

Decreased water flowing from a forest amended with calcium silicate

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Contributed by Gene E. Likens, February 21, 2013 (sent for review March 23, 2012)

Acid deposition during the 20th century caused widespread depletion of available soil calcium (Ca) throughout much of the industrialized world. To better understand how forest ecosystems respond to changes in a component of acidification stress, an 11.8-ha watershed was amended with wollastonite, a calcium silicate mineral, to restore available soil Ca to preindustrial levels through natural weathering. An unexpected outcome of the Ca amendment was a change in watershed hydrology; annual evapotranspiration increased by 25%, 18%, and 19%, respectively, for the 3 y following treatment before returning to pretreatment levels. During this period, the watershed retained Ca from the wollastonite, indicating a watershed-scale fertilization effect on transpiration. That response is unique in being a measured manipulation of watershed runoff attributable to fertilization, a response of similar magnitude to effects of deforestation. Our results suggest that past and future changes in available soil Ca concentrations have important and previously unrecognized implications for the water cycle.

Transpiration by trees represents a major loss of water from forested watersheds (1–4) that is sensitive to forest nutrition (5–9). Plot-scale chemical amendments to forest soils can result in 16–155% increases in transpiration during the first 60 d to 11 mo (5–9), yet it is unclear how these responses are expressed at the whole-watershed scale over longer periods. The magnitude of change in transpiration at the plot scale suggests that water yield from forested watersheds may be impacted by forest nutritional status. Watershed-scale soil amendments present a unique opportunity to improve understanding of hydrologic changes resulting from altered forest nutrition because of their larger scale and often more detailed and accurate water budgets.

Calcium (Ca) is an essential plant nutrient. For trees in particular, Ca is important for structural integrity and physiological functions, including cell division, cell-wall maintenance, stomatal regulation, and stress signaling and response (10). The importance of Ca supply for individual trees emerges at the ecosystem scale where Ca can limit forest primary production, influence forest nitrogen uptake, change cation exchange capacity, and alter other ecosystem dynamics (10–15). The critical role of Ca in forests has highlighted the need to understand better the consequences of available soil Ca depletion. Acid deposition has caused rates of Ca leaching to far exceed rates of replenishment through weathering and atmospheric deposition, making soil Ca loss a threat to long-term forest vitality in regions prone to acid deposition (13, 16–21).

In October 1999, a catchment-scale experiment was initiated at the Hubbard Brook Experimental Forest (HBEF) in the White Mountains of New Hampshire. (Fig. S1) to understand the biogeochemical and ecological consequences of the depletion of available soil Ca. The objective of the experiment was to restore soil Ca concentrations to preindustrial levels by applying finely ground and pelletized wollastonite at 1,062 kg Ca ha⁻¹ across an 11.8-ha watershed. Vegetation on Watershed 1

(W1) is dominated by multiaged, second-growth northern hardwoods with sugar maple (*Acer saccharum*), yellow birch (*Betula alleghaniensis*), and American beech (*Fagus grandifolia*) making up about 80% of the basal area. At the higher elevations, the forest canopy includes significant components of two coniferous tree species—red spruce (*Picea rubens*) and balsam fir (*Abies balsamea*)—along with deciduous paper birch trees (*Betula papyrifera* Marsh. var. *papyrifera*). The current forest has developed without further management since the end of the last major logging activity in 1917. A more recent disturbance occurred in 1998 when an ice storm caused localized structural damage to the forest. Most of the damage was restricted to an elevation band between 600 and 800 m (22), and by 2001 leaf area had recovered in affected areas (23). The forest was monitored before and after the 1999 wollastonite addition to evaluate biogeochemical, ecological, and physical responses.

Results

Here, we report on an unexpected alteration of the W1 water balance following wollastonite addition. Five months after wollastonite was applied, W1 evapotranspiration (*ET*; calculated as the difference between precipitation and runoff) (*Methods*) substantially increased relative to *ET* at the nearby hydrologic reference watershed (W3) at the HBEF (Fig. 1A). Other untreated watersheds at the HBEF did not show a similar *ET* response. The W1 *ET* deviations in 2000, 2001, and 2002 were 25%, 18%, and 19% higher, respectively, than mean annual *ET* before wollastonite addition. Cumulative daily *ET* deviation from the hydrologic reference watershed demonstrates that the W1 *ET* deviation occurred between March 2000 and May 2002 (Fig. 1B). The beginning of the hydrologic response in March 2000 coincided with the onset of the first substantial sapflow after the wollastonite treatment, suggesting that the Ca addition stimulated transpiration. Notably, the cumulative daily *ET* deviation ceased increasing in May 2002 and abruptly began decreasing thereafter, indicating less *ET* in W1 compared with W3. Previously at HBEF, catchment-scale *ET* deviations have occurred three times, each following experimental deforestation: at W2 (1965–1967), W4 (1970–1974), and W5 (1983–1984). The *ET* response to wollastonite reported here was of a similar magnitude to the changes that followed deforestation, and is unique in being a report of a runoff decrease induced by alteration of a nutrient cycle (Fig. 1A).

Author contributions: S.W.B., C.T.D., T.J.F., and G.E.L. designed research; J.J.B., C.T.D., T.J.F., L.C.L., G.E.L., and S.V.O. performed research; M.B.G., A.S.B., J.J.B., T.J.F., L.C.L., and S.V.O. analyzed data; and M.B.G., S.W.B., J.J.B., J.L.C., C.T.D., T.J.F., L.C.L., G.E.L., S.V.O., and P.G.S. wrote the paper.

The authors declare no conflict of interest.

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This article contains supporting information online at www.pnas.org/lookup/suppl/doi:10.1073/pnas.1302445110/-DCSupplemental.

Fig. 2. Time series of streamwater and soil water in W1 (A) Si concentrations, (B) Ca concentrations, and (C) Ca:Si ratios.

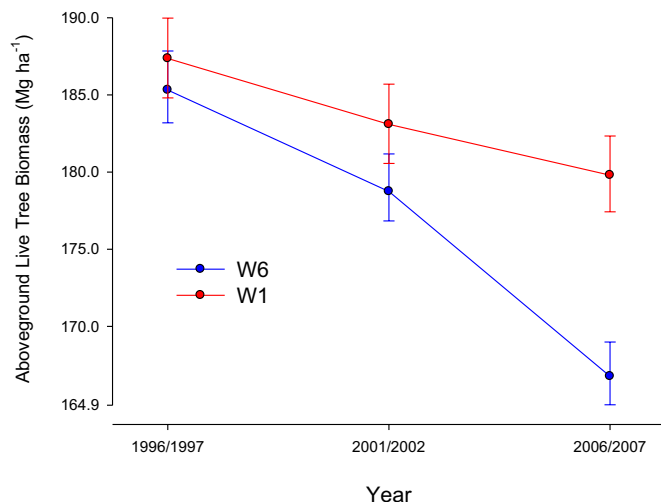


Fig. 5. Trends in aboveground live tree biomass in W1 and W6 for all trees ≥ 10 cm in diameter at breast height (1.37 m). Mean values with 95% confidence intervals shown.

acquisition and improved transport capacity within trees because greater xylem growth would make transpiration-induced leaf-water deficits less likely or less intense. Persistent *ET* deviation throughout the fall and winter suggests a significant response of coniferous species to Ca fertilization. The health and foliar function of red spruce, the dominant conifer on W1, was notably improved by Ca addition there (29, 33, 34), and this species is known to photosynthesize and transpire on a year-round basis given favorable environmental conditions (40). Deficiencies of Ca impair guard cell physiology in red spruce (41), thus the Ca from wollastonite likely improved stomatal function and enhanced winter transpiration.

Other studies have shown that fertilization can stimulate forest transpiration (5, 38–41), including fertilization by Ca (41); however, the impact on hydrology at this spatial and temporal scale has not been witnessed previously. The watershed-scale response to fertilization demonstrates that ecosystem available Ca can be depleted to levels where it becomes physiologically limiting not only to specific plant populations but also to the biogeochemical functioning of the watershed. Our results demonstrate that under conditions of Ca depletion, a substantial increase in available soil Ca can stimulate uptake and primary production, and thereby alter forest hydrology. However, questions remain about whether a proportional decrease of available soil Ca would cause a proportional decrease in *ET*. If so, the 20th century depletion of available soil Ca from acid deposition may

have caused a corresponding decrease in *ET* and increase in streamwater yield, whereas forest recovery from acid deposition may show a decrease in water yield.

The *ET* change in W1 was apparent in stream flow [because *ET* is calculated as the difference between precipitation and stream flow (42)], which is significant because it demonstrates that a transpiration response to fertilization can have a profound effect on a part of the hydrologic cycle that humans most readily interact with: flowing water. As the human need for carbon sequestration, biofuels, and other forest products increases, fertilization becomes a more likely tool to maintain or enhance forest productivity. Unintended forest fertilization is already occurring because of enhanced atmospheric CO₂ concentration and nitrogen deposition (43, 44). Whether intentional or unintentional, alleviation of limiting factors to forest productivity will likely broadly alter the water-provisioning ecosystem service (45), which must be recognized as a trade-off for the enhanced ecosystem services provided by fertilization.

Methods

Watershed scale *ET* was estimated by subtracting runoff from precipitation, which assumes that groundwater exchange and interannual water storage is negligible (42). Interannual *ET* dynamics were demonstrated by calculating annual scale *ET* deviations from W3—the hydrologic reference watershed—and subtracting the median annual *ET* deviation of a watershed from W3 for the entire monitored record (so that the *ET* deviation varied around zero). Finer-scale *ET* dynamics were analyzed by calculating the cumulative daily *ET* deviation from W3 beginning in January 1, 1990. Streamwater sampling, soil water sampling, foliar sampling, laboratory chemical methods, and above-ground biomass determination are described in detail by previous authors (38, 46–49). The composite soil water curve was produced with all soil lysimeter data (13 lysimeter plots) by calculating the daily running median Si and Ca concentrations and Ca:Si ratios with a 365-d moving window (Figs. S2 and S3). The LAI data were collected by measuring the area of freshly fallen leaves (50). The median LAI for three W1 plots was subtracted from the median LAI for seven reference plots to calculate the deviation of W1 LAI from the reference. Statistical significance of LAI differences between W1 plots and reference plots were assessed with a two-way ANOVA with year and treatment as the variables.

ACKNOWLEDGMENTS. We thank Don Buso for calculating Ca application rates in wollastonite; Don Buso and Tammy Wooster for collecting stream-water chemistry samples; Cynthia Wood and Alexis Heinz for field collection and analysis of leaf area index; Chris Eagar for use of the foliar Ca data; and Lawrence Band, Rob Jackson, and Nathan Phillips for critical reviews of this paper. Data used in this work were obtained by scientists of the Hubbard Brook Ecosystem Study. The Hubbard Brook Experimental Forest is operated and maintained by the Northern Research Station, US Department of Agriculture, Newtown Square, PA. The Watershed 1 experiment was funded by the National Science Foundation Ecosystem Studies program. Collection of long-term streamwater chemistry data were supported by the National Science Foundation, including the Long-Term Ecological Research and Long-Term Research in Environmental Biology programs and The A.W. Mellon Foundation.

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