

Attributes of Windthrown Trees in a Sierra Nevada Mixed-Conifer Forest

Kathleen Hilimire, Jonathan C.B. Nesmith, Anthony C. Caprio, and Rhett Milne

ABSTRACT

On Nov. 30 to Dec. 1, 2011, an extreme wind event affected the central Sierra Nevada mountain region of California, causing extensive windthrow of trees. The wind event was caused by an extreme pressure gradient from north to south over Nevada and the Sierra that was unusual for the region in its duration, atypical wind direction, and high-intensity wind. Within Devils Postpile National Monument, there were approximately 118.5 windthrown trees km^{-1} . The average diameter at 1.37 m of windthrown trees was 55.36 cm, 2.2 times greater than that for pre-windstorm standing trees. Trees differed in damage type; 86% of trees were uprooted, whereas 14% were snapped, and dead trees were more likely to snap than uproot relative to live trees. Tree species was not a factor in likelihood of windthrow because species composition and relative abundance of windthrown trees were representative of the preexisting forest composition. This wind event is the most extensive on record for California's Sierra Nevada range and may have long-lasting effects on forest composition and function.

Keywords: blowdown, infrequent forest disturbance, wind

Infrequent, large disturbances can have long-lasting effects on forest structure, species composition (Veblen et al. 2001, Woodall and Nagel 2007), and ecosystem processes (Foster et al. 1998). Wind, in particular, is a major determinant of forest structure and succession, both at the scale of the stand and of the landscape (Woodall and Nagel 2007, Xi et al. 2008). Infrequent, high-intensity wind events, therefore, can create long-lasting changes to forest structure, composition, and ecosystem processes in a relatively short period of time. Changes to forest structure and composition created by large wind events are controlled by multiple interactions between wind, topography, and prior forest structure (Veblen et al. 2001, Kulakowski and Veblen 2002). The resulting landscape may be characterized by greater fire risk, decreased canopy, and altered forest floor topography (Fraser 1962, Lindemann and Baker 2001, Woodall and Nagel 2007, Peterson and Leach 2008). Severe wind events are important drivers of forest structure and composition in eastern North America, affecting thousands of ha annually (Peterson 2000, Veblen et al. 2001). However, in the Sierra Nevada, these events are rare and have been largely undocumented.

On Nov. 30 to Dec. 1, 2011, an extreme wind event affected the central Sierra Nevada mountain region of California, causing extensive windthrow of trees. All Sierra Nevada national park units were affected, including Yosemite, Devils Postpile, and Sequoia and Kings Canyon, as well as large portions of Inyo National Forest. The wind event was caused by an extreme pressure gradient from north to south over Nevada and the Sierra and was unusual for the region in three ways: long duration, atypical wind direction, and high-

intensity wind. Extreme wind speeds lasted for 12 hours, from 6:00 pm to 6:00 am, with the strongest winds occurring from 10:00 pm to 4:00 am. Wind speeds at the nearest anemometer to the site of this study (Mammoth Mountain, California, at 3,369 m elevation and 4.5 km distance) recorded winds that exceeded 145 km hour^{-1} for the duration of the event, with gusts of at least 240 km hour^{-1} . Wind direction was strongly north-northeast with shorter periods of northeast and east winds occurring. Prevailing winds for this region are from the southwest, although strong east winds are not uncommon and typically occur several times per year. Although strong winds and blowdowns are not unprecedented for the Sierra region, the November/December blowdown was the most extensive on record.

The winds had a particularly strong effect in the Upper Middle Fork of the San Joaquin River drainage (UMFSJ) within Devils Postpile National Monument. The UMFSJ has a north-northeast orientation, and extreme channeling and acceleration of wind down the drainage led to extensive blowdown in Devils Postpile National Monument. The goal of this study was to use inventory data from National Park Service fire effects monitoring plots in combination with post-blowdown field data to summarize the characteristics of windthrown trees and assess pre- and post-blowdown forest structure in the UMFSJ. Specific objectives were to understand the relationship between tree size and wind damage by comparing diameter at 1.37 m (dbh) of pre-blowdown standing forest to dbh of windthrown trees, to assess factors associated with uprooting versus snapping caused by wind, and to compare vulnerability by species of the

Manuscript received August 24, 2012; accepted November 21, 2012. <http://dx.doi.org/10.5849/wjaf.12-027>.

Kathleen Hilimire (khillimire@fortlewis.edu), Devils Postpile National Monument, Mammoth Lakes, CA. Jonathan C.B. Nesmith (jonathan_nesmith@nps.gov), Sierra Nevada Network-National Park Service. Anthony C. Caprio (tony_caprio@mps.gov), Sequoia National Park. Rhett Milne (rmilne@sbcglobal.net), National Weather Service. This research was completed as part of the Natural Resources program at Devils Postpile National Monument, in association with partnership from Sierra Nevada Inventory and Monitoring Network. We thank Deanna Dulen, superintendent of Devils Postpile National Monument, for collaboration on this research. Thank you also to John Anderson, Visitor Protection Ranger at Devils Postpile National Monument, for assistance with field equipment.

This article uses metric units; the applicable conversion factors are: meters (m): 1 m = 3.3 ft; cubic meters (m^3): 1 m^3 = 35.3 ft^3 ; centimeters (cm): 1 cm = 0.39 in.; millimeters (mm): 1 mm = 0.039 in.; kilometers (km): 1 km = 0.6 mi; hectares (ha): 1 ha = 2.47 ac.

This article was written and prepared by a US Government employee on official time, and is therefore in the public domain and not subject to US copyright protection.

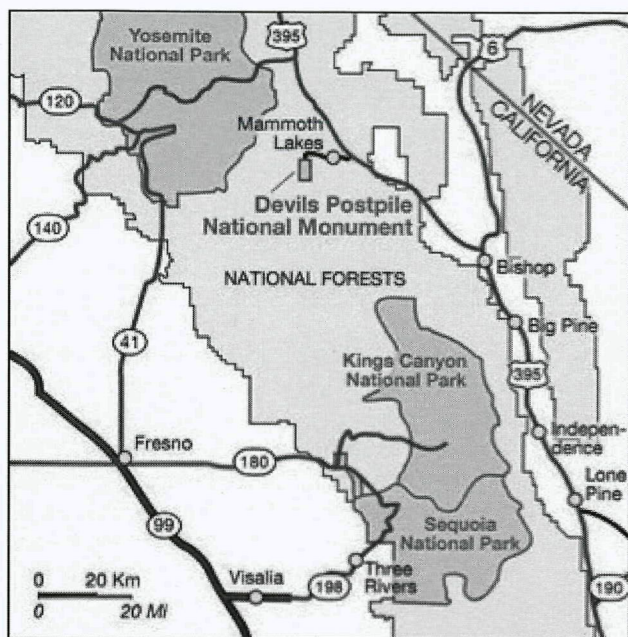


Figure 1. Map of Sierra Nevada region showing national parks and Devils Postpile National Monument (Universal Transverse Mercator zone 11, 315704E, 4166996N).

windthrow by assessing species composition of the forest before and after blowdown.

Methods

Research was conducted at Devils Postpile National Monument (Figure 1). The monument is 322 ha and is encompassed by the UMFSJ. Elevations range from 2,182 to 2,485 m. The monument is characterized by mixed-conifer forests, composed primarily of red fir (*Abies magnifica*), white fir (*Abies concolor*), and lodgepole pine (*Pinus contorta*; Caprio and Webster 2006). Jeffrey pine (*Pinus jeffreyi*) is also prevalent at lower elevations, whereas mountain hemlock (*Tsuga mertensiana*) and western white pine (*Pinus monticola*) are found at higher elevations (Caprio and Webster 2006). Soils are Typic Cryorthents (sandy with 35% or more coarse fragments of cinders, pumice, or volcanic glass; Entisols). Mean annual precipitation is 600–800 mm year⁻¹, most of which falls as snow (mean of 251–500 cm of snowfall year⁻¹; Davey et al. 2007).

Study sites were located in preexisting fire effects monitoring (FMH) plots to allow for a close comparison of forest attributes before and after the blowdown event. Plots were initially installed to assess the effects of fire on forest ecosystem processes and to detect trends over time (US Department of the Interior-National Park Service 2003). Eight FMH plots were installed in 1992 after the Rainbow Falls fire and were remeasured in 2002 with two additional unburned plots added in 2005. The 2002 and 2005 data, which included 390 live trees, were used to assess pre-blowdown forest structure and composition. Plots were distributed according to a stratified, random sample that placed two plots in high-severity burned areas, two in moderate severity areas, two in low-severity areas, and four in “control” sites unaffected by the Rainbow Falls fire. In May 2012, 100-m-long transects were established at each FMH plot that ran side-slope to the origin point of the plot ($n = 10$). Additional transects ($n = 3$) were also established to augment sample size. The location for additional transects was established by

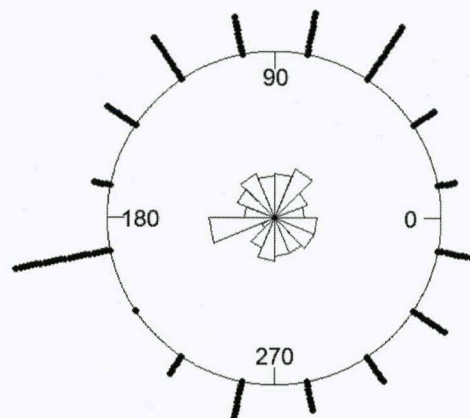


Figure 2. Distribution of fall angles of windthrown trees. Tree fall angles were grouped into 16 bins for plotting.

randomly locating sites within Devils Postpile using aerial photographs. The origins of these transects were in areas that burned at low severity in 1992. Along each transect, we used a line-intercept transect methodology to locate new windthrown trees. Trees were sampled if the bole root collar or above was under the transect tape and if the tree was ≥ 1.37 -m height. For each tree, we recorded fall angle (recorded as orientation of the tree from roots to tip), dbh, damage type (uprooted or snapped), pre-blowdown status (live or dead), and species. For dead trees, a determination of whether they were recently snapped or uprooted was made based on presence of weathering of the wood at the break, presence of freshly exposed soil, and position of the fallen tree in relation to duff and litter. Average volume per ha of windthrown trees was calculated using the equation

$$y_i \left(\frac{\text{m}^3}{\text{ha}} \right) = \frac{\pi^2}{8 \times L} \times \sum_{j=1}^{m_i} \frac{d_{ij}^2}{\cos \lambda_{ij}}$$

where L is transect length (m), m_i is the number of windthrown trees crossed by transect i , d_{ij} is the diameter (cm) of piece j crossed by transect i , and λ_{ij} is the angle from the horizontal of piece j where it crosses transect i (Marshall et al. 2000). The Raleigh test of uniformity was used to test whether fall angles differed from a uniform distribution, using the CircStats package (Lund and Agostinelli 2009) in R version 2.15.0 (R Development Core Team 2012). Generalized nonlinear mixed models (GNMMs), using a binomial distribution, were used to evaluate differences in damage type based on species, dbh, or pre-blowdown status (living or dead) (Gelman and Hill 2007). The lme4 package in R (Bates et al. 2011) was used for these analyses with an α level of 0.05.

Results

We sampled 154 trees across 13 transects (range = 0–40 trees/transect), resulting in a mean density of windthrown trees of 118.5 (SD = 104.6) trees km⁻¹. This corresponded to an average volume of windthrown trees of 959.3 (SD = 1480.3) m³ ha⁻¹. Mean fall angle was strongly south-southwest (north-northeast wind direction) at 202° (circular range = 302°) and differed significantly from a uniform distribution (Raleigh test of uniformity, $P < 0.001$; Figure 2). The average dbh of windthrown trees was 55.36 cm compared with the prestorm average dbh of 24.79 cm. This corresponded to average windthrown tree diameter being 2.2 times

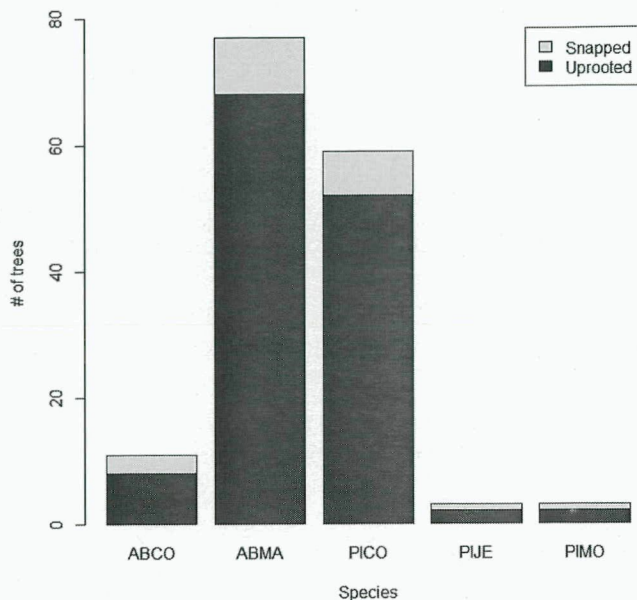


Figure 3. Number of windthrown trees that were uprooted or snapped as a function of species. ABCO, *Abies concolor*; ABMA, *Abies magnifica*; PICO, *Pinus contorta*; PIJE, *Pinus jeffreyi*; PIMO, *Pinus monticola*.

greater than pre-windstorm standing trees. Average dbh of windthrown trees in burned areas versus unburned areas was 47.1 cm ($n = 70$) and 62.1 cm ($n = 84$), respectively, compared with 39.4 cm ($n = 55$) and 22.4 cm ($n = 335$) of live trees in burned and unburned areas before the windstorm. Windthrown trees differed in damage type because 86% of trees were uprooted, whereas 14% were snapped. Species did not differ significantly in their susceptibility to damage type (GNMM, $df = 4$, $F = 1.018$, $P = 0.4$) because most species were more likely to uproot than to snap (Figure 3). There was also no relationship between dbh and damage type (GNMM estimate = 0.0023, SE = 0.0074, $P = 0.76$). Whether a tree was living or dead at the time of the windstorm was a factor in damage type; however, because standing live trees were far more likely to uproot than snap (GNMM estimate = -2.6814, SE = 0.6044, $P < 0.001$; Figure 4). Species composition and abundance of windthrown trees were representative of pre-blowdown stand composition and abundance (Figure 5).

Discussion

Our results are consistent with other studies that documented a strong relationship between tree size and amount of damage from windstorms (Peterson 2000, Canham et al. 2001, Veblen et al. 2001, Xi et al. 2008). Tree size may correspond to amount of wind damage because larger trees present more surface area to wind and may extend above average canopy height, increasing exposure to aerodynamic forces such as drag (Veblen et al. 2001, Wellpott 2008, Xi et al. 2008). By primarily affecting larger trees, windstorms are likely to have different affects on forest regeneration and function than other disturbances such as fire (Gandhi et al. 2008, D'Amato et al. 2011).

The type of damage trended strongly toward uprooting. Whether a stem is uprooted or snapped by wind has been attributed to precipitation, stem rot, tree species growth form, specific gravity of the wood, status (living or dead), slope, soil tension and shear,

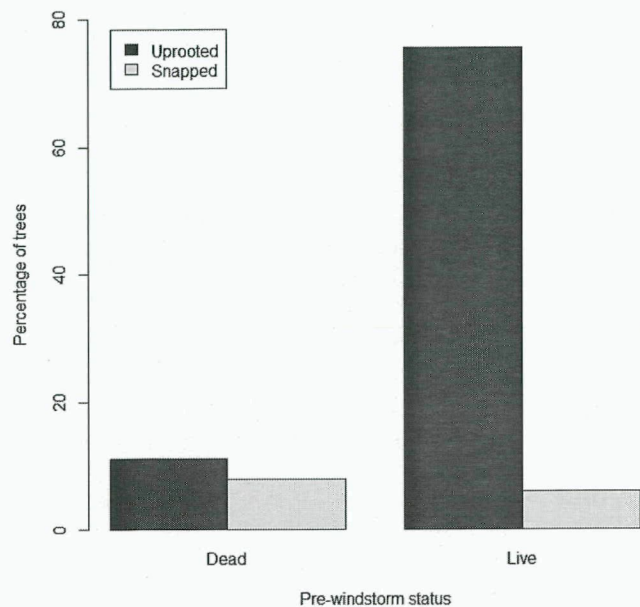


Figure 4. Percentage of windthrown trees that were uprooted or snapped as a function of pre-windstorm status (live or dead).

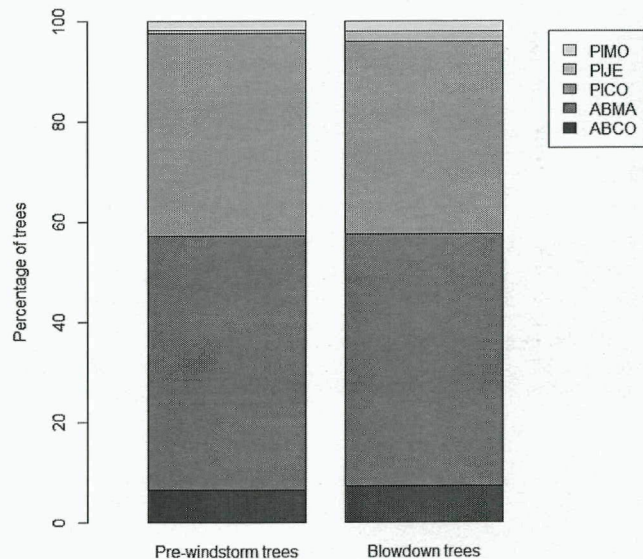


Figure 5. Species composition as a percentage of total number of trees from pre-windstorm FMH data and of windthrown trees. ABCO, *Abies concolor*; ABMA, *Abies magnifica*; PICO, *Pinus contorta*; PIJE, *Pinus jeffreyi*; PIMO, *Pinus monticola*.

root-soil resistance, and stem size (Everham and Brokaw 1996, Veblen et al. 2001, Nicoll et al. 2005, Peltola 2006, Xi et al. 2008). In this study, there was not a significant relationship between a tree being uprooted or snapped and dbh or species. Status (living or dead) at the time of the wind event did play a role in determining whether a tree would uproot or snap, however. Living trees were far more likely to uproot than snap, whereas snags were only marginally more likely to uproot than snap. Dead trees are more likely to snap than live trees because of more advanced rot and decay in the stem (Veblen et al. 2001). The type of wind damage (uprooted versus snapped) has important ecological implications for both wildlife and forest regeneration (Schaeztl et al. 1989). Uprooting can create mounds of exposed soil that can facilitate seedling establishment,

whereas snapping can create dead snags that are important habitat features for wildlife such as cavity nesting birds. The type of wind damage that occurs may be linked to properties of the disturbance event including wind speed and pre-blowdown environmental conditions, although these relationships appear to be inconsistent and are not clearly understood (Everham and Brokaw 1996).

Finally, there was no differential damage to a particular species in this event, meaning that the relative overall standing forest species composition and abundance were not substantially affected by the blowdown. However, given the edaphic, light, and bare-ground changes caused to the forest ecosystem by this blowdown, what successional trends will now occur remain to be seen (Woodall and Nagel 2007). This study describes the forest stand structure at time zero after this unusual windstorm. Implications for future forest structure and diversity remain to be understood and described.

Literature Cited

- BATES, D., M. MAECHLER, AND B. BOLKER. 2011. *lme4: Linear mixed-effects models using Eigen and Eigen*. R package version 0.999375-42. Available online at CRAN.R-project.org/package = lme4; last accessed Oct. 12, 2012.
- CANHAM, C.D., M.J. PAPAIA, AND E.F. LATTY. 2001. Interspecific variation in susceptibility to windthrow as a function of tree size and storm severity for northern temperate tree species. *Can. J. For. Res.* 31:1–10.
- CAPRIO, A.C., AND K. WEBSTER. 2006. P. 1–15 in *Fire effects monitoring of the 1992 Rainbow Fire, Devils Postpile National Monument: Vegetation response ten years postfire*. Division of Natural Resources, Sequoia and Kings Canyon National Parks, Three Rivers, CA.
- D'AMATO, A.W., S. FRAVER, B.J. PALIK, B.J. BRADFORD, AND L. PATTY. 2011. Singular and interactive effects of blowdown, salvage logging, and wildfire in sub-boreal pine systems. *For. Ecol. Manage.* 262:2070–2078.
- DAVEY, C.A., K.T. REDMOND, AND D.B. SIMERAL. 2007. P. 1–97 in *Weather and climate inventory*. Natural Resource Tech. Rep. NPS/SIEN/NRTR—2007/042. National Park Service, Sierra Nevada Network, Fort Collins, CO.
- EVERHAM, E.M., AND N.V.L. BROKAW. 1996. Forest damage and recovery from catastrophic wind. *Bot. Rev.* 62:113–185.
- FOSTER, D.R., D.H. KNIGHT, AND J.F. FRANKLIN. 1998. Landscape patterns and legacies resulting from large, infrequent forest disturbances. *Ecosystems* 1:497–510.
- FRASER, A.I. 1962. The soil and roots as factors in tree stability. *Forestry* 34:117–127.
- GANDHI, K.J.K., D.W. GILMORE, S.A. KATOVICH, W.J. MATTSON, J.C. ZASADA, AND S.J. SEYBOLD. 2008. Catastrophic windstorm and fuel-reduction treatments alter ground beetle (Coleoptera: Carabidae) assemblages in a North American sub-boreal forest. *For. Ecol. Manage.* 256:1104–1123.
- GELMAN, A., AND J. HILL. 2007. *Data analysis using regression and multilevel hierarchical models*. Cambridge University Press, New York.
- KULAKOWSKI, D., AND T.T. VEBLEN. 2002. Influences of fire history and topography on the pattern of a severe wind blowdown in a Colorado subalpine forest. *J. Ecol.* 90:806–819.
- LINDEMANN, J.D., AND W.L. BAKER. 2001. Attributes of blowdown patches from a severe wind event in the Southern Rocky Mountains, USA. *Landsc. Ecol.* 16:313–325.
- LUND, U., AND C. AGOSTINELLI. 2009. S-plus original by Ulric Lund, R port by Claudio Agostinelli. In *CircStats: Circular statistics, from "Topics in circular statistics" (2001)*, Jammalamadaka, S.R., and A. SenGupta (eds.). R package version 0.2-4. Available online at CRAN.R-project.org/package = CircStats; last accessed Oct. 12, 2012.
- MARSHALL, P.L., G. DAVIS, AND V.M. LEMAY. 2000. P. 1–34 in *Using line intersect sampling for coarse woody debris*. For. Res. Tech. Rep. TR-003, Ecology. Forest Service, Vancouver Forest Region, Vancouver, BC, Canada.
- NICOLL, B.C., A. ACHIM, S. MOCHAN, AND B.A. GARDINER. 2005. Does steep terrain influence tree stability? A field investigation. *Can. J. For. Res.* 35:2360–2367.
- PELTOLA, H.M. 2006. Mechanical stability of trees under static loads. *Am. J. Bot.* 93:1501–1511.
- PETERSON, C.J. 2000. Catastrophic wind damage to North American forests and the potential impact of climate change. *Sci. Total Environ.* 262:287–311.
- PETERSON, C.J., AND A.D. LEACH. 2008. Salvage logging after windthrow alters microsite diversity, abundance and environment, but not vegetation. *Forestry* 81:361–376.
- R DEVELOPMENT CORE TEAM. 2012. *R: A language and environment for statistical computing*. R Foundation for Statistical Computing, Vienna, Austria. Available online at www.R-project.org/; last accessed Oct. 12, 2012.
- SCHAETZL, R.J., D.L. JOHNSON, S.F. BURNS, AND T.W. SMALL. 1989. Tree uprooting: a review of terminology, process, and environmental implications. *Can. J. For. Res.* 19:1–11.
- US DEPARTMENT OF THE INTERIOR-NATIONAL PARK SERVICE. 2003. *Fire monitoring handbook*. Fire Management Program Center, National Interagency Fire Center, Boise, ID. 274 p.
- VEBLEN, T.T., D. KULAKOWSKI, K.S. EISENHART, AND W.L. BAKER. 2001. Subalpine forest damage from a severe windstorm in northern Colorado. *Can. J. For. Res.* 31:2089–2097.
- WELLPOTT, A. 2008. Critical wind speed estimates for individual trees from a field experiment. P. 55–77 in *The stability of continuous cover forests*. PhD Thesis. School of Geoscience, Univ. of Edinburgh, Edinburgh, UK.
- WOODALL, C.W., AND L.M. NAGEL. 2007. Downed woody fuel loading dynamics of a large-scale blowdown in northern Minnesota, USA. *For. Ecol. Manage.* 247:194–199.
- XI, W.M., P.K. PEET, J.K. DECOSTER, AND D.L. URBAN. 2008. Tree damage risk factors associated with large, infrequent wind disturbances of Carolina forests. *Forestry* 81:317–334.

Copyright of Western Journal of Applied Forestry is the property of Society of American Foresters and its content may not be copied or emailed to multiple sites or posted to a listserv without the copyright holder's express written permission. However, users may print, download, or email articles for individual use.