between burned areas and wetter soil-drainage classes (fig. 5).

Discussion

Despite the huge, stand-killing fires that typify North American boreal forests (Stocks, 1993), a positive correlation exists between poorly drained soils and the extent of burning (table 2). Another conundrum of the association between wetness and burning is that on the basis of tree coring and stand-age histories in the Canadian Shield region, dry areas would be expected to burn more frequently, with fire-return intervals of 80 to 100 years in well-drained areas (Stocks, 1989) and of 150 to 200 years in more poorly drained stands (Stocks, 1980). Thus, we would expect drier areas to be positively correlated with fire occurrence, rather than wetter areas, as we found (table 2).

Our result probably stems from the fact that in interior Alaska, fire-return interval and fire occurrence may depend

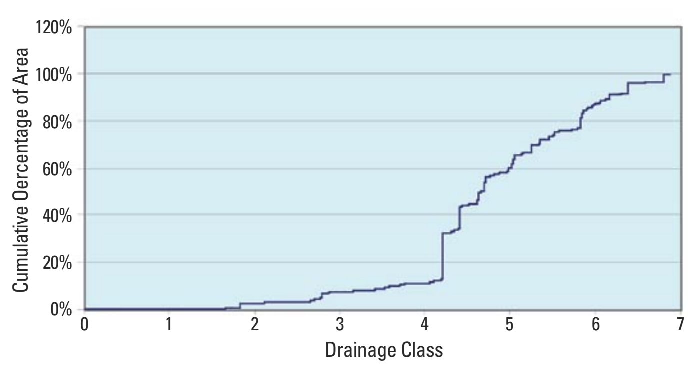

Figure 4. Percentage of map areas represented by soil-drainage classes, based on attribute tables of map subunits from Rieger and others (1979).

more on fuels and fire weather—the quality and quantity of organic matter—than on soil wetness. For example, highly flammable fuels can accumulate on wet soils, and under the right conditions, these wetter areas burn, as in the Alaskan taiga, where highly flammable black spruce and feathermosses commonly grow on wet soils. In addition, an important effect of large fires and severe fire weather may not be well reflected by the fire-return intervals calculated from stand ages. For example, historical data (Murphy and others, 2000) show that most of the burning within a given decade occurs during a single high-fire year, as is supported by climate analyses of fire weather (Hess and others, 2001). Regrowing vegetation and its influence on recurrent burns are also important. Manies and others (this volume) report that although "fire mosses" regenerate quickly after fire, feathermosses and ground fuels take at least 20 years to produce a "dead moss" layer. Also, many stands pass through a longer stage of less flammable deciduous cover before returning to more flammable evergreen vegetation (Viereck, 1975; Foot, 1983).

Conclusion

From the perspective of the long-term C budget of soil C studies, the greater long-term C storage in wetter soils suggests that because fire occurrence (return interval) is higher for "wetter" than drier soil types, fire severity (total combustion losses) must be lower for wet than for dry systems. This

Table 2. Chi square tests on colocation of burning and wetness.

[Low *P* value indicates a positive correlation between "wet" soils and historical burning, where "burning" is defined as having burned since 1950 and "wetness" is defined as a soil-drainage class >5 ("wet") or <5 ("dry"). df, degrees of freedom]

		Burned		
		Yes	No	row marginals
Drainage	>5	75746	527793	603539
	<5	54548	843175	897723
	col marginals	130294	1370968	1501262
	Expected =	52380.9	551158.1	
		77913.1	819809.9	
	Fo - Fe =	23365.1	-23365.1	
		-23365.1	23365.1	
	(Fo-Fe)^2/Fe =	10422.2	990.5	
		7006.9	665.9	
	Chi sq =	19085.5		
	df =	1.0		

Chi Squared critical at .05 with 1df is 3.84

For df=1, the calculated value of chi-sq is corrected for continuity

Corrected Chi sq = 19084.7

p = < 0.0001

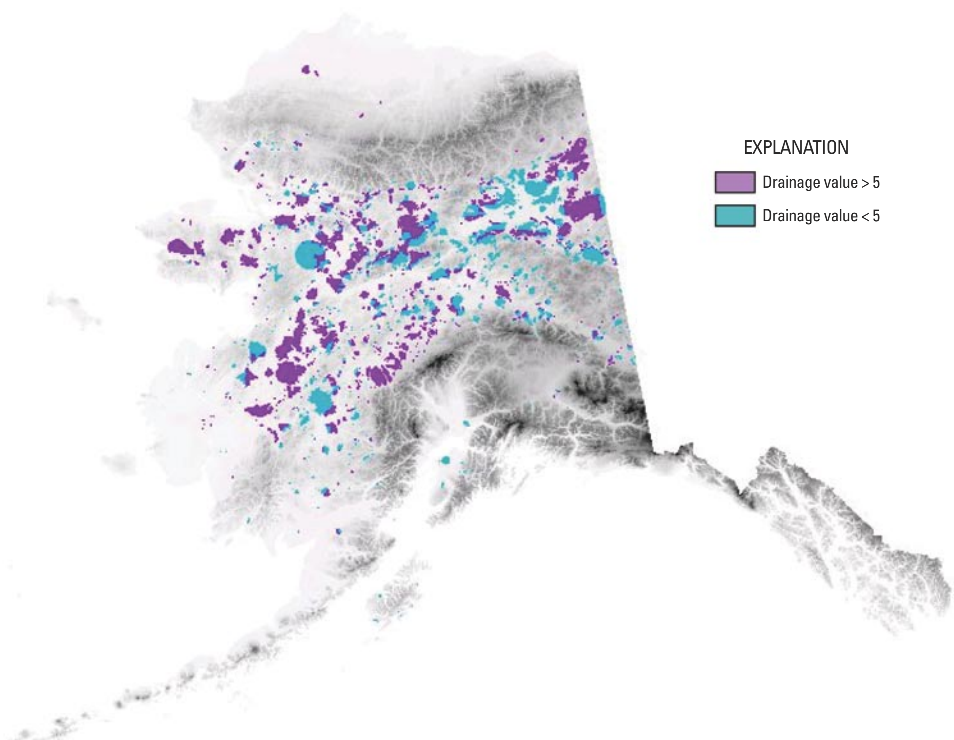

Figure 5. Alaska, showing locations of fire-scar areas (1950–97) that are underlain by two classes of soils: well to moderately well drained (drainage classes <5) and poorly draiend (classes >5) soils, which include soils underlain by shallow permafrost.

argument stems from the observation that net primary production and decomposition losses are more similar in magnitude than deep C contents of wet and dry soils (Harden and others, 2000). Permafrost in these wet soils may play a central role in limiting fire severity to shallow layers (see Swanson, 1986), while also allowing large fuel buildup and large fires to occur. To date, the data on fire severity, combustion losses, climate change and spatial variability, and soil-drainage class are insufficient to separate these factors.

Climatic shifts will influence the control of fire by soil drainage, first and most rapidly by influencing fire weather and secondarily and more gradually by affecting long-term water tables and active layers (fig. 2). Whereas some attributes of soil drainage, such as permeability and elevation, are stable in the climatic environment, other attributes, such as depths to the active layer and water table, are responsive to climate change. If climate change were to lead to greater extremes in extreme drought, the likelihood of wetlands burning greatly increases. In the future, new perspectives are needed to explore the interactions between fire-weather patterns and landscape drainage patterns, vegetation- and fuel-buildup associations, and fire extent and severity.

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