Development of a Norway Spruce Stand on a Gauged Watershed in the Fernow Experimental Forest, West Virginia

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Abstract

In 1973, a 55-acre watershed at the Fernow Experimental Forest (FEF) in West Virginia was planted with 2-0 Norway spruce (*Picea abies*) seedlings to evaluate the effects of conifers on streamflow and water quality. This conversion required considerable effort to ensure survival of the Norway spruce "island" in the sea of hardwoods. After nearly 50 years of tree growth and stand development, we report the impacts of the forest type conversion on stand and biomass development, water yield, water quality, soils, and nutrient cycling within the watershed. Conversion from hardwoods to Norway spruce resulted in significant decreases in annual water yield, relative to the reference watershed. Stream water quality was also significantly altered, with virtually no nitrate being detected in the stream water and a significantly lower stream pH, in contrast to the other FEF watersheds. The stream channel has also been altered. The forest floor in the spruce watershed exhibits an accumulated mass and increased carbon and nitrogen storage. However, mineral soil carbon and nitrogen storage are significantly lower relative to the hardwood reference. We discuss the implications of this unusual research project.

INTRODUCTION

Long-term watershed research studies allow scientists to evaluate the effects of manipulations over the lifetime of trees and forest ecosystems. Such research also improves understanding of ecosystem processes and their variability. In this paper we report on one such study conducted on the Fernow Experimental Forest (FEF) in West Virginia, where a gauged watershed was planted to Norway spruce (*Picea abies*) in 1973. We report on nearly 50 years of stand development, water yield, water chemistry, soil nutrients, and soil carbon (C) and compare the conifer watershed with a nearby native hardwood watershed of the same stand age. Conversion of native forests to planted conifer stands is a common anthropogenic landscape alteration. Understanding ecosystem biogeochemistry in these altered systems is necessary for management of ecosystem services and forecasting future ecosystem processes. Alterations to canopy architecture, litter chemistry and mass, and root exudation processes affect the chemical and biological processes in forest soils, which may influence ecosystem C and nitrogen (N) retention or loss.

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METHODS

Site Description

Watershed 6 (WS6) is a 22.34-ha, south-facing catchment located on the FEF. Prior to clearcutting in 1964 through 1969, the stand was mature second-growth mixed hardwood, and the dominant tree species were white oaks (*Quercus alba*) and chestnut oaks (*Q. montana*), with a basal area of 33.06 sq. m/ha (Patric and Reinhart 1971). Elevation ranges from 730 to 830 m. Soils in the watershed are mapped as Calvin channery silt loam (loamy-skeletal, mixed, active mesic Typic Dystrudepts), and as Cateache channery silt loam (fine loamy-mixed active, mesic Ultic Hapludalfs) (Adams et al. 2020).

Conversion from Hardwood to Conifer Species

A 120° V-notch weir was installed in November 1956 (weir coordinates 39.06612N, 79.67698W) and the initial calibration period occurred between November 1956 and February 1964. Between March and October 1964, the lower half of the watershed was clearcut, which removed 51 percent of the original basal area, followed by the removal of pulpwood and all other standing vegetation greater than 1 inch in diameter. Between May 1965 and October 1969, the lower half was maintained barren with herbicides (Patric and Reinhart 1971). Between October 1967 and February 1968, the remaining upper half of the watershed was clearcut, removing 49 percent of the original stand basal area. From May 1968 to October 1969, the upper half was also maintained barren with herbicides.

Natural regeneration occurred from 1970 to 1973, mostly from seed sources from the surrounding forest. During March and April 1973, 2-0 Norway spruce seedlings were planted at a 3.05 m × 3.05 m spacing, resulting in 1,077 trees/ha; however, notes in the study file suggest the trees were planted more closely than the original design.[2] Follow-up herbicide treatments in August 1975 and September 1980 were performed to release the Norway spruce trees from competing hardwood tree species, hay-scented fern (*Dennstaedtia*), and blackberry (*Rubus*) (Wendel and Kochenderfer 1984).

Stand growth and development were measured periodically during the next 50 years (Adams et al. 2020). Allometric equations for calculating aboveground and belowground biomass are described in Kelly (2010). Streamflow and stream chemistry were monitored routinely (Rau et al. 2022), and several studies of N and C biogeochemistry have been added (Kelly 2010, Kemner 2020). The nearby hardwood watersheds used for reference purposes (WS7 and WS4) are described in Adams et al. (2012).

RESULTS

Stand Development

The initial stocking survey in December 1975 found 1,371 live trees/ha (Adams et al. 2020). Repeated herbicide treatments allowed the Norway spruce trees to survive and develop. As measured in 2018, total spruce basal area was 39.2 sq. m/ha, and density was around 824 spruce trees/ha. By that point, a hardwood tree component had developed. Hardwood basal area was 4.1 sq. m/ha (9.5 percent of total stand basal area) and the hardwood tree density was 270 stems/ha (about 25 percent of spruce density; Fig. 1). The most common hardwoods in WS6 include yellow poplar (*Liriodendron tulipifera*), red maple (*Acer rubrum*), and black cherry (*Prunus serotina*).

[2] All study files and reports referenced are on file at the USDA Forest Service Timber and Watershed Laboratory, 459 Nursery Bottom Road, Parsons, WV 26287.

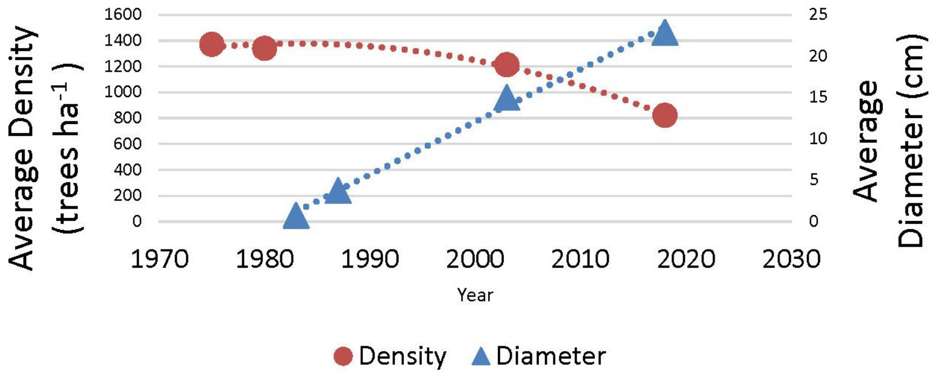

Figure 1.—Average density and diameter of Norway spruce on watershed 6, Fernow Experimental Forest, measured over time. Spruce trees were planted in 1973.

As measured in 2008, total aboveground biomass estimates were approximately 30 percent less in WS6 (116,800 kg/ha) relative to WS7 (166,000 kg/ha). Estimates of belowground biomass were approximately 45 percent lower in WS6 (21,000 kg/ha) relative to WS7 (38,000 kg/ha; Kemner 2020). Total biomass of both watersheds increased since 2008, though live tree biomass in WS6 increased more (136 percent) compared to WS7 (49 percent) as measured in 2020. However, total biomass values did not differ significantly between the watersheds (WS6: 260,471 kg/ha, WS7: 242,660 kg/ha; Kemner 2020).

Streamflow and Stream Chemistry

During the pretreatment period (1957–1964) stream discharge from WS6 (and WS7) closely followed the discharge of WS4, the long-term reference watershed. Discharge increased in WS6 and WS7 after harvesting and herbicide treatments relative to WS4 until the late 1980s (Fig. 2) (Rau et al. 2022). Beginning after 1994, annual discharge from WS6 decreased significantly relative to both WS4 and WS7. Analysis of seasonal stream discharge (growing season versus dormant season) revealed that dormant season discharge in WS6 decreased dramatically beginning in the late 1980s relative to both WS4 and WS7, and that growing season discharge declined faster in WS7 relative to WS6. Overall, the spruce vegetation has dramatically decreased stream discharge relative to the hardwood reference watersheds, especially in the dormant season.

One of the most striking trends is the absolute decline in N exports in stream water from WS6 (Fig. 3) (Kemner et al. 2020, Rau et al. 2022). This is a result not only of decreased streamflow volume—mostly due to changes in dormant season flows—but also decreased concentrations of nitrate (NO_3-N) in stream water. WS7, a 50-year-old hardwood stand, exports approximately 8 kg/ha/ year NO_3-N, while NO_3-N exports from WS6 have been nearly zero for almost 40 years (mean of about 0.6 kg/ha/year; Adams and Kochenderfer 2007, Kelly 2010, Kemner et al. 2020). Ammonium export is minimal, as it is from most FEF streams (Adams and Kochenderfer 2007, Adams et al. 1994, Kelly et al. 2011a) and dissolved organic N (DON) concentrations are also very low from WS6 relative to WS7 (Kelly 2010). Annual DON export from WS6 was also very low (mean of 0.48 kg ha/year).

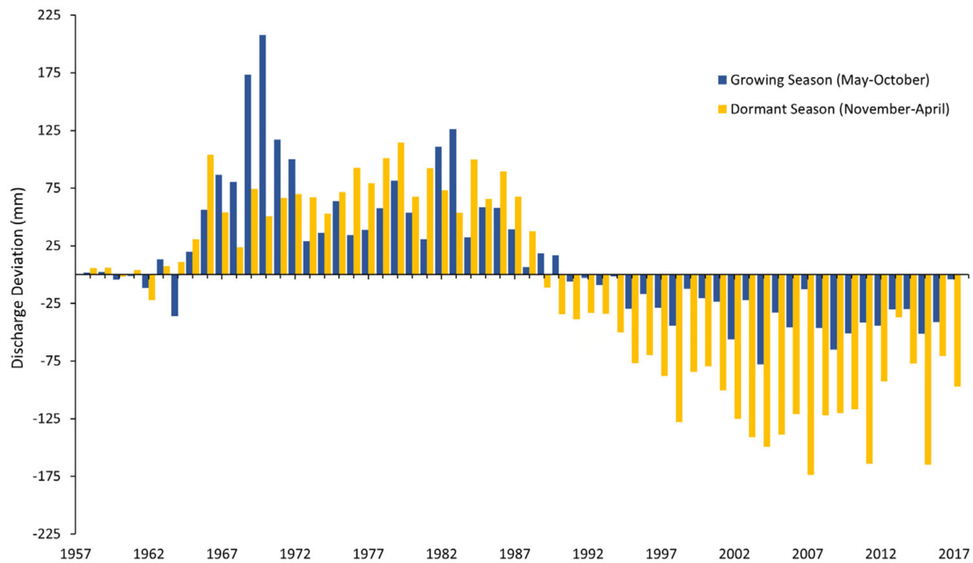

Figure 2.—Growing season and dormant season stream discharge from watershed 6, Fernow Experimental Forest, measured as the departure from the predicted discharge, 1960–2018. Watershed 4 was the reference watershed used to calculate the prediction equation.

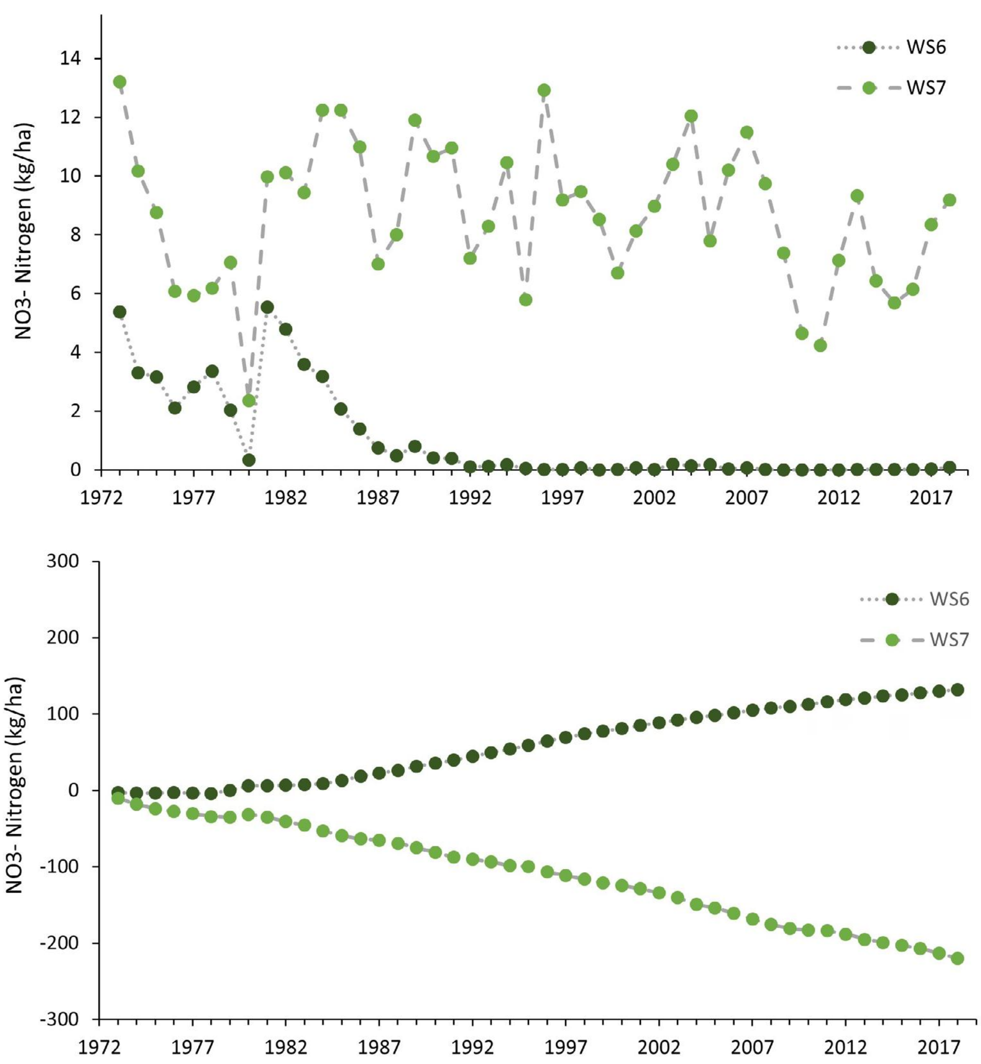

Figure 3.—Export of nitrate (NO_3-) nitrogen over time from watershed 6 (WS6; Norway spruce) and watershed 7 (WS7; hardwood reference), Fernow Experimental Forest, 1973–2018. Upper panel is annual export, and bottom panel represents a cumulative flux.

Soil Properties

The deforestation experiment had a nearly immediate impact on the soil, with most of the litter layer (L layer or Oi horizon, estimated at 2,300 kg/ha) removed by the end of the first year of devegetation (Troendle et al. 1974). The F+H (Oe+Oa) layer also appeared to decrease in depth, but the net weight of organic matter content remained consistent throughout the first 4 years. Roots in the upper 15 cm of soil decreased linearly during the 4 years, as did soil bulk density (rock-free). Carbon content (measured as loss on ignition) decreased in the A horizon, as did the infiltration rate (from 250 cm/hour to 50 cm/hour; Troendle et al. 1974).

However, Kelly et al. (2011a) described the forest floor (O horizon) of WS6 approximately 45 years after planting (2008) as a relatively thick horizon (2 to 8 cm) of nondecomposed needles (Oi) above further decomposed organic material of spruce origin (Oe+Oa). The forest floor C content in WS6 was 3.814 kg C/ha (Kelly 2010) and was significantly greater than that of the hardwood watershed (WS7; 2,343 kg C/ha). In 2020, forest floor biomass had increased in both watersheds, although to a much greater extent in WS6, and C content for WS 6 was 24,034 kg C/ha (Kemner 2020), almost 3 times the 8,322 kg C/ha in WS7.

In 2008, mineral soil from WS6 contained significantly less C and N than soil from WS7 in both A- and B-horizons (Fig. 4). For example, in 2008, A-horizon soil WS6 contained approximately 17 percent less C (kg/ha) than spruce soil from WS7, and also a smaller pool of N than WS6. Mean annual net nitrification rates were significantly less under spruce WS6: 4.2 kg NO_3-N/ha/year compared with 144.8 kg NO_3-N/ha/year under hardwood WS7 (Kelly 2010, Kelly et al. 2011b).

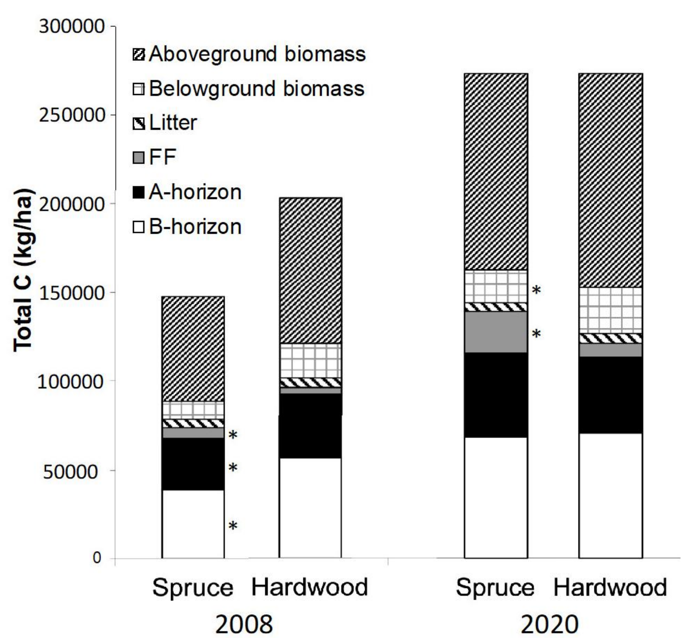

Figure 4.—Watershed budget depicting carbon (C) content contained within each soil and biomass compartment in the spruce (watershed 6) and hardwood (watershed 7) watersheds, Fernow Experimental Forest. Asterisks denote significant differences between watersheds in the associated pool in the respective year (α = 0.05) (Kemner 2020). FF = forest floor.

Rates of C and N accumulation changed, however, and by the 2020 assessment, no significant differences were detected in soil C or N content between watersheds in either soil horizon (Kemner 2020). Moreover, in the 2020 assessment, inorganic N content in WS6 as extracted from field-fresh soil is less than one-fifth the content in WS7 soil (WS6 = 0.97; WS7 = 5.3 mg inorganic N/kg soil; $p < 0.001$). When total inorganic N is separated into NO_3-N and NH_4-N pools, soil from WS6 has significantly less NO_3-N than soil from WS7 (WS6 = 0.25; WS7 = 4.3 mg/kg soil; $p < 0.001$), though there is no significant difference in extractable NH4-N between watersheds.

Soil aggregate distribution in WS6 exhibited a strong shift to dominance by micro-aggregates (53 to 250 μm and less than 53 μm) relative to soil from WS7), which was observed in both A- and B-horizons (Kemner 2020, Kemner et al. 2020). This may be a function of macro-aggregate dispersion via acidification of soil (A-horizon soil pH WS6 = 3.85, WS7 = 3.97; B-horizon soil pH WS6 = 4.03, WS7 = 4.16) and lower microbial activity and byproducts. Changes in aggregation are likely related to more recalcitrant litter, and acidic conditions in WS6 would result in decreased bacterial activity and therefore a greater proportion of organic matter occurring in larger aggregate size classes or as particulate organic matter unassociated with soil particles.

DISCUSSION

The Norway spruce seedlings planted on WS6 in 1973 have matured into a stand that approximates the level of productivity of the native hardwood forest above-ground and below-ground. We estimate crown closure occurred in the late 1990s or early 2000s, based on observations during our 2003 measurements. At that time, the stand was very dense, with little self-pruning having taken place little light hitting the forest floor, resulting in large populations and diversity of mushrooms (see Figure 5 in Adams et al. 2020). As the trees continued to grow and the stand developed, however, self-pruning occurred and more light reached the floor of the watershed; hardwoods began to grow as well. Currently, the stand on WS6 contains a little less than 25 percent hardwood stems (density). There is some evidence of spruce regeneration occurring, albeit limited (M.B. Adams, personal observation, July 2018).

The planted spruce also resulted in changes in the soil on the watershed, particularly related to C storage. The deforestation experiment prior to planting eliminated the forest floor (at least the Oi layer) from both WS6 and WS7, yet within a short period of time two distinctive forest floors had developed. The forest floor (O horizon) eventually accumulated significantly more C in WS6, relative to that in the hardwood WS7. The mineral soil in WS6 became more acidic, as a result of the uptake and leaching from the conifer litter. There were differences in other chemical and physical soil properties, including soil pH and aggregation. There is also evidence of a spodic E-horizon in some locations in the watershed (Kemner et al. 2020), which can be an important property linked to the presence of spruce (Nauman et al. 2015). All these changes point to significant alterations in C cycling and storage due to afforestation with spruce. Such changes were observed only after decades of tree growth and development, however. The results of other studies support these observations. Other research has reported that soils under conifer forests generally store more organic C throughout the soil profile compared to hardwood stands (Chiti et al. 2012, Nauman et al. 2015, Ohno et al. 2017). In addition, Diochon et al. (2009) showed that for red spruce, soil organic C stocks shrank during the first 45 years of stand development, but grew quickly after that point, similar to what has been observed on WS6.

Changes in C cycling will also alter the cycling of other nutrients. Our data show that the rate of N accumulation in the spruce watershed is accelerating in the most recent sampling relative to that of the hardwood system, and is likely linked with the rate of accumulation of C. There likely occurred a significant loss of both C and N immediately after conversion from hardwoods to Norway spruce, and as the stand on WS6 ages, this spruce watershed may store more biomass, C, and N relative to the hardwood forest of the same age. We are still unable to account for the large long-term discrepancy of N export from the two watersheds, however.

Finally, changes above-ground and below-ground had important implications for water use and water quality. Decreased annual stream discharge in WS6 relative to the hardwood watersheds is attributed to greater annual transpiration by the spruce and potentially less throughfall in the spruce vegetation. Although not measured, there was likely greater interception by the higher leaf area on the spruce watershed, with the possibility of greater evaporation back into the atmosphere, resulting in less water reaching the soil. A thicker forest floor on WS6, of more recalcitrant litter, also likely contributed to more water being held in the rooting zone of the spruce relative to the hardwood forest floor.

CONCLUSIONS

Despite the large investment required up-front to establish the Norway spruce stand on WS6, the current stand is productive and reasonably stable at 50 years of age, although native hardwood trees are again becoming more common. The species conversion, from hardwood to conifer, significantly altered the soil properties, water use, and biogeochemistry of the stand. More carbon is being stored in the conifer stand, which is encouraging in a world where elevated carbon dioxide threatens to lead to drastic changes in climate. Elevated carbon storage and evidence of spodic horizon podzolization have significance for land managers interested in restoring native red spruce to the landscape of the central Appalachians after 100 years of dominance of northern hardwoods. Considerations for water availability, carbon cycling, nutrient cycling, and costs of restoration should be included in all plans for species conversion, as the effects are likely to be slow to develop and long-lasting.

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LITERATURE CITED

Adams, M.B.; Edwards, P.J.; Ford, W.M.; Schuler, T.M.; Thomas-Van Gundy, M.; Wood, F. 2012. **Fernow Experimental Forest: research history and opportunities.** Experimental Forests and Ranges EFR-2. Washington, DC: U.S. Department of Agriculture, Forest Service. 26 p. https://www.fs.usda.gov/research/treesearch/41145.

Adams, M.B.; Kelly, C.; Simpson, B.; Juracko, J. 2020. **Growth and productivity of a 45-year-old Norway spruce plantation on the Fernow Experimental Forest.** Res. Note NRS-253. Madison, WI: U.S. Department of Agriculture, Forest Service, Northern Research Station. 11 p. https://doi.org/10.2737/NRS-RN-253.

Adams, M.B.; Kochenderfer, J.N. 2007. **Long-term stream chemistry monitoring on the Fernow Experimental Forest: implications for sustainable management of hardwood forests.** e-Gen. Tech. Rep. SRS-101. In: Buckley, D.S.; Clatterbuck, W.K., eds. Proceedings of the 15th Central Hardwood Forest Conference. U.S. Department of Agriculture, Forest Service, Southern Research Station: 97–106 [CD-ROM].

Adams, M.B.; Kochenderfer, J.N.; Wood, F.; Angradi, T.R.; Edwards, P. 1994. **Forty years of hydrometeorological data from the Fernow Experimental Forest, West Virginia.** Gen. Tech. Rep. NE-184. Radnor, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station. 24 p. https://doi.org/10.2737/NE-GTR-184.

Chiti, T.; Díaz-Pinés, E.; Rubio, A. 2012. **Soil organic carbon stocks of conifers, broadleaf and evergreen broadleaf forests of Spain.** Biology and Fertility of Soils. 48(7): 817–826. https://doi.org/10.1007/s00374-012-0676-3.

Diochon, A.; Kellman, L.; Beltrami, H. 2009. **Looking deeper: an investigation of soil carbon losses following harvesting from a managed northeastern red spruce (*Picea rubens Sarg.*) forest chronosequence.** Forest Ecology and Management. 257(2): 413–420. https://doi.org/10.1016/j.foreco.2008.09.015.

Kelly, C.; Schoenholtz, S.; Adams, M.B. 2011a. **Contrasts in carbon and nitrogen ecosystem budgets in adjacent Norway spruce and Appalachian hardwood watersheds in the Fernow Experimental Forest, West Virginia.** In: Medley, C.N.; Patterson, G.; Parker, M.J., eds. Observing, studying and managing for change—proceedings of the fourth Interagency Conference on Research in the Watersheds. Scientific Investigations Rep. 2011-5169. Reston, VA: U.S. Department of the Interior, Geological Survey: 121–126.

Kelly, C.N. 2010. **Carbon and nitrogen cycling in watersheds of contrasting vegetation types in the Fernow Experimental Forest, West Virginia.** Blacksburg, VA: Virginia Tech University. 126 p. doctoral dissertation. Available at: https://vtechworks.lib.vt.edu/handle/10919/26860 (accessed July 21, 2023).

Kelly, C.N.; Schoenholtz, S.H.; Adams, M.B. 2011b. **Soil properties associated with net nitrification following watershed conversion from Appalachian hardwoods to Norway spruce.** Plant and Soil. 344(1–2): 361–376. https://doi.org/10.1007/s11104-011-0755-5.

Kemner, J.E. 2020. **Stable aggregate dynamics and carbon storage in acidified forest soils: influence of atmospheric deposition and conifer conversion at the Fernow Experimental Forest.** Morgantown, WV: West Virginia University. 57 p. M.S. thesis. Available at: https://doi.org/10.33915/etd.7688 (accessed July 21, 2023).

Kemner, J.E.; Adams, M.B.; McDonald, L.M.; Peterjohn, W.T.; Kelly, C.N. 2020. **Fertilization and tree species influence on stable aggregates in forest soil.** Forests. 12(1): 39. https://doi.org/10.3390/f12010039.

Nauman, T.W.; Thompson, J.A.; Teets, S.J.; Dilliplane, T.A.; Bell, J.W.; Connolly, S.J.; Liebermann, H.J.; Yoast, K.M. 2015. **Ghosts of the forest: mapping pedomemory to guide forest restoration.** Geoderma. 247–248: 51–64. https://doi.org/10.1016/j.geoderma.2015.02.002.

Ohno, T.; Heckman, K.A.; Plante, A.F.; Fernandez, I.J.; Parr, T.B. 2017. **^{14}C mean residence time and its relationship with thermal stability and molecular composition of soil organic matter: a case study of deciduous and coniferous forest types.** Geoderma. 308: 1–8. https://doi.org/10.1016/j.geoderma.2017.08.023.

Patric, J.H.; Reinhart, K.G. 1971. **Hydrologic effects of deforesting two mountain watersheds in West Virginia.** Water Resources Research. 7(5): 1182–1188. https://doi.org/10.1029/wr007i005p01182.

Rau, B.M.; Adams, M.B.; Kelly, C.N. 2022. **Conversion of an Appalachian hardwood forest to a Norway spruce plantation: effects on hydrologic processes and function.** In: Latimer, J.S.; Bosch, D.D.; Faustini, J.; Lane, C.R., Trettin, C.C., eds. Enhancing landscapes for sustainable intensification and watershed resiliency—proceedings of the seventh Interagency Conference on Research in the Watersheds. Gen. Tech. Rep. SRS-264. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station: 132–133.

Troendle, C.A.; Aubertin, G.M.; Kochenderfer, J.N. 1974. **Decomposition of the forest floor following deforestation and annual herbiciding.** American Society of Agronomy Abstracts. (1974): 179.

Wendel, G.W.; Kochenderfer, J.N. 1984. **Aerial release of Norway spruce with Roundup in the central Appalachians.** Northern Journal of Applied Forestry. 1(2): 29–32. https://doi.org/10.1093/njaf/1.2.29.

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