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COARSE WOODY DEBRIS IN RIPARIAN CORRIDORS OF CENTRAL PENNSYLVANIA: HOW ABUNDANCE, CHARACTERISTICS, AND DYNAMICS VARY WITH ANTHROPOGENIC DISTURBANCE

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ABSTRACT

The wetlands and riparian corridors of North America's Mid-Atlantic Region (MAR) have been under constant and continuing pressure from anthropogenic settlement since before the arrival of the first Europeans on the continent. Disturbances related to human development have impeded the functioning of these ecosystems and reduced the quantity and quality of services they provide to society. An understanding of the detrimental effects of landscape alteration has grown within the past few decades, and in this relatively short period of time, a wealth of research has been compiled on how to reverse these effects through restoration. Floodplains, often heavily settled and modified, have been of particular interest as they provide valuable services such as flood attenuation, soil enrichment, and water storage. Within the context of floodplains, limited attention has been paid to coarse woody debris (CWD) and its role in the ecosystem. Historically, coarse woody debris has been removed from channels and riparian corridors by people for a number of reasons. It is now understood to be a crucial element of ecosystem architecture, and efforts are being made to characterize how CWD dynamics within the landscape affect functioning and service provisioning. Although a body of work on this subject has been produced in the Pacific Northwest of the U.S., there are still many questions that remain to be answered. This research utilizes data collected during rapid field assessments of habitat quality, in conjunction with intensive surveys of debris, to determine how anthropogenic disturbance influences debris abundances and characteristics in floodplain systems. This study was completed in the central Pennsylvania portion of the MAR, an area that, though heavily forested, has received little attention in debris studies. Results demonstrate that the greatest quantities of debris are associated with sites experiencing the least amount of anthropogenic disturbance, and that the debris found at these sites shows greater diversity in size than debris found elsewhere. A moderately-robust mathematical relationship was also established between debris counts and riparian forest basal areas, indicating that this measurement of habitat quality may be the best predictor of debris concentration. These findings have important implications for both ecological integrity and ecosystem service provisioning, and will hopefully enable land managers in the Mid-Atlantic Region to make informed choices regarding debris installations on their properties.

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INTRODUCTION

Wetlands as Disturbed Landscapes

The natural systems of the Mid-Atlantic Region (MAR), situated as they are in one of the most densely populated portions of North America, are under constant and continuing pressure from anthropogenic activities. In many cases, intense development has completely altered and fragmented the landscape. This is especially true of floodplains, which have been utilized by humans in this region since before the arrival of the first Europeans (Stinchcomb et al. 2011). Traditionally, colonial societies were thought to be the progenitors of both direct and indirect hydrologic modification of floodplains throughout the MAR. However, recent archaeological work has demonstrated that aboriginal Americans deforested eastern floodplains up to 500 years before the arrival of Europeans in an effort to intensify maize production (Stinchcomb et al. 2011). It is clear why both native and later societies valued these environments so highly, and why modern society continues to value them today. Often located in proximity to large, navigable bodies of water (e.g., rivers and estuaries), and possessing soils rich in nutrients and organic matter (Wei et al. 2002), these areas had and continue to have significant economic value. Cash crops can be grown in large quantities and transported with relative ease via the accessible waterways, which simultaneously enable long-distance trade in commercial goods. In this manner, floodplains serve as hubs of both agricultural and economic activity (Stinchcomb et al. 2011). As such, they are often densely occupied. Many of the world's major cities are located on either coastal or riverine floodplains.

Unfortunately, the same unique characteristics that make floodplains idealized centers of human activity often prevent intense development and utilization of these environments. Many floodplains of the eastern United States are (or were) naturally forested, impeding large-scale human settlements and leading to anthropogenic clearing, primarily for agricultural activities (Williams 1989, Sweeney 1992). Once cleared, the type of predictable cultivation required by industrialized societies was in many cases precluded by the frequent inundation resulting from relatively high water tables, while occasional intense flood flows presented significant threats of damage or destruction to buildings and infrastructure (Pinter 2005). Wet conditions have also historically, and perhaps somewhat erroneously, been associated by the public with disease and decay. Words such as “bog”, “swamp”, and “marsh” frequently carry negative connotations when found in popular literature, and mythical descriptions of wetlands frequently associate these landscapes with mischief or evil. It is, therefore, not surprising that potential inhabitants often sought to alter floodplain morphology and hydrology through clearing, draining, infilling, channelizing streams, and constructing levees (Williams 1989, Nelson et al. 1994, Detenbeck et al. 1999, Pinter 2005). These processes were thought to create a more “stable” environment, allowing for the establishment of agriculture and accompanying urban centers in some of the most fertile regions of the continent (Sweeney 1992, Pinter 2005).

Anthropogenic modifications like those highlighted above almost always carry a number of unintended and undesirable consequences, bringing about negative changes within floodplains (Sweeney 1992, Caraco and Cole 2001, Sweeney et al. 2004, Pinter 2005). Unaltered, floodplains are typically well-connected to their associated channels, and provide expansive areas over which flood waters can disperse. This facilitates the slowing of flood flows and the temporary storage of large quantities of water, reducing both the intensity of these events and the damage that might otherwise be wrought downstream (Krieger 2001). In many regions with dense human populations, reaches have been channelized or levees have been constructed as a means of confining flood flows to the channel. Although this is done with an eye toward protecting homes and other structures, disconnecting channels and floodplains frequently generates more intense downstream flooding events, as the energy is unable to dissipate as it would naturally within a vegetated floodplain. This increases local erosion and downstream sedimentation rates, and leads to significantly more damage than if the floodplain had remained undeveloped and the channel unaltered (Krieger 2001, Pinter 2005, Grygoruk et al. 2013). On a smaller scale, ditches and retention ponds may be constructed to control run-off, and microtopography can be eliminated to allow for ease of cultivation. These sorts of hydrological and morphological alterations can have myriad effects on the ecosystem by changing both local microtopography and ground and surface water flow regimes.

Hydrology and morphology may also be modified indirectly via the clearing of native vegetation (i.e., deforestation), which reduces surface roughness and allows flood waters to move unimpeded over the floodplain. With no vegetative cover for protection, soil easily erodes and downstream sedimentation rates increase (Krieger 2001). Conversely, the types of alterations to morphology and hydrology discussed above can exert some control over plant biodiversity. Many species of floodplain and wetland plants possess relatively narrow tolerances for environmental conditions, and human disturbance of the flooding regime, regardless of how minor, can preclude them from a given area (Hughes 1997). Additionally, there is potential for a concurrent loss in faunal diversity related to habitat homogenization and disappearance of critical plant species. These changes in faunal diversity have the potential to spur further shifts in the plant species composition for a given floodplain, perpetuating the feedback loop. Though alterations of this kind may seem inconsequential to the average person, a number of the species that stand to be affected perform essential functions (e.g., pollination, pest control) that, if lost, would result in significant economic costs (Krieger 2001).

Deforestation and physical modifications of floodplain systems can also alter nutrient cycling processes, potentially leading to decreased nutrient uptake capacity, resulting in downstream waters receiving increased loads (Caraco and Cole 2001). When combined with the quantities of nutrient-rich fertilizer applied to many of the agricultural lands that have replaced forested floodplains in the MAR, the loss of this valuable service is particularly devastating. Large quantities of nutrients move through the watershed, generating eutrophic conditions when they encounter lacustrine or estuarine conditions and become further concentrated (Caraco and Cole 2001). Eutrophication causes numerous additional problems, including algal blooms, plant and fish die-offs, and a dramatic shift in habitat availabilities (Carpenter et al. 1998).

Finally, the clearing of forested floodplains and the disappearance of the wetland environments they contain are associated with a reduced cultural and aesthetic value for many members of society (Krieger 2001). Individuals and communities may consider certain areas to be important for the natural beauty they possess, for the habitat they provide for endangered or game species, such as waterfowl, and for cultural heritage tied to the land in its undisturbed state (Krieger 2001). Though these values can be difficult to define, they should not be dismissed, as an increasingly important aspect of natural spaces is the feeling of beauty and connection they inspire in people. When infrastructure and agriculture replace natural floodplain morphology, these feelings are often compromised.

Ecosystem Services: A Primer

Humankind has long depended upon and valued floodplain ecosystems for the unique conditions they provide, qualities they possess, and functions they serve. Many cultures and societies continue to do so today, and the beneficial goods and services that they derive from these environments are collectively known as ecosystem services.

Although ecosystem services are not a new idea, and many naturalists, ecologists, and earth scientists have been speaking of their importance in a wide variety of settings for decades using varied terminology (Leopold 1966, Costanza et al. 1997), it is only recently that the general public and policy makers have truly begun to consider the ramifications of altering systems in a manner that impairs the provisioning of these services (Krieger 2001, Hairston-Strang 2010, De Steven and Lowrance 2011, Grygoruk et al. 2013, Ringold et al. 2013). This has largely been spurred by numerous efforts to quantify these services in economic terms, making them easier to compare to factors more commonly considered when valuing landscapes (e.g., potential profits from selective forestry in a given stand) (Costanza et al. 1997, Grygoruk et al. 2013).

There is, perhaps predictably, considerable ongoing debate surrounding the manner in which ecosystem services should be managed and considered, and how dollar values should be assigned (Krieger 2001, Light et al. 2013, Ringold et al. 2013). Discussion of ecosystem services has been added to both the natural science and social science dimensions of ecosystem study. With persistent and intense development pressures impacting many sensitive environments, it is important to determine the value of maintaining a natural state, and to communicate this value in a common language. This necessity drives the continued refinement of the ecosystem services concept. By conveying the potential economic value of an undisturbed ecosystem that might otherwise appear to be an opportunity not capitalized upon, those interested in conservation and restoration might find themselves successful in arenas where they would otherwise have failed against competing economic interests. Working to place dollar values on intangible qualities such as aesthetic beauty and cultural value, while simultaneously calculating disaster remediation costs avoided by allowing an unaltered floodplain to continue to attenuate flood flows (Grygoruk et al. 2013), allows those investigating ecosystem services to quantify the true worth of natural systems.

Many of the ecosystem services provided by floodplains are discussed in some detail above, including flood flow attenuation, sediment and nutrient storage, and the genesis of fertile soils (Caraco and Cole 2001, Krieger 2001, Wei et al. 2002). In addition, biodiversity and concurrent genetic diversity of hydrophilic flora and fauna must be considered, along with the potential cultural, spiritual, and intrinsic value of the undisturbed landscapes.

The Role of Coarse Woody Debris

In recent years, the growing understanding of and appreciation for the importance of ecosystem services within both the scientific community and the general public has led to a number of changes in management practices focused on maintaining or restoring natural form and function, with the goal of maximizing the value of these services. These new management practices have taken myriad forms, including efforts to retain coarse woody debris (CWD) in lotic and riparian ecosystems (Roni et al. 2015). Coarse woody debris is a blanket term used here in reference to all large pieces of dead and downed wood within a stream reach or its associated floodplain. The pieces can be highly variable in morphology, orientation, composition, and origin. In unaltered, “natural” locales, these pieces of debris enter the system via a number of processes, including floods, wind storms, landslides, and fallen snags (Maser et al. 1979). In systems disturbed or developed by humans, woody debris recruitment can also occur as a result of this disturbance (e.g., logging), or can be anthropogenic in origin (e.g., railroad ties) (Krejčí and Máčka 2012).

Formerly, it was considered to be best practice for land managers to remove CWD of all types from floodplains and channels. This belief was perpetuated for a number of reasons. First and foremost, CWD can become dangerous when mobilized during a flood, with the largest pieces (sometimes entire tree boles) capable of demolishing small bridges and other man-made structures. It can prove disruptive to recreational activities, acting as both a hazard and an obstacle for fishers, canoeists, and swimmers. Finally, any CWD located on the floodplain can potentially fuel forest fires, especially in drought years when the floodplain is less often inundated (Maser et al. 1979, Roni et al. 2015). With little apparent value in place, it seemed like a simple solution to clear CWD from a system and solve multiple problems at once. These types of management activities, combined with widespread logging throughout the 19th and early 20th centuries that reduced recruitment, left many ecosystems with a fraction of their historic quantities of CWD.

A significant body of research performed over the course of the last half-century has demonstrated that CWD and the processes surrounding it are important pieces of the floodplain environmental architecture, performing numerous vital functions and providing ecosystem services (Elton 1966, Maser et al. 1979). In the channel, both single pieces and logjams can influence channel morphology by widening reaches, diverting water into side channels, or creating plunge pools (Robison and Beschta 1990, Fetherston et al. 1995, Sweeney et al. 2004). Jams also disrupt flood flows, pushing large quantities of water laterally onto the floodplain and slowing the overall velocity, helping to prevent downstream scouring and the transport of heavy sediment loads (Nakamura and Swanson 1993). Coarse woody debris deposited on the floodplain slows and stores flood waters, creating unique microclimates and helping recharge groundwater. Debris also stores significant quantities of carbon in both temperature and tropical forests, and represents a critical component of normal carbon cycling in many ecosystems. (Jomura et al. 2007, Iwashita et al. 2013)

Logs and jams, both in the channel and on the floodplain, provide critical habitat for aquatic and terrestrial species from a number of guilds (Graham 1925, Maser et al. 1979, McCay 2000, Greenberg 2002, Roni et al. 2015). The most frequent uses seem to be for cover, reproduction, and feeding (Maser et al. 1979, McCay 2000, Greenberg 2002), although uses vary among clades depending upon CWD characteristics (location, decay class, size) (Bowman 2000). Even if CWD does not necessarily provide habitat for species that would otherwise be absent (i.e., doesn't increase biodiversity), it has been shown by some studies to improve habitat quality and increase local concentrations of species already extant (i.e., increases species' abundance) (Loeb 1999). Although some work has countered these conclusions (Bowman 2000), numerous other studies have demonstrated that locales harboring reduced quantities of dead and downed woody debris have significantly reduced diversity and abundance of both avifauna and invertebrates (Riffell et al. 2011). At the same time, intense concentrations of debris can impede the movement of larger organisms on which humans rely (e.g., cattle, horses), which may be yet another reason why downed wood was historically removed from floodplains (Maser et al. 1979).

The presence of coarse woody debris also generates a number of unique nutrient cycling processes that would not occur without these ecosystem features. During decomposition, logs absorb and store large quantities of water and nitrogen. After moisture and nitrogen levels have become appreciably elevated above those found in recently downed wood, these logs serve as fertile ground for both fungi and seedling establishment. The fungi serve to further concentrate nutrients, while the seedlings provide for new growth on forested floodplains and increase habitat heterogeneity (Maser et al. 1979). Debris within the channel can also affect the manner in which nutrients move through a system. Past work has demonstrated that increases in CWD concentrations within channels can improve the uptake of nutrients, suggesting that systems with greater upstream quantities of CWD will experience reduced nutrient loading (Roberts et al. 2007). This is primarily a function of increased connectivity between the channel and the floodplain, and the increased residence time of water once it reaches the floodplain, both of which facilitate distributed uptake of nutrients.

With this renewed interest in CWD and the various ways it benefits both natural ecosystems and human societies, many studies have focused on refining our understanding of how CWD reaches the floodplain and the channel, and what forces control the downstream movement of these pieces once they have been recruited. In addition to those discussed above (e.g., Maser et al., 1979), debris can be generated via a number of natural and anthropogenic processes, including: beaver felling, bank erosion, input of wood products from nearby settlements (Krejčí and Máčka 2012), and artificial placement during restoration/mitigation projects (Roni et al. 2015), with natural inputs far outpacing anthropogenic sources. Numerous controls on movement within the channel and floodplain have also been investigated, including geomorphology, wood length, wood species (and associated density), channel depth, and flow velocity. Often, a combination of these factors dictates which pieces of CWD are mobile. Dixon and Sear (2014) highlighted a number of important controls on CWD movement, including an increase in mobility during periods of intense flow, an increase in mobility for conifer logs, and an increased variation in mobility in channelized versus well-connected systems. These researchers also demonstrated that likelihood of movement decreases with both increasing log length and diameter, and that pieces of CWD with length more than 2.5 times the width of the channel should be considered functionally immobile (Dixon and Sear 2014). Work performed by Bertoldi et al. (2013) suggests similar trends, demonstrating that deposition of CWD is highest following peak flows (i.e., at reduced water velocity and depth), and that larger fragments of CWD are retained more often than smaller fragments.

Coarse Woody Debris in the Mid-Atlantic Region

Despite this growing appreciation for the importance of coarse woody debris in riparian systems, and the increasing body of knowledge concerning its dynamics, there has been little research done within the continental U.S. outside the Pacific Northwest. There is a paucity of information from the MAR, one of the most densely populated (and altered) regions of North America (Sweeney 2004, Selego 2012). Although the bias is understandable, given the enormous quantity of debris in the Northwest, the Mid-Atlantic is also heavily forested, and much of this forest is relatively close to human settlements. These forests are largely hardwood-dominated, in contrast to the conifer-dominated forests of the Northwest. Composition is further differentiated by the unique land-use history of this region. Much of the acreage is relatively young (<150 years old), owing to large-scale logging throughout the 19th century (Vale 1982). In addition, Mid-Atlantic forests (particularly those in central Pennsylvania) experienced unusual and accelerated succession trajectories as a result of this disturbance, and exhibit dynamics markedly different from those of the “climax state” forests of the Northwest (Abrams and Nowacki 1992).

Novel and invasive diseases are further altering the forests dynamics of this region. Hemlock wooly adelgid, emerald ash borer, and birch bark disease have all caused wide-spread mortality, altering stand structure and composition in some floodplains (Ehrlich 1934, McClure 1991, Poland and McCullough 2006). Many of the species these invasives are affecting are critically important in riparian ecosystems, dominating their respective environments. Although the effects of these diseases on debris loading have not been directly quantified, it seems reasonable to predict that volumes will increase across the landscape as these diseases expand their geographic range and affect more of the Mid-Atlantic. For many of these diseases this increase in volume of dead and down woody material will happen over a relatively short period of time (i.e., 3-5 years), and the rapid nature of this change will bring both short and long-term habitat alterations. The effects of this increased loading, both short-term (e.g., increased habitat complexity, modified hydrodynamics) and long-term (e.g., transformed channel morphologies) will interact with the effects of reduced canopy cover and altered microclimate to produce new ecological conditions in many forested stream habitats throughout the Mid-Atlantic (Brantley et al. 2013).

Restoration Potential

Aside from the lack of data from the Mid-Atlantic, there has also been little work done to directly quantify how loading, recruitment, and distribution of CWD vary between sites in a natural state and those that have been disturbed by human activity. Moving forward, this information will be especially important, given the increasing use of CWD installations as a restoration/remediation tactic. More and more often, traditional "hard" structures (anchored log weirs and sills, rock berms, etc.) are being replaced with untethered logs and root wads (Roni et al. 2015). This is being done for a number of reasons. Unanchored wood requires less machinery and human labor to install, it requires less disturbance of the surrounding area, and it more closely mimics the natural state of the stream. There is a substantial body of literature concerning strategies and best practices for CWD installations, but most of these refer to reference conditions, or debris as it would be found in a relatively undisturbed forested system (e.g., MacNally et al. 2002, Hassett et al. 2005, Sullivan et al. 2012, Roni et al. 2015). There is significantly less data on how debris occurs in or moves into agricultural and semi-agricultural settings. These types of landscapes are being managed now more than ever, as land easements move to include working agricultural lands as well as riparian areas as part of their focus. It is crucial that land management professionals across the continent understand how CWD would naturally be concentrated within the stream reaches and floodplains on their individual properties, regardless of their disturbance state, as this could be vital to restoring appropriate ecosystem functions and garnering the benefits of such functions.

Hypotheses and Goals

The primary goal of this study was to determine how coarse woody debris abundance, characteristics, and dynamics vary between anthropogenically-disturbed and reference (natural) landscapes. The primary hypotheses are as follows:

I. Larger quantities (volumes, counts, or both) of CWD will be associated with sites closer to reference standard condition (i.e., highest ecological integrity).

II. CWD associated with sites closer to reference standard condition will show a broader range of sizes and will, on average, be larger than CWD associated with more anthropogenically-disturbed sites.

III. Sites closer to reference standard condition, which are expected to possess the largest volumes of CWD, will provide more and better-quality ecosystem services (i.e., will possess higher-quality habitat).

IV. Pieces of CWD in sites closer to reference standard condition will move less often and over shorter distances than debris in sites in a more disturbed state.

V. Large pieces of CWD will not travel in large concentrations downstream from forested reaches (i.e., debris will not migrate in great quantity from sites closer to reference condition to sites in a more disturbed state).

MATERIALS AND METHODS

Study Area

This study was conducted is the Mid-Atlantic Region, specifically the portion of the Ridge and Valley Province surrounding State College in central Pennsylvania. This area is so-called because the landscape is dominated by the southwest-to-northeast oriented ridges of the Appalachian Mountains and their associated valleys. The slopes of these ridges are composed of shale, and the ridges are capped by sandstone. The valleys are underlain by carbonate rocks, which give rise to the unique karst geology for which this region is well-known. This influences the local hydrology, which is characterized largely by headwaters and smaller tributaries running from the ridges into the valleys, where large rivers typically parallel the ridges in a trellis drainage pattern, or cut through the ridges at water gaps (Shultz 1999).

The long history of logging and anthropogenic disturbance throughout central Pennsylvania following the establishment of the iron industry has left the region, particularly in Centre and Huntingdon counties, with a patchwork of different forest types, many containing species associations that typically do not occur naturally. Presently, the upland forests are dominated by *Quercus* and *Acer* species, notably *Q. rubra, Q. alba*, *Q. velutinum, A. rubrum*, and *A. saccarhium.* The riparian and more internal portions of the forest tend to be dominated by *Tsuga canadensis, Betula alleghaniensis, Betula lenta*, *Acer negundo*, *Fraxinus pennsylvanica*, and *Acer saccharium*. Therefore, the majority of the debris being recruited to the streams of interest is expected to be generated by these five species.

It is worth noting that major shifts in forest composition are currently occurring throughout eastern North America, including in the forests associated with the reaches surveyed for this study. *T. canadensis* is experiencing significant population reductions following the introduction of hemlock wooly-adelgid, an invasive insect (McClure 1991). This will likely cause a short-term increase in debris recruitment, especially in mountain headwater streams, where *T. canadensis* often composes the majority of the riparian forest. However, over the long term, debris recruitment may decrease for a significant period of time, as new seedlings establish and grow in the gaps left by the deceased hemlocks. These changes will be accompanied by dramatic shifts in stream conditions, most notably temperature, which will increase as the shading effect of the hemlocks disappears. These processes are co-occurring with a region-wide transition in the mesic and xeric forests from *Quercus*-dominated stands to *Acer*-dominated stands, largely as a result of shifting fire regimes and the large populations of white-tailed deer following abundance of early-successional forests in the early 20th century, and local extirpation of wolf and mountain lion populations in the latter part of the 19th century (Abrams 1992, Abrams 1998). Although this will not influence CWD dynamics nearly as heavily as the hemlock die-off, it is still worth mentioning, as changes in forests rarely occur in isolation.

Site Selection

Within the Ridge and Valley Province of Central Pennsylvania, the Shaver Creek and Standing Stone Creek watersheds were chosen as the focal points of this project (Fig. 1). All water within these watersheds in destined for the Chesapeake Bay, by way of the Juniata and Susquehanna Rivers. Both watersheds are predominantly forested, but were chosen because they contain both undeveloped and agricultural land in close proximity. From these watersheds, a subset of headwater and midreach streams (orders 2-4) were utilized for data collection. This range of sizes was chosen in an effort to capture meaningful CWD dynamics in as many channels as possible. In streams of the lowest orders (i.e., the smallest headwaters), even moderately large trees can potentially block the entire width of the channel, effectively preventing movement except during the most intense flow events. In contrast, in streams with orders larger than those chosen for this study, there is little potential for smaller debris to become lodged in the channel, making relationships between anthropogenic disturbance, flow intensity, and CWD dynamics difficult to assess. Bearing these factors in mind, 20 sites (Table 1) representing a range of environmental conditions and geophysical locations were selected. These were largely drawn from past projects completed by Riparia at Penn State, although several were identified specifically for this sampling effort. Of the original 20 sites, 18 were eventually surveyed in the field; the remaining two were visited and found to be unsuitable for the completion of this protocol: Henry's Run was overgrown and largely inaccessible, and had little perceptible water movement, while Fungus Amongus had recently been heavily logged, and multiple access roads crossed the channel, which was ill-defined and dry.

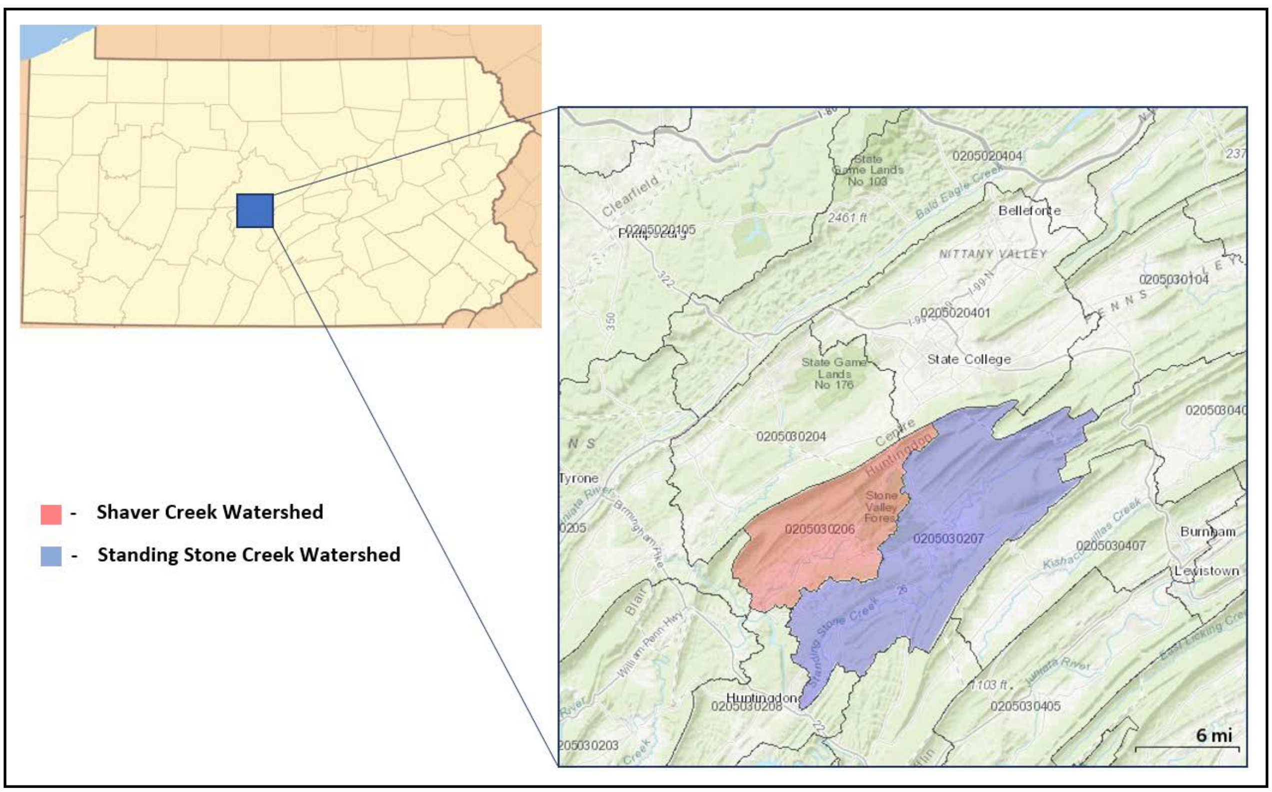

Figure 1. Shaver Creek and Standing Stone Creek Watersheds

Table 1. Headwater riparian study sites in central Pennsylvania

Site Name	Latitude	Longitude
Whipple Dam SP	40.68780	-77.86140
Laurel Run	40.69670	-77.85440
Shaver’s Creek	40.64400	-77.93060
Mosquito	40.60430	-78.01360
Davis	40.61010	-78.00810
McGuire Rd	40.59920	-78.06780
McGuire Rd 2	40.59820	-78.06439
Buffalo Run	40.85230	-77.89030
State College H.S.	40.81150	-77.83190
Joke	40.64270	-77.84030
Cedar Run	40.79370	-77.75560
Davis 2	40.60978	-78.01019
Fungus Amongus*	40.63750	-77.77130
Henry's Run*	40.62041	-77.92876
Armond Run	40.63354	-77.93079
Secret Seeger	40.69228	-77.76339
Shavers Cole	40.63031	-77.94482
Globe Run Shedd	40.61801	-77.98329
Shavers Shedd	40.61497	-77.97396
Rothrock	40.72280	-77.86080

*Not surveyed for this project.

Preliminary Site Characterization

Following selection, the latitude and longitude of the central point at each site were determined. Once geolocated, study plots were characterized and classified utilizing the Stream Wetland Riparian (SWR) Assessment protocol developed by Brooks et al. (2009). This protocol relies on two levels (Level 1 and 2) of assessment, which vary in intensity and methodology (Brooks et al. 2004, 2009). The characterization of CWD performed for this study would be considered a Level 3, or Intensive, assessment. Before field surveys were undertaken, a preliminary assessment (Level 1) of synoptic maps established a basis for what to expect at each site, and gave a broad view of landscape-level characteristics, including land use, vegetative cover, and percent forest cover (among other variables).

These maps were also used to characterize the contributing area for each site, namely the size and average slope gradient. These variables served as proxies for expected flow intensity, where sites associated with larger or steeper upstream regions were assumed to experience floods consisting of larger volumes of water moving at higher velocity.

Rapid Field Assessment

Following Level 1 assessment of sites of interest, completion of a site-by-site SWR Index (Level 2) was undertaken (Brooks et al. 2009). The full SWR protocol includes surveys for an extensive range of variables, not all of which were employed during the completion of this study. This served as the primary characterization of ecological condition at each locale, and as a type of ground-truthing for the conclusions drawn during the Level 1 survey. At each site where sampling was possible, a 100 m by 100 m study plot centered on the geolocated plot point was delineated using two 100 m tapes (as shown in Fig. 2). When possible, this point and the study plot were centered in the stream channel. If the width of the stream exceeded 10 m or was not wadeable, the plot was placed along one bank, and surveys involved only the channel and the accessible side (Brooks et al. 2009). Regardless of where it was located, each plot contained two crossed 100 m transects utilized for the CWD survey (Fig. 2) (discussed in detail below).

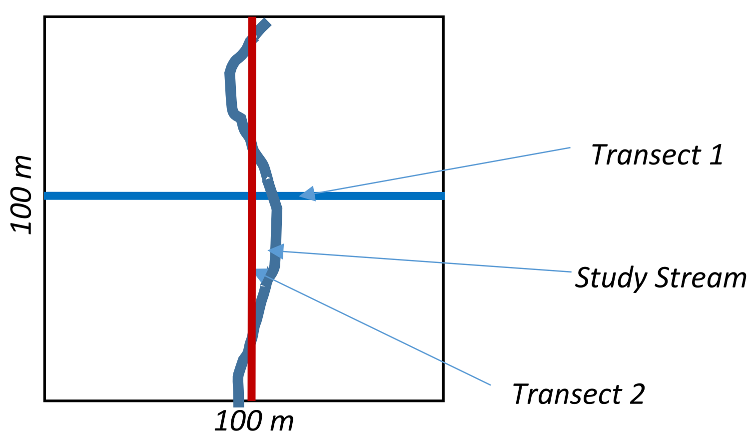

Figure 2. A schematic representation of the sampling plots to be utilized for this riparian study

Following delineation, a sketch map of each site was created. This was intended to show the orientation of the site with respect to north, the direction of stream flow, and any major changes in elevation or hydrologic modifications within the survey area. Large pieces of debris and locations of soil pits and tree surveys (all discussed in detail below) were also marked on the map.

The riparian area of each study plot was classified using a codified system (Brooks et al. 2009). This process involved the identification and characterization of important landscape features, including the levee, the floodplain, the uplands, and any wetlands present, and the occurrence of stressors in each of the three components – stream, wetland, and floodplain. See Appendices for the data sheet used in this classification. The numerical values assigned to each type of land cover correspond to relative habitat quality, with larger numbers representing higher quality habitats. These habitats are assumed to provide more and better ecosystem services than habitats with lower scores.

After each riparian area was classified, several measurements were taken in an effort to determine the amount of incision present in a given reach (separate measurements were taken at the upper and lower extent of the plot and at the central point). The thalweg water depth was measured using a 3m stick. Then, using a laser level to ensure the correct height was recorded, the bankfull height and bank height were measured. Bankfull is the height at which the lowest vegetation is found growing, and bank height is the top of the bank (as determined by best professional judgment). The width of the channel at the bankfull height was also measured. From these values others were calculated: Floodprone Height, which is equivalent to twice bankfull height, and Incision Ratio, which is equivalent to the Bank Height divided by the Bankfull Height (Rosgen 1996). These values serve as proxies for connectivity between the channel and the associated floodplain and, in turn, flood attenuation and water storage services: sites with lower Incision Ratio values should provide more of these services than sites with relatively high Incision Ratio values.

If the floodplain was determined to be a wetland, it was classified based upon a hydrogeomorphic system (Brooks et al. 2011). This same classification was applied to all additional wetlands found within the assessment area. Data sheets utilized for this classification are included in the appendices.

Following wetland classification, a soil and hydrology assessment was completed to determine the degree to which the area was saturated and experienced hydrologic events. A data sheet (included in the Appendices) containing various indicators of hydrologic activity was utilized to classify the area as very, moderately, or not very wet. A soil pit typical of wetland delineation protocols was dug to about 45 cm to aid in site characterization, with the soil described using a Munsell soil chart and texture analysis by touch. This process was completed at the upper and lower extent of the assessment area, and also once at the center. The soil pits themselves were approximately 15-20 cm in diameter and 45-50 cm in depth, typical of wetland delineation investigations.

At each location where a soil and hydrology assessment was completed, a vegetation assessment was undertaken as well. Tree point-counts were completed using the Bitterlich plotless method, and an effort was made to capture all representative habitat types while establishing the locations of these point counts. For each tree, species and DBH were recorded. In addition, an invasive species assessment allowed for an approximation of the quantity of nonnative species present at each site, and a sense of relative population sizes.

Finally, two sets of questionnaires were completed at each site: a Stressor Checklist, and a Stream Habitat Assessment. These used best professional judgment to look for a number of different indicators of ecological health and habitat quality (both can be viewed in the Appendices). The Stressor Checklist is a presence/absence assessment (Brooks et al. 2009), while the Stream Habitat Assessment utilizes a 1-20 scale to quantify selected physical factors (EPA's RBP manual for citation).

Survey of Coarse Woody Debris

There are a number of different established methods for surveying coarse woody debris, and a combination of these methods was utilized for the completion of this study, dependent upon site conditions.

Ground surveys were utilized to determine the quantities, locations, and qualities (e.g., dimensions, decay classes) of CWD on the landscape (Bertoldi et al. 2013). Crossed, perpendicular transects 100m long were fit within the SWR plots at each site (Fig. 2). All pieces of CWD greater than 1m in length (with at least 0.5 m of that length within the channel) were measured and recorded, with the following determined for each piece of debris: species (hardwood or conifer), maximum and minimum diameter, length, and presence/absence of a root ball. In addition, conifer logs were categorized on the Maser (1979) decay scale (Bowman et al. 2000), and hardwood logs were classified according to the scale developed by Pyle and Brown (1998). All pieces of CWD intersecting the transect running perpendicular to the channel were recorded in one of three coarse size classes: Fine (1-5 m), Medium (5-15 m), Large (>15 m). Where quantities of debris were found together, either within the channel or on the floodplain, every effort was made to survey each individual piece of wood. At the very least, the dimensions of the pile were noted (including width, depth, and height). The location of each individual piece of debris (in the channel) or jam surveyed was marked on the maps prepared during the completion of the SWR Index, within reason (at some sites, the quantity of debris made this task impossible; at these locations, only tagged pieces were mapped).

At each site, a number of pieces of debris were selected from the larger pool within the channel to be tagged and tracked for movement over 12 months . The number of pieces utilized varied from site to site based on the quantity of "appropriate" debris present, but never exceeded 12. This upper limit was imposed in an effort to keep tracking operations manageable at each site. "Appropriate" debris was selected based on possession of the following characteristics: greater than 1 m in length, and likely to move. In several cases, debris of a size that was unlikely to move was chosen in an effort to clarify the distinction between mobile and immobile sizes for a given channel. Individually-numbered, colored aluminum tags were affixed to each piece in an easily-visible, secure (i.e., not decomposing) location. Each piece of tagged wood was then geolocated using a GPS device.

Sites were resurveyed every month for approximately eight months in an attempt to recover debris that had been numbered. These "resurveys" included not only the study plot but also, where necessary, several hundred meters downstream of the study plot. This extensive search was undertaken in an effort to improve "recapture" numbers. During each resurvey, any debris that was found to have moved from its last surveyed location was geolocated again in its new location. If the tagged piece moved between areas with significantly different land cover classes or anthropogenic disturbance regimes, this was noted as well.

Due to the difficultly of relocating individual pieces of debris, particularly during periods of heavy leaf/algal cover, in many cases it was necessary to simply note that the debris had moved from its last noted location, with no indication of how far it had traveled. Although this prevents a quantification of how far pieces are moving, it still gives a sense of how often debris is shifting in a given channel and, through correlation with precipitation and stream gauge records, provides data on the amount of rainfall/snow melt needed to move debris of a particular size and/or orientation.

In addition to this empirical data, at every site where landowners and/or managers were cooperative, discussions were undertaken regarding their interactions with the stream channels and the woody debris therein. Although the majority do little with the debris in their channels, some admitted to clearing larger branches and trunks, especially from areas where they presented a threat to infrastructure and property. It is difficult to quantify this type of anthropogenic influence, but it is important to note that it is occurring. In addition, any records regarding past improvement or mediation efforts at each site (if extant) were also collected as part of the preliminary assessment. Although no sites have received artificial debris treatments, one (State College High School) is known to contain several large, artificial log weirs, known as crossvanes, which alter hydrodynamics and, in turn, debris movement patterns.

Data Analysis

Riparia has surveyed many of the sites utilized for this study in the past, and where possible, previously collected data were employed to predict Reference or Non-Reference status before field work began. In most cases, data collected for this study supported the established statuses (Table 2). The 18 sites were divided into two groups: Reference and Non-Reference (Table 2). Many variables were assessed according to these two groups; for example, debris counts from reference sites were compared to debris counts from non-reference sites to look for consistent, significant differences.

The relatively small number of sites surveyed for this study generated correspondingly small sample sizes, necessitating normality testing for all variables prior to the statistical analysis discussed above. The Shapiro-Wilkes test was employed for this purpose. The results of this analysis dictated whether variables were assessed using parametric or non-parametric methods.

Fisher's F-tests were performed for each normally-distributed variable to compare variances between the reference and non-reference groups. One-tailed t-tests ($\alpha = 0.05$, upper- or lower-tailed depending on the relationship of interest) were then used to highlight directional differences between reference and non-reference sites for possible explanatory variables associated with coarse woody debris.

Non-normally distributed variables were assessed using the Mann-Whitney test ($\alpha = 0.05$, upper- or lower-tailed depending on the relationship of interest) to highlight differences between reference and non-reference sites for possible explanatory variables associated with coarse woody debris.

For a number of variables, following difference testing, linear regression analysis was conducted to investigate predictable relationships between potential explanatory characteristics of debris and the SWR Index score.

RESULTS

Habitat Quality Assessments

The final SWR Index scores for all sites were compared to data collected during previous Riparia studies to confirm or challenge predicted reference status (Table 2). All predicted reference sites had final scores above 0.8 (on a scale of 0-1), and all predicted non-reference sites had final scores below this threshold (Fig. 3). The difference between these two groups was significant ($p < 0.0001$). Therefore, predicted Reference and Non-Reference designations were used for the remainder of data presentation and analysis.

Table 2. SWR scores for Reference and Non-Reference sites

Site ID	Predicted Reference Status	Final Score
18	No	0.70
35A	No	0.62
35	No	0.52
230	No	0.65
233	No	0.74
151	No	0.78
234	No	0.43
239	No	0.66
31	No	0.50
64	No	0.64
130	No	0.69
23	Yes	0.86
241	Yes	0.95
19	Yes	0.92
T1	Yes	0.91
24	Yes	0.81
60*	Yes	0.83
10*#	Yes	0.93
	Reference Avg.	0.89
	Non-Reference Avg.	0.65

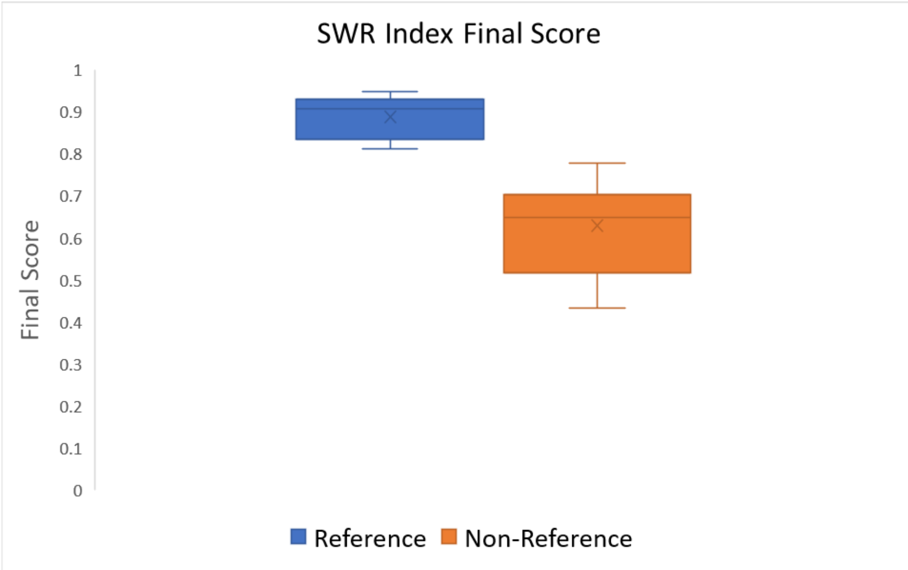

Figure 3. Box-and-whisker plot of SWR Index scores at Reference and Non-Reference sites.

Debris Count and Volume

At each site, two variables were used to assess the quantity of debris: a count of individual pieces and the total volume of debris (Table 3). Debris volume was calculated using two component variables:

a) The summative volume of all individual pieces, derived from the dimensions recorded for each individual piece using Smalian's formula

b) The volume of any jams wherein individual pieces could not be counted, calculated using the formula from Haschenburger's (2012) report on debris in the San Antonio River, and Dixon's (2016) method for visual assessment of log jam porosity

Table 3. Debris metrics (count and volume) per 100 m of channel length

Site ID	Reference Status	Debris Count	Debris Volume (cm^3)
18	No	54	5360833
35A	No	51	2397413
35	No	30	775011
230	No	82	73149171
233	No	52	843772
151	No	7	172767
234	No	36	1089673
239	No	40	3845486
31	No	3	25038
64	No	18	505835
130	No	20	1095249
23	Yes	41	8037073
241	Yes	42	2494208
19	Yes	163	5366134
T1	Yes	100	856653
24	Yes	105	3521921
60*	Yes	236	30923884
10*#	Yes	316	31459201

Table 4. Descriptive statistics for debris count and volume

	Mean Count	Count S.D.	Mean Volume (cm^3)	Volume S.D. (cm^3)
All Sites	77.6	83.3	9551073	18503995
Reference Sites	143.3	102.4	11808439	13432809
Non-Reference Sites	35.7	23.4	8114568	21632736

Debris volume values (Fig. 4) followed a non-normal distribution, so an upper-tailed (Sample 1 – Sample 2 > 0, where Sample 1 includes Reference sites and Sample 2 includes Non-Reference sites) Mann-Whitney test was used to assess significant difference. The test demonstrated that References sites do contain significantly greater volumes of debris than Non-Reference sites ($p = 0.023$).

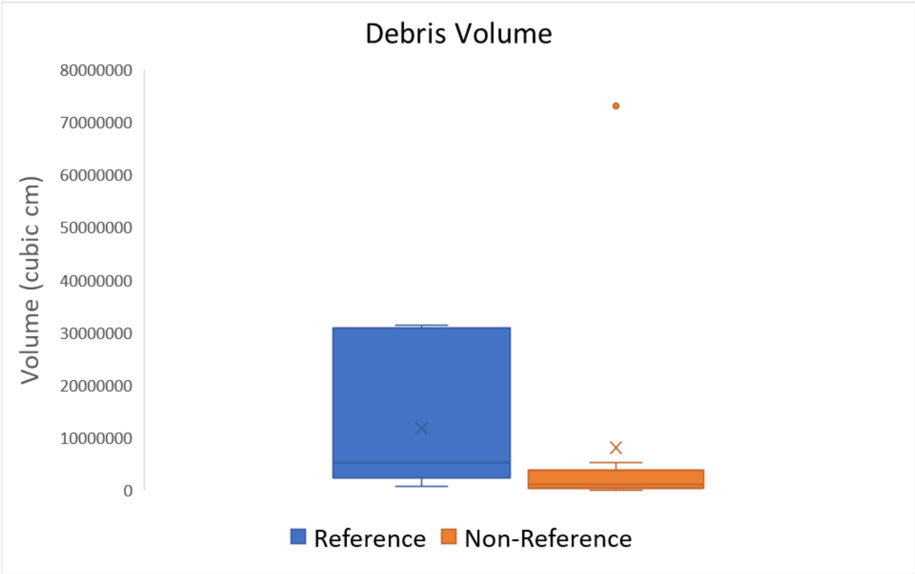

Figure 4. Box-and-whisker plot of debris volume at Reference and Non-Reference sites.

The number of pieces of debris at each site (Fig. 5) also followed a non-normal distribution, and the difference between Reference and Non-Reference sites was, therefore, assessed utilizing the same methods as volume of debris. The upper-tailed Mann-Whitney test demonstrated that the difference is significant ($p = 0.003$), with Reference sites containing more pieces of debris than Non-Reference sites.

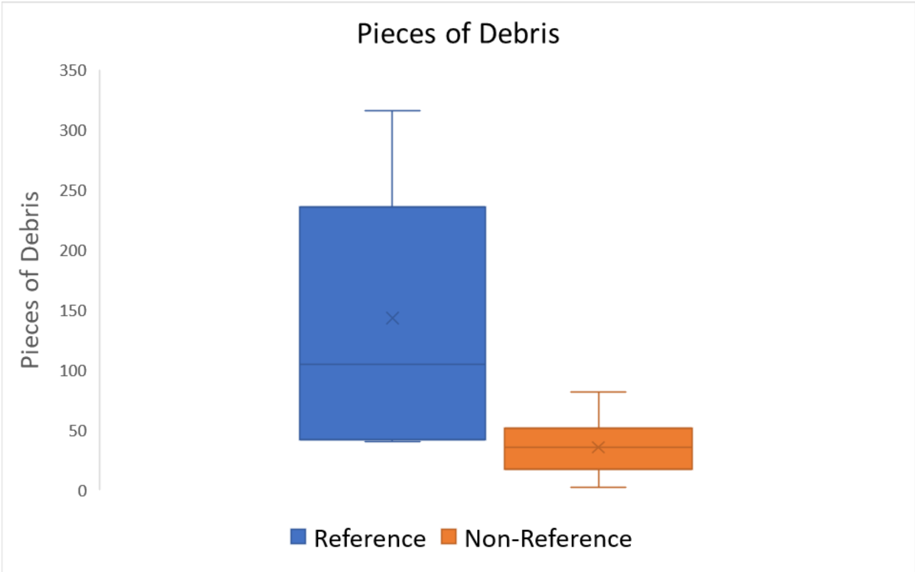

Figure 5. Box-and-whisker plot of the number of pieces of debris at Reference and Non-Reference sites.

The above tests demonstrated that Reference sites generally contain greater quantities of debris than Non-Reference sites. Regression analyses revealed that neither variable is strongly correlated with SWR Index score via a predictable mathematical relationship. Linear relationships were quite weak (R^2 [volume] = 0.012, R^2 [pieces of debris] = 0.315). However, this did serve to illustrate that a greater deal of the observed variation in habitat quality is explained by the number of pieces of debris present than by the volume comprised by that debris.

Carbon Storage

A rough estimate of the volume of carbon stored in the surveyed debris at each site was calculated by dividing the volume of debris at each site in half. Results were expected to mirror those achieved for debris volume, as the variables are directly related. Carbon volume data followed a non-normal distribution, and were, therefore, analyzed utilizing the Mann-Whitney test. Results indicated that Reference sites store significantly ($p = 0.022$) larger volumes of carbon in debris than Non-Reference sites.

Debris Characteristics

Over 1,100 individual pieces of debris were surveyed over the course of the study period, and measurements of length and diameter were taken for each. The volume of debris was calculated on a site-by-site basis using these dimensions, and variation in the measurements themselves facilitated a comparison of debris characteristics across sites. Four variables were analyzed to assess the variability in size across sites: maximum length (the longest piece of debris at a given site), maximum diameter (the largest diameter measured for a piece of debris at a given site), and the range of both of these variables at each site. Values for maximum length followed a normal distribution, and were analyzed using an upper-tailed t-test. Results demonstrate that Reference sites contain significantly ($p = 0.025$) longer pieces of debris than Non-Reference sites (Fig. 6).

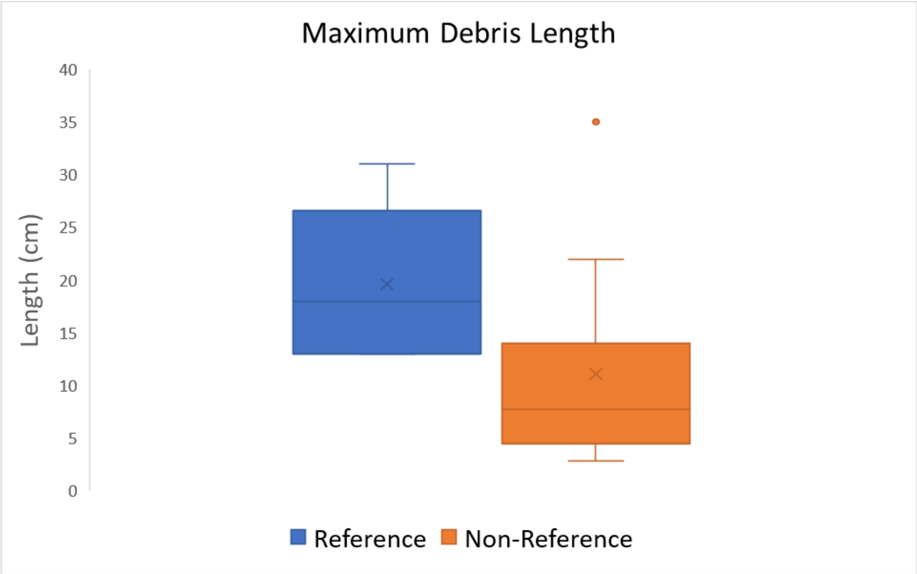

Figure 6. Box-and-whisker plot of the maximum debris length at Reference and Non-Reference sites.

The maximum diameter values were also normally distributed, and were analyzed in the same manner as the maximum length values. Similar results demonstrated that the largest debris at Reference sites is significantly ($p = 0.022$) larger than the largest debris at Non-Reference sites in most respects (Fig. 7).

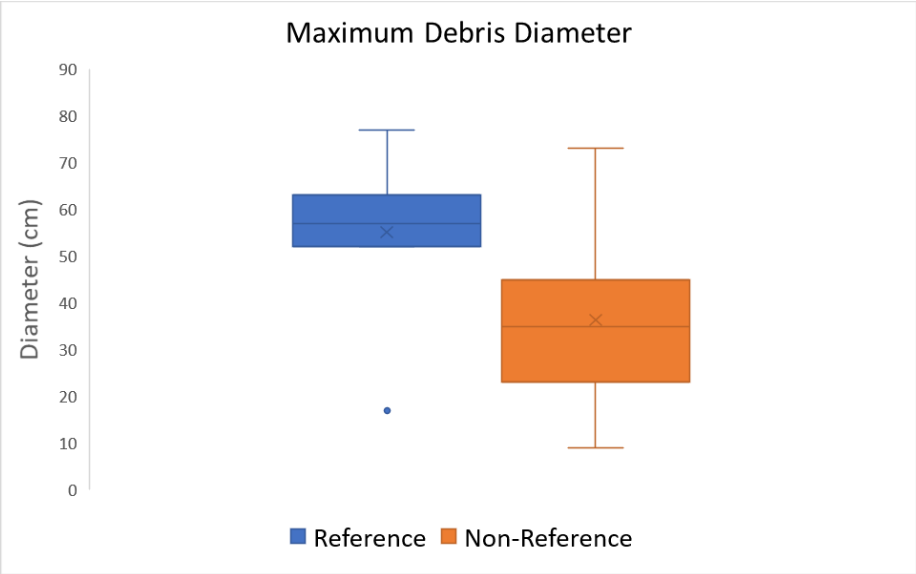

Figure 7. Box-and-whisker plot of the maximum debris diameter at Reference and Non-Reference sites.

The range in debris characteristics also was analyzed in an attempt to determine whether or not Reference sites contain a greater variability in debris sizes than Non-Reference sites. The range values for maximum length were normally distributed, and were analyzed using an upper-tailed t-test. Results demonstrate that Reference sites contain a significantly ($p = 0.049$) greater range of debris lengths than Non-Reference sites (Fig. 8). Range values for maximum diameter were also normally distributed (Fig. 9), and were analyzed using the same methods as above. Results showed that the difference between Reference and Non-Reference sites was close to being significant ($p = 0.051$).

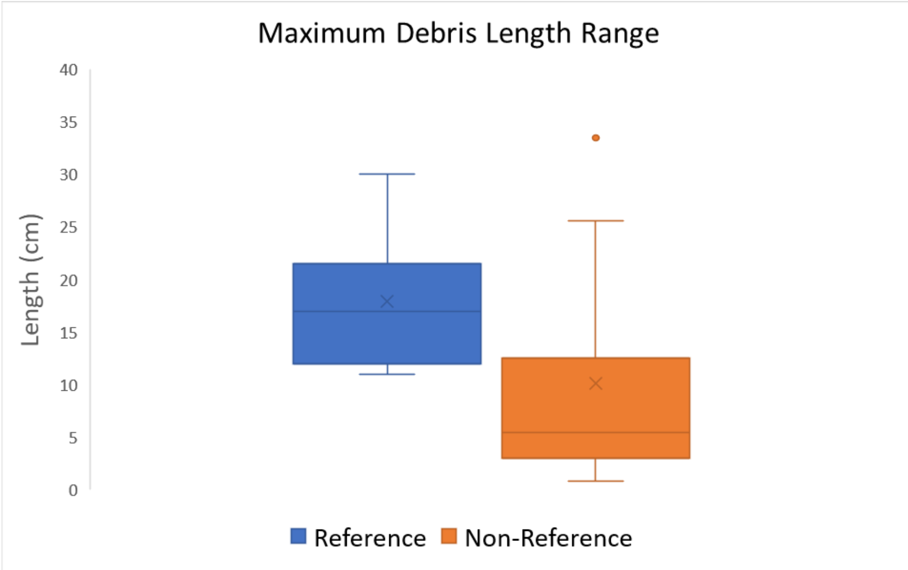

Figure 8. Box-and-whisker plot of the maximum debris length range at Reference and Non-Reference sites.

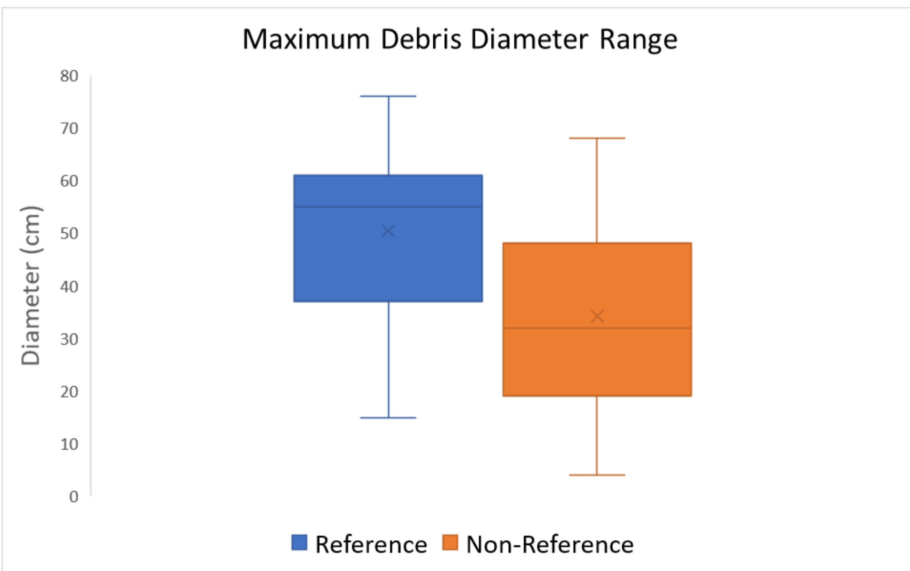

Figure 9. Box-and-whisker plot of the maximum debris diameter range at Reference and Non-Reference sites.

Linear regression analyses were performed for both length and diameter to determine if a predictable relationship exists between these variables and SWR Index score. Both showed similar, weak relationships (R^2 [length] = 0.220, R^2 [diameter] = 0.148).

Apart from debris size, decay class and root ball presence/absence were also recorded for each piece of channel debris in an attempt to further characterize individual pieces. Averaged decay data for each site followed a normal distribution, and were analyzed using a two-tailed t-test (as there was some uncertainty as to whether Reference sites could be expected to have more or less decay than Non-Reference sites). There was found to be no significant difference ($p = 0.612$) in average debris decay between Reference and Non-Reference sites (Fig. 10).

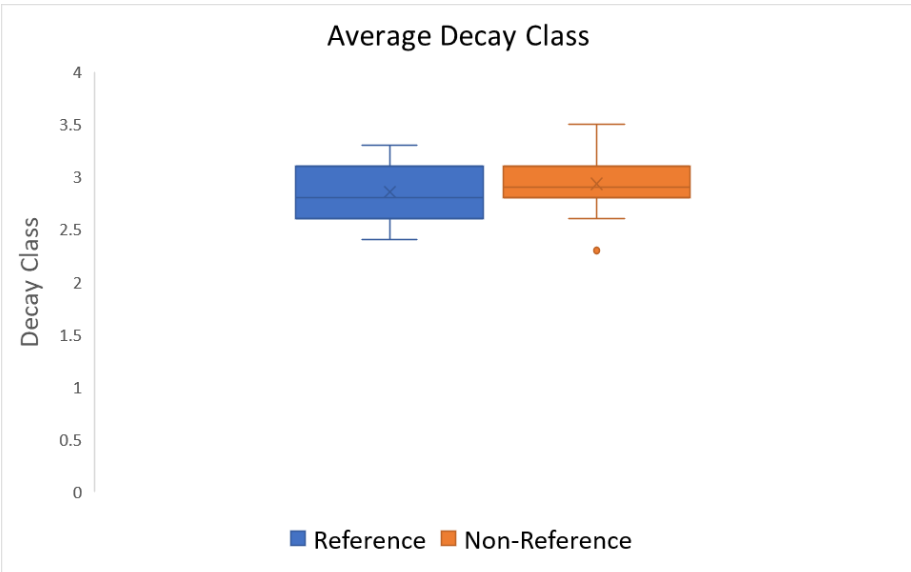

Figure 10. Box-and-whisker plot of average debris decay values at Reference and Non-Reference sites.

The number of pieces of debris possessing a root ball at each site was tabulated, and the counts were found to have a non-normal distribution. An upper-tailed Mann-Whitney test demonstrated that Reference sites are likely to contain a significantly ($p = 0.002$) greater number of pieces of debris with root balls intact than Non-Reference sites (Fig. 11).

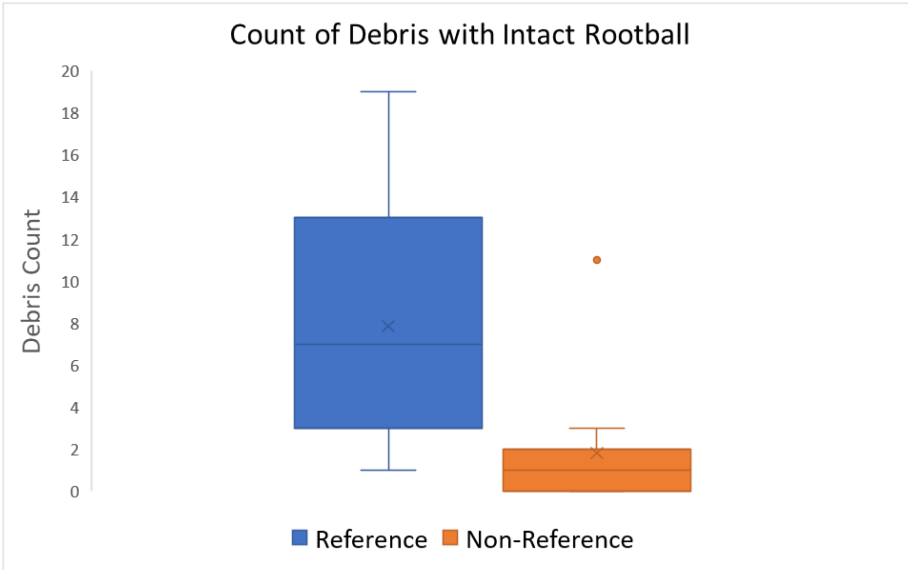

Figure 11. Box-and-whisker plot of average counts of debris with root wads at Reference and Non-Reference sites.

Linear regression analyses were performed for both of these additional descriptive characteristics. Linear regression R^2 values for both characteristics were quite low: 0.119 for root wad count, and 0.078 for average decay class. Neither is a strong explanatory/predictive variable for SWR Index score.

Floodplain Debris

The provisioning of debris to channels, and consequently services to the surrounding area, is facilitated in large part by the presence of debris and snags on the floodplain. Counts of both snags and debris on the floodplains of the channels of interest were performed to determine how closely related these variables are. Snag counts were not normally distributed, and were, therefore, analyzed utilizing an upper-tailed Mann-Whitney test. Results demonstrated that floodplains associated with Reference sites do contain significantly ($p = 0.003$) more snags than Non-Reference sites (Fig. 12).

Floodplain debris counts also followed a non-normal distribution, and were analyzed in the same manner as the snag counts. Results demonstrated that Reference site floodplains do contain significantly ($p = 0.006$) larger quantities of debris than Non-Reference site floodplains (Fig. 13).

These results suggest that floodplain debris count is likely more closely related than floodplain snag count to SWR Index score. Linear regression analyses were performed for both of these variables to determine if this is the case. Floodplain debris showed a weak linear relationship ($R^2 = 0.296$), and that of floodplain snags was even weaker ($R^2 = 0.009$). Although this does show that floodplain debris counts explain more variability in SWR Index score than floodplain snag counts, neither has predictable relationship.

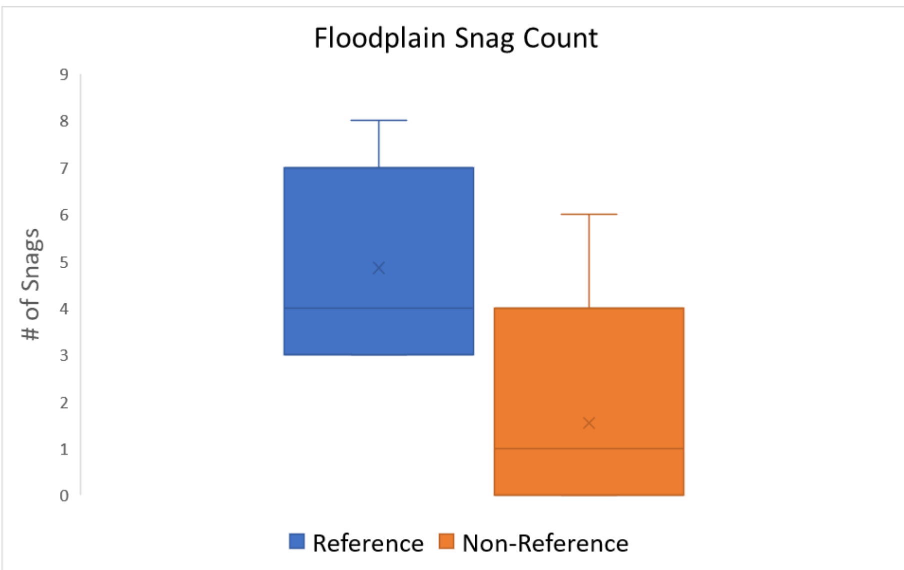

Figure 12. Box-and-whisker plot of the floodplain snag count at Reference and Non-Reference sites.

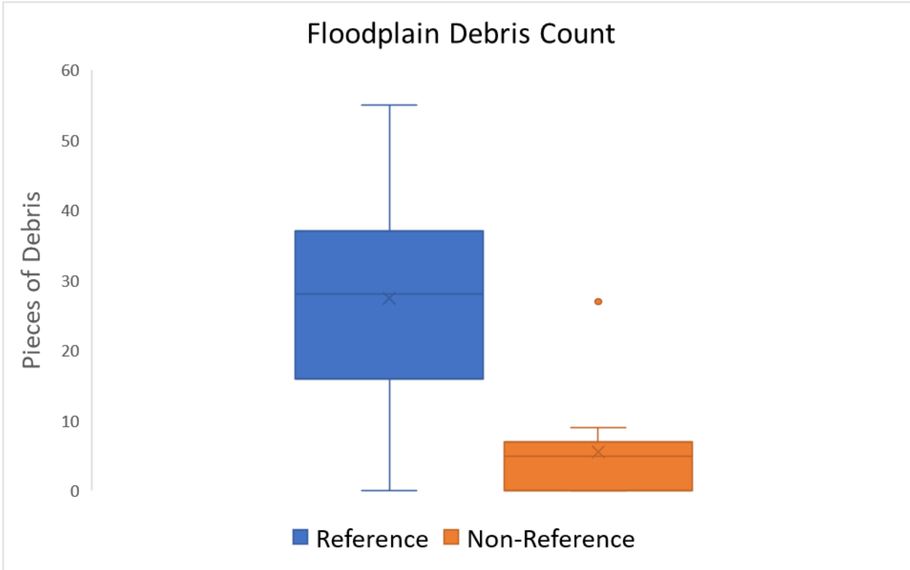

Figure 13. Box-and-whisker plot of the floodplain debris count at Reference and Non-Reference sites.

The relationship between floodplain debris count and channel incision was also investigated in an attempt to determine how strongly channel incision controls the movement of debris between the channel and the floodplain, and whether or not this influences the quantity of debris on the floodplain. Linear regression of floodplain debris by the Incision Ratio calculated for the SWR Index revealed a very weak relationship (R^2 = 0.002), indicating that for the sites surveyed for this study, these variables were not closely related.

Riparian Forest Basal Area

Past studies conducted by Riparia have demonstrated that, in many cases, the individual components comprising the SWR Assessment serve as better explanatory variables than the composite score. Knowing this, several component variables were compared to debris quantities across sites in an effort to determine whether these serve as better predictors than the final SWR score.

Of these, basal area of the trees surveyed across all three Bitterlich plots (Brooks et al. 2009) at each site proved to be the most interesting. It is worth noting that basal area data were non-normal, but showed a significant ($p = 0.001$) difference between Reference and Non-Reference sites, with Reference sites having larger basal area values than Non-Reference sites (Fig. 19).

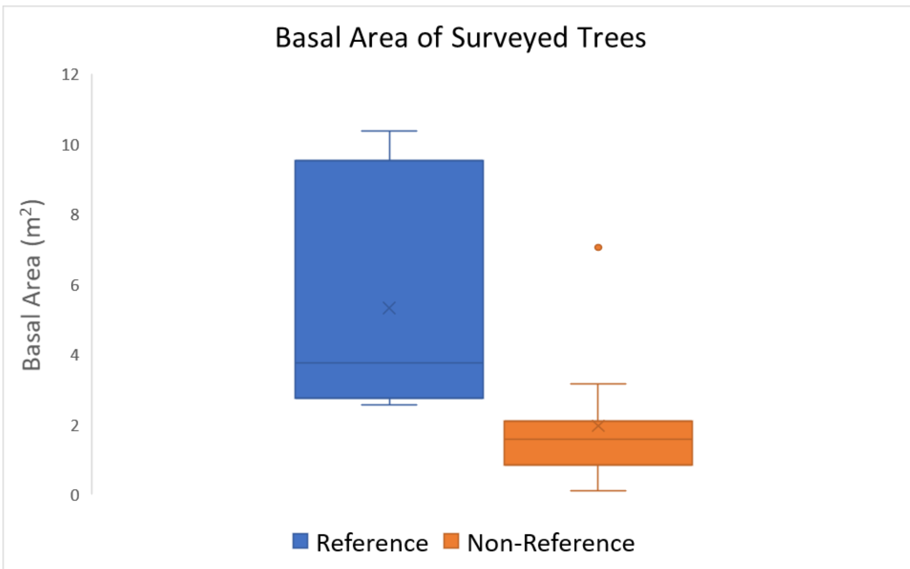

Figure 14. Box-and-whisker plot of the total basal area of surveyed trees at Reference and Non-Reference sites.

When the relationship between basal area and debris count was analyzed using linear regression, the two variables show a relatively strong association ($R^2 = 0.652$) (Fig. 20). This is much stronger than the relationship revealed by a linear regression of the debris by SWR Index score ($R^2 = 0.315$), indicating that riparian forest basal area is a better predictor of debris quantity than composite SWR Index score. The relationship took the following form:

$$D = 3.12 + (22.78 * A)$$

where "D" represents the debris count and "A" represents the basal area of the surveyed portion of the riparian forest.

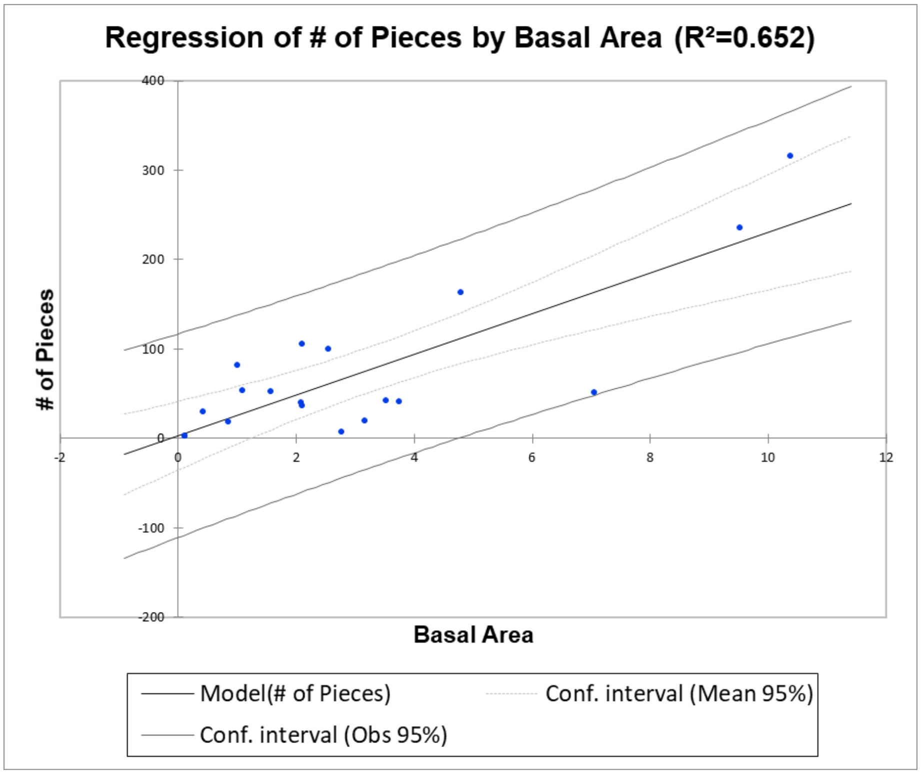

Figure 15. Linear regression of debris count by basal area of the surveyed riparian forest.

Conifer Proportions

In the forests surveyed for this study, Eastern Hemlocks were the dominant conifer species. The average proportion of conifers among all trees sampled on the floodplain at each site was compared between Reference and Non-Reference sites in an effort to determine how potential future losses due to invasive diseases will differentially affect these two types of environments. The data did not follow a normal distribution, and were analyzed using the upper-tailed Mann-Whitney test. Results clearly show that Reference sites contain significantly ($p < 0.0001$) larger numbers of conifers than Non-Reference sites (Fig. 14).

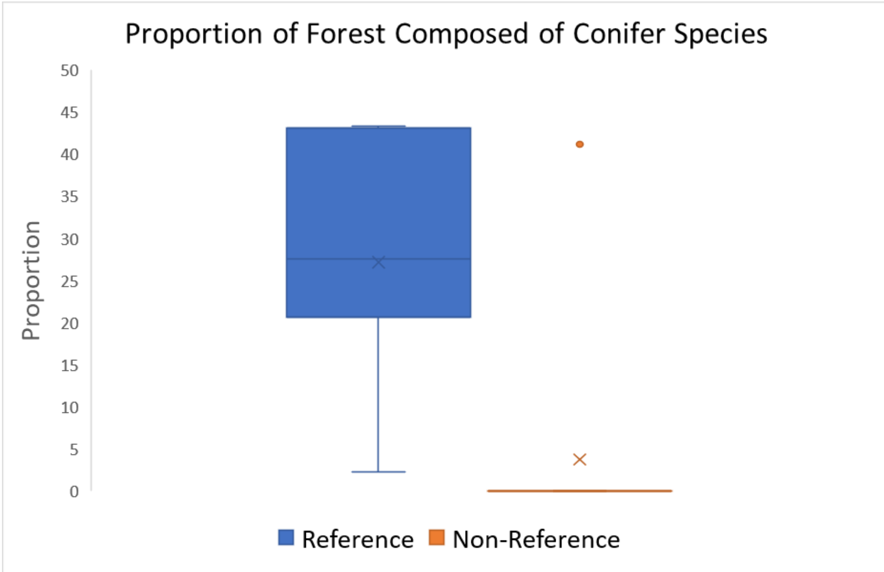

Figure 16. Box-and-whisker plot of the proportion of conifers in forests at Reference and Non-Reference sites.

As for all other variables, linear and regression analyses were performed for the conifer data. Linear regression analysis produced a relatively robust relationship (R^2 = 0.422), at least in comparison with the other variables considered. Of all of the variables studied, conifer proportion seems to be the best predictor of SWR Index score over a range of values.

Movement

Across the 18 sites surveyed for this study, 177 pieces of debris were tagged and monitored monthly over a period of approximately 8 months. Of the 177 pieces, 60 (33.8%) shifted from their original positions. There was no evidence of human interference with the debris at any of the sites, so all movement is assumed to be the result of natural processes (i.e., freeze/thaw cycles and increased flow volumes and velocities following precipitation and snow melt).

There are a number of debris characteristics that influence whether or not a piece of debris is likely to move, and several were explicitly measured during this study: debris size/volume, decay class, and root wad presence/absence. Data on movement and each of these variables were compared in an attempt to determine how these factors influenced movement patterns over the course of the study period. To investigate whether or not debris size had a noticeable effect on likelihood of movement, the average size of stationary pieces was compared to the average size of mobile pieces across three variables: length, maximum diameter, and volume. Data for debris length followed a non-normal distribution, and were analyzed accordingly. Results demonstrated that mobile and non-mobile pieces monitored for this study did not vary significantly ($p = 0.302$) in their lengths. Maximum diameter data also followed a non-normal distribution, but analysis revealed that this variable likely does effect mobility significantly ($p < 0.0001$): stationary pieces of debris had, on average, larger maximum diameters than mobile pieces. When both and length and diameter were combined in a calculation of volume, the data still followed a non-normal distribution. Results demonstrated that volume does have a significant ($p = 0.005$) influence on mobility, with larger pieces of debris being less likely to move than smaller pieces (Fig. 15).

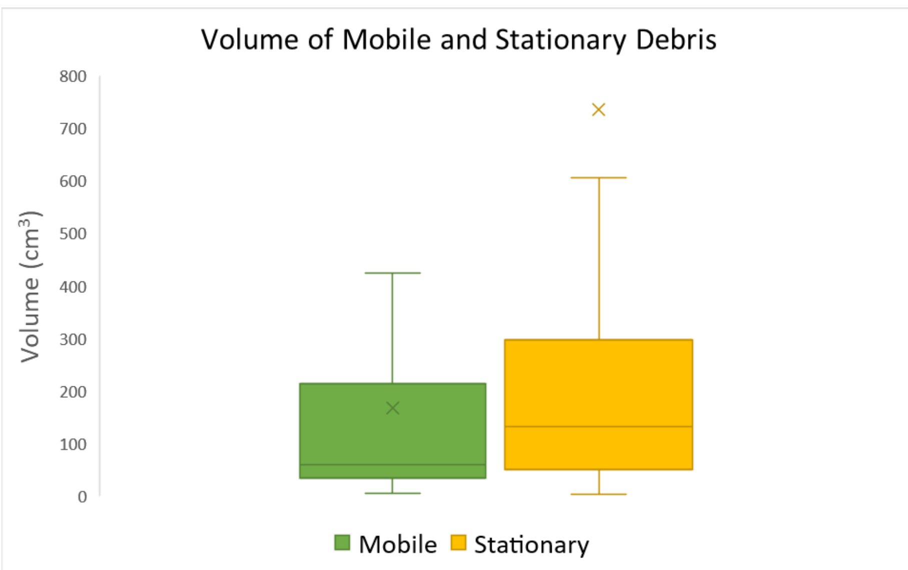

Figure 17. Box-and-whisker plot of the average volume of mobile and stationary debris. Medians are denoted by “X”s. Outliers are not shown.

Decay data also followed a non-normal distribution, but analysis demonstrated that this variable had no significant (p = 0.369) effect on mobility. The influence of root wad presence/absence on mobility was investigated via a site-by-site comparison of the proportion of mobile pieces with a root wad to the proportion of stationary pieces with a root wad. Data were non-normal, and results demonstrated that, at each site, a significantly (p = 0.015) larger proportion of stationary pieces possessed a root wad than mobile pieces.

The counts of tagged pieces of debris that moved at Reference and Non-Reference sites were calculated and compared. The data followed a normal distribution, and a two-tailed t-test was employed for analysis. Results demonstrated that there is no significant (p = 0.873) difference between overall debris movement at Reference and Non-Reference sites (Fig. 16).

In an effort to account for the variable amount of debris tagged at each site, proportions of the tagged pieces that moved at Reference and Non-Reference sites were also calculated. The data follow a normal distribution again, and a one-tailed upper-tailed t-test was used for analysis. Results supported the earlier finding of no significant (p = 0.341) difference between overall debris movement at Reference and Non-Reference sites (Fig. 17).

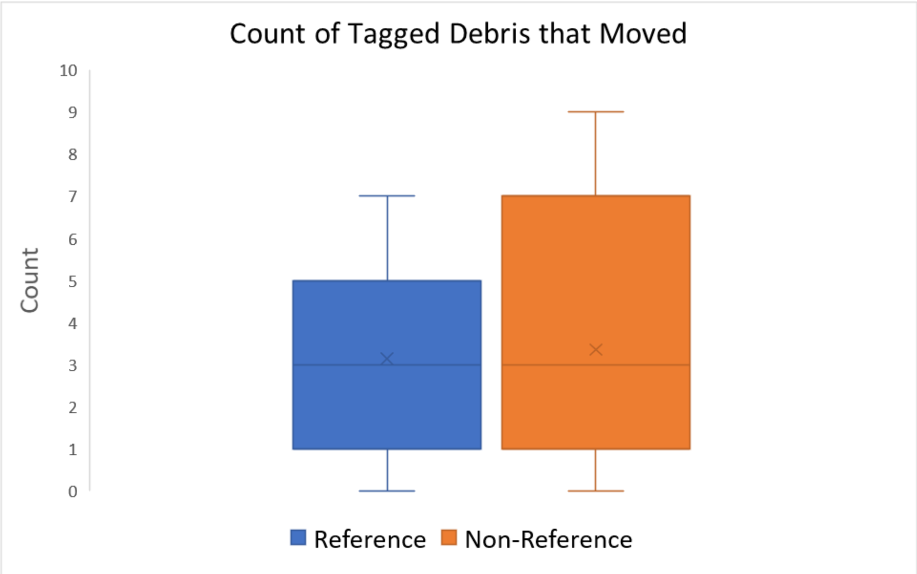

Figure 18. Box-and-whisker plot of the count of pieces of debris that moved at Reference and Non-Reference sites.

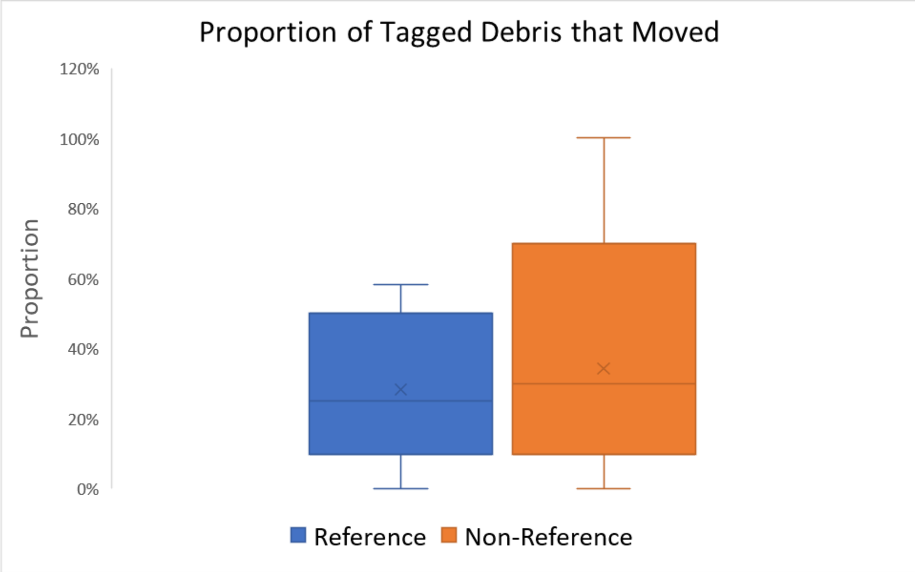

Figure 19. Box-and-whisker plot of the proportion of tagged pieces of debris that moved at Reference and Non-Reference sites.

Movement patterns at Reference and Non-Reference sites were also compared to precipitation patterns (Fig. 17). Precipitation data were retrieved from the NOAA website. Sites 18, 31, and 64 used the State College 2.6 station, sites 10*#, 60*, 23, 130, 241, and 19 used the Boalsburg station, and sites 151, 35, 24, T1, 35A, 239, 233, 230, 234 used the Tyrone station.

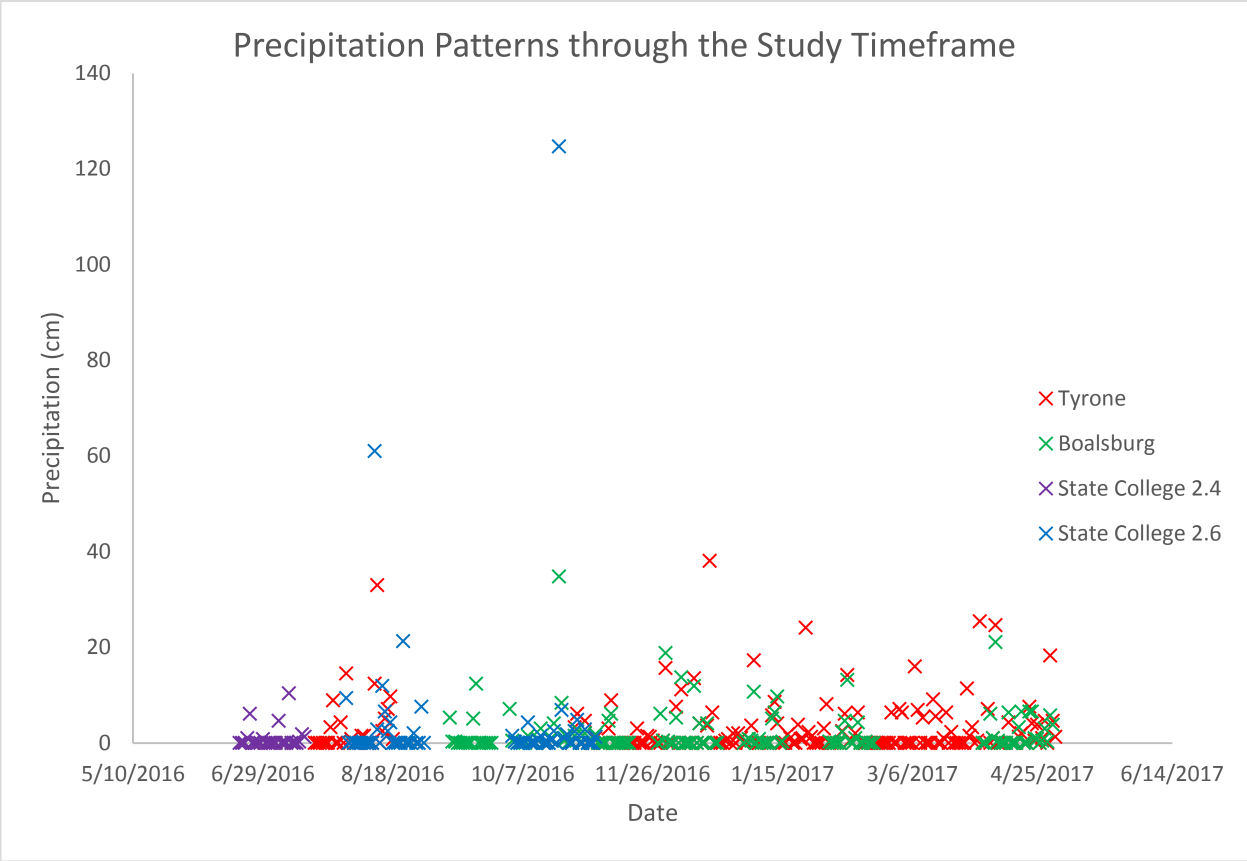

Figure 20. Precipitation patterns through the study timeframe at the four NOAA stations utilized for this study.

For the purposes of this analysis, in each instance of debris movement, the piece was assumed to have been moved by the largest precipitation event recorded during the period of time between field surveys. With this is mind, the average precipitation event sizes required to move a piece of debris at Reference and Non-Reference sites were compared. These data were non-normal, and were analyzed using a lower-tailed Mann-Whitney test (i.e., the expected outcome was that Reference sites would require, on average, larger precipitation events to experience mobility than Non-Reference sites). The p-value was 1.000, indicating that any directional difference was insignificant. However, an upper-tailed Mann-Whitney test (i.e., the expected outcome was that Reference sites would require, on average, smaller precipitation events to experience mobility than Non-Reference sites) returned results indicating a highly significant ($p < 0.0001$) difference between the two types of sites. Potential explanations for this pattern are explored in the Discussion.

The number of movement events at Reference and Non-Reference sites were compared in an attempt to determine any differences in the "flashiness" of flow and movement events between these two types of sites. Data on the number of movement events at each site followed a non-normal distribution, and were analyzed using the lower-tailed Mann-Whitney test. Results indicated that there is no significant ($p = 0.704$) difference between the average number of movement events at Reference and Non-Reference sites. The largest proportion of mobile pieces of debris that moved in a single event was also calculated for all sites. Again, data followed a non-normal distribution, and were analyzed utilizing the lower-tailed Mann-Whitney test. Results indicated that there was no significant ($p = 0.582$) difference between Reference and Non-Reference sites in this measure of "flashiness" as well.

Finally, although flow velocity was not directly measured for this study, several of the component variables from the SWR Index can be considered as proxies for flow velocity. The first of these is Incision Ratio, which is calculated from a number of measurements of bank and channel characteristics related to incision and flooding. Sites with lower Incision Ratios have less channel incision, greater connectivity between the channel and floodplain, and experience fewer intense, flashy floods because water is able to move from the channel onto the floodplain and disperse. Consequently, these sites score higher in the SWR Index. When this component of the Index was analyzed in isolation, results demonstrated that Reference sites do have significantly ($p = 0.043$) lower Incision Ratios than Non-Reference sites, indicating that they also likely have significantly less incision and more flood dispersal and flow attenuation, making movement at these sites less likely. To corroborate this finding, Habitat Parameter 8 (Bank

Stability) of the Stream Habitat Assessment, another component of the SWR Assessment, was analyzed in isolation. This Parameter addresses bank erosion and failure, and in this way, serves as another proxy for flood intensity. Higher scores indicate better quality habitat. Unlike the Incision Ratio, this is a subjective visual assessment, which makes it an excellent counterpoint for the aforementioned variable. Again, analysis showed that Reference sites contain banks that are in significantly ($p < 0.0001$) better condition than Non-Reference sites, implying fewer intense, destructive floods likely to carry away debris.

Contributing Area Analysis

Though the immediate surroundings of a site exert substantial influence over the site's condition and phenomena, in lotic and riparian studies, it is nearly as important to consider upstream conditions. Contributing area size and average slope gradient were analyzed for each site for this study in an effort to account for the influence of these factors on both debris occurrence and movement.

Contributing area size data were found to follow a non-normal distribution, and the relationship between this variable and Reference condition was analyzed using a two-tailed Mann-Whitney test. Results demonstrated that there is a significant difference ($p = 0.011$) in contributing area size between Reference and Non-Reference sites, with Non-Reference sites having larger contributing areas (Fig. 19).

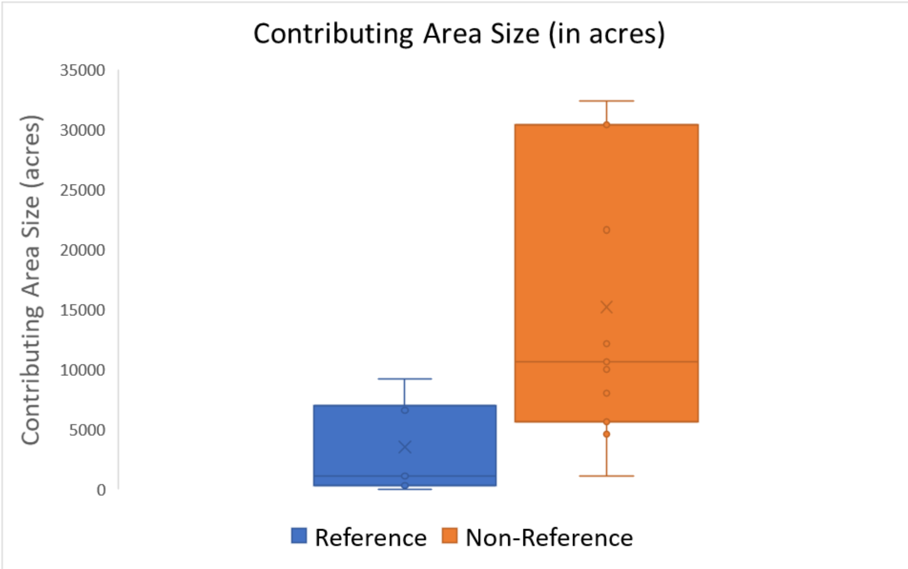

Figure 21. Box-and-whisker plot of the contributing area size at Reference and Non-Reference sites.

The relationship between contributing area and movement was also investigated, as sites with larger contributing areas are expected to experience higher-stage flood flows during precipitation events than sites with smaller contributing areas, and may therefore also experience increased debris movement. Linear regression analyses of both the number of pieces of debris moved and the number of movement events at each site by the contributing area size were completed, but both showed very weak relationships ($R^2 = 0.061$ and 0.059, respectively). A discussion of possible explanations for these results can be found in the Discussion.

The average slope of each site's contributing area was also calculated. Data followed a non-normal distribution and were analyzed using a Mann-Whitney test. Results demonstrated that the contributing areas of Reference sites possessed, on average, significantly ($p = 0.022$) steeper slopes than the contributing areas of Non-Reference sites (Fig. 20).

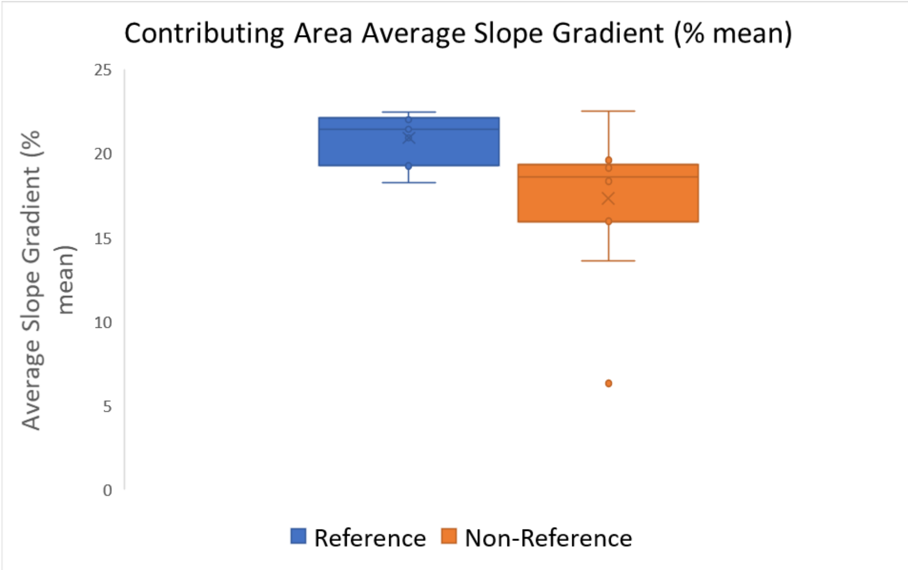

Figure 22. Box-and-whisker plot of the average contributing area slope gradient at Reference and Non-Reference sites.

The relationship between average slope and debris dynamics was investigated using linear regression. Much like contributing area size, the relationships between slope and the number of debris pieces moved and the number of movement events were relatively weak (R^2 = 0.017 and 0.108, respectively).

DISCUSSION

Riparian Debris Conceptual Model

This study investigated several types of debris across variables sites possessing diverse environmental characteristics and processes. In the midst of such variability, it is easy to lose sight of the consistent, unifying factors that enable comparison of debris quantities, characteristics, and dynamics across sights. A conceptual model and accompanying explanation were developed, based on the literature review completed prior to the initiation of this study, in an effort to combat this tendency and more explicitly highlight the portions of the riparian debris "life cycle" that were of interest during this study (Fig. 21). This conceptual model is loosely based upon, and serves as a simplification of, those proposed by Keller and Swanson (1979) and Swanson (2003).

Regardless of the location being studied, debris is recruited to the site in either an autogenic or allogenic manner. Autogenic debris is generated by the standing live and dead trees present at the site, and recruitment can be initiated by a number of processes, including wind, landslides, fire, downstream flows, and anthropogenic disturbances (Maser et al. 1979, Fetherston et al. 1995). These processes can place debris either on the floodplain or in the channel. The final location of the debris is dependent upon the process by which it was felled, whether or not it was alive when it was felled, the tree's species and, if dead, the snag's decay class (Wohl et al. 2010).

Allogenic debris comes from beyond the borders of the site or reach of interest, either from upstream or adjacent upland areas. Generally, if generated upstream, debris is transported to the site via downstream flows, and the deposition location of the debris within the site depends on the debris size, species and decay class, and the intensity of the flow moving the debris. The channel morphology is also an important factor dictating where debris will be deposited, with deposition much more likely to occur on meander bends and point bars (Bertoldi et al. 2013). If generated in upland areas, debris can be transported by landslides or overland flows (Fetherston et al. 1995). Whether or not the debris comes to rest on the floodplain or in the channel is dependent upon the nature of the process transporting the debris and the species and decay class of the debris itself (Wohl et al. 2010). Debris can also enter a site via anthropogenic processes, whether these involve the intentional placement of debris or the unintentional felling of trees that then move or are moved within the site (Krejčí and Máčka 2012).

Debris, whether on the floodplain or in the channel, can exit a site via several different processes. If moving downstream, downstream flows generally initiate the movement of the debris, and the distance over which the debris is moved is dictated by debris size, species, and decay class, and channel morphology (Wohl et al. 2010, Bertoldi et al. 2013, Dixon and Sear 2014). Transport away from a site is also made less likely by a high concentration of log jams, or by the presence of a root wad, both of which physically impede movement of the debris (Braudrick et al. 1997, Curran 2010). Debris also can leave a site as a result of anthropogenic activities; indeed, throughout much of history, humans intentionally removed debris from channels and floodplains to help clear riparian areas for recreation and protect downstream infrastructure from damage (Krejčí and Máčka 2012). Finally, debris can decay to such an extent that it is no longer considered to be coarse debris, at which point it has left the site, in a sense (MacNally et al. 2002).

Of course, the dynamics of debris while at the site itself are nearly as complex and interesting as the dynamics that move the debris to and from the site. Debris in the channel or on the floodplain does not necessarily remain in either of these pools, and both downstream flows and anthropogenic activities can spur movement between the two. Much as they do in other scenarios where debris is being moved either in the channel or over the floodplain, debris species, decay class, and flow intensity act as controlling variables, dictating how far each piece of debris moves, and in which direction. When considering debris that moves from the channel to the floodplain, incision is of particular importance. Channels that have experienced a great deal of incision tend to be disconnected from their associated floodplains, a state that disrupts normal flooding regimes and prevents the transport of debris from the channel to the floodplain (Amoros and Bornette 2002).

Though all of this is understood in a broad sense, much remains to be learned about the specifics of coarse woody debris recruitment and dynamics (Wohl et al. 2010, Dixon and Sear 2014). Reliable data on debris occurrences and movements will be required to build an understanding of how debris is recruited and transported through the landscape, and one of the central goals of this study was to collect data that would strengthen the hypotheses put forth in previous publications and this conceptual model.

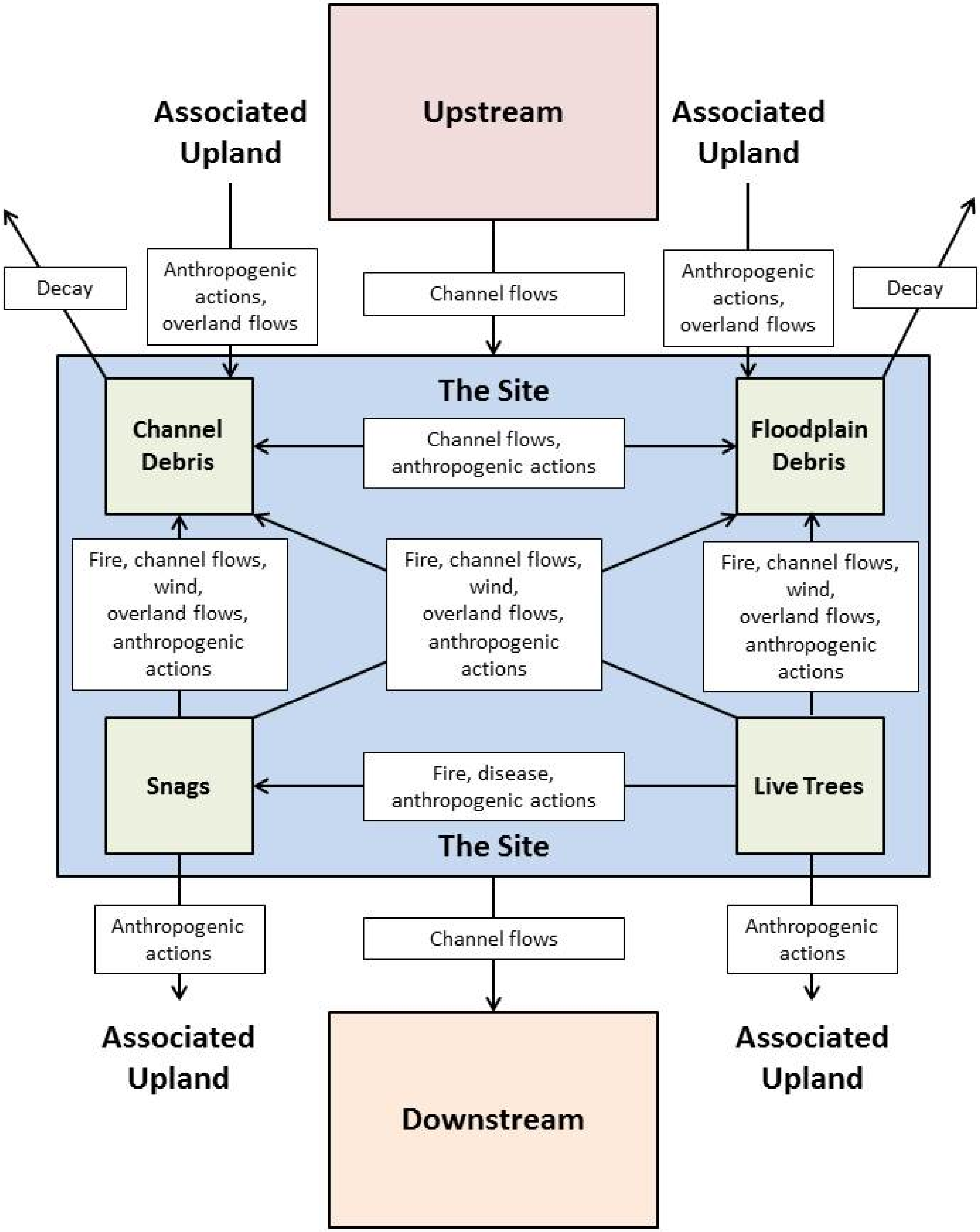

Figure 23. A conceptual model of the manner in which debris moves through a site of interest.

Debris Abundance and Habitat Quality

This study was developed primarily to assess how quantities and characteristics of coarse woody debris vary with anthropogenic disturbance levels in the headwater channels of the Mid-Atlantic Region. Therefore, of the five hypotheses discussed at the beginning of this paper, perhaps the most central is that Non-Reference sites, those subject to more intense human pressure, would contain reduced quantities of debris in comparison to Reference sites. The collected data show a clear and significant difference: of the 18 sites surveyed, those determined to be of Reference quality were found to contain, on average, a greater quantity of debris than Non-Reference sites. This trend is the same regardless of whether the metric used to quantify debris is number of pieces or volume of wood.

The results presented above align with those published by a number of researchers who have undertaken similar studies in other regions (Graham 1925, Elton 1966, Maser et al. 1979, Robison and Beschta 1990, Nakamura and Swanson 1993, Fetherston et al. 1995, McCay 2000, Greenberg 2002, Sweeney et al. 2004, Roni et al. 2015), demonstrating that the fundamental association between debris concentration and habitat quality exists in the headwaters of Mid-Atlantic channels much as it does elsewhere.

Unfortunately, the results of this study and those referenced above create something of a "chicken-or-egg" paradox. Where large quantities of debris become concentrated, via either natural or anthropogenic processes, ecosystem characteristics are altered (and often improved) in a myriad of ways (Nakamura and Swanson 1993, Fetherston et al. 1995, Sweeney et al. 2007). A number of these alterations create conditions that are conducive to, and likely lead to, further debris recruitment. Reduced flow velocities increase the probability that a given piece of debris will be deposited by flowing water at a location, and decrease scouring along the banks, allowing riparian vegetation to remain intact and trap additional debris. Greater connectivity between the channel and the floodplain increases debris recruitment to the channel and simultaneously increases the likelihood that a piece of debris will move from the channel to the floodplain. Both of the changes discussed above increase local sedimentation rates on floodplains associated with debris-rich reaches, which improves soil quality and vegetation health, and leads to larger and healthier riparian forests. It is not hard to imagine that these forests then generate more debris in turn, further increasing local recruitment rates. The question then becomes: is the habitat of Reference-quality because it has a large quantity of debris, or is there a large quantity of debris because the site is of Reference quality? The difficulty in answering a question of this nature means it was not addressed by this study, and is little discussed in the body of work referenced above, although Fetherston et al. (1995) gives it some attention. Although this study did not have the temporal resources necessary, it did lay the groundwork for such a study to take place. Knowing that there is a predictable relationship between debris quantity and habitat quality permits future researchers to monitor Reference-quality sites with a smaller quantity of debris than would be expected, and Non-Reference-quality sites with a larger quantity of debris than would be expected. If the Reference sites of interest accumulate and maintain more debris through time, it may be that the environmental conditions are a prerequisite for debris recruitment. In contrast, if the Non-Reference sites possessing large quantities of debris are shown to improve in quality over time, it may be that debris concentrations are necessary for the improvement of the local ecosystem. It is probable that at most locations a hybrid of these two hypotheses is true, and the degree to which one or the other process is dominant is dependent upon the individual site. Regardless of the initiating factor, it seems likely that once the recruitment and improvement process begins, a positive feedback loop continues to move the channel and associated floodplain toward improved habitat quality.

Debris Characteristics and Habitat Quality

Aside from possessing, on average, greater quantities of debris, Reference sites also possessed larger pieces of debris, both in terms of length and maximum diameter. This correlation is likely the result of a number of factors, including reduced flow velocities and localized debris dynamics. Flow velocity was not measured for this study, but the variables chosen as proxies (Incision Ration and bank stability) indicate that Reference sites are likely subjected to fewer extreme flood events than Non-Reference sites. In addition, a number of variables related to debris recruitment and dynamics were surveyed, including several related to riparian forest condition. At Reference sites, riparian forests contained, on average, more trees than were found on the floodplains of Non-Reference sites, and more trees with larger maximum diameters (Appendix A). On their own, these characteristics of the riparian forest provide a fairly obvious explanation for the increased prevalence of larger pieces of debris at Reference sites. However, they are especially relevant when the relationship between size and transport distance for debris is considered. Most large pieces of debris are recruited from very near the channel and, once in the channel, generally only travel short distances (Sweeney et al. 2004, Bertoldi et al. 2013). The greater local availability of trees capable of producing large pieces of debris is almost certainly primarily responsible for the increased concentrations of pieces of debris of this size at Reference sites.

This is not to say that other factors should be completely discounted. The reduced frequency and intensity of flood flows through Reference reaches may also play a role in maintaining large pieces of debris at these sites. A survey of this variable was not undertaken for this study, but the potential utility of such an endeavor is discussed below.

Reference sites were also shown to contain, on average, debris of a greater range of sizes (data for diameter were not significant) than Non-Reference sites. This is of importance when one considers environmental heterogeneity and the various habitat requirements of the aquatic species that utilize CWD. While hatchling and juvenile fish may utilize fine debris for shelter and as a hunting ground (Everett and Ruiz 1993), mammals like Eastern gray squirrels and Eastern chipmunks use larger debris to cross channels and access new resources (personal observation). The largest pieces alter flow patterns and create plunge pools (Maser et al. 1979), areas that harbor adult fish. The broad range of debris sizes present at Reference sites helps improve habitat quality and generate suitable conditions for a number of different species.

This range of sizes is likely the result of the broader range of tree sizes present in the floodplain forests at Reference sites (Appendix A). Many Non-Reference sites were located in portions of the landscape that had been heavily altered through anthropogenic influence. People frequently remove a majority of the small trees from stands on their property, leaving one or a few medium/large trees in place. This practice would severely limit the production and recruitment of extremes of fine or large debris at these sites, restricting in-stream debris sizes to a narrow, intermediate range.

In the case of the finest debris, it could also be that the more intense, flashy flood flows at Non-Reference sites readily transport this debris downstream to reaches with reduced flow velocities or shallower water depths. As was mentioned above, analysis of Incision Ratios and bank conditions demonstrated that Reference sites are likely subjected to fewer intense, destructive flows than Non-Reference sites, implying fewer opportunities for smaller pieces of debris to be transported downstream.

No significant difference in average decay class was found between the debris at Reference sites when compared to the debris at Non-Reference sites. The less frequent movement and associated increased residence times expected at these sites were predicted to lead to greater levels of debris decay. In reality, it is likely that debris shows a similar amount of decay across almost all sites. Except in areas that have been recently and heavily impacted by disturbance (anthropogenic or otherwise), it is unusual to find large quantities of debris that have not undergone any decay in the channel. Similarly, it is unlikely that debris in advanced stages of decay is capable of remaining intact when acted upon by the constant flow of water. Therefore, it follows that a majority of the debris encountered during the average survey, regardless of location, would display an intermediate amount of decay. This pattern was borne out over the course of this study.

Unlike decay class, root wad presence/absence did differ significantly between Reference and Non-Reference sites, with Reference sites possessing larger quantities of debris with root wads than Non-Reference sites. This has implications both for habitat quality and debris dynamics. Root wads generate habitat heterogeneity by offering fine structures for small organisms to utilize for cover and hunting, creating a suitable environment for species that would otherwise likely have to move elsewhere. The dense and complex network of roots is easily trapped and held by bank vegetation, rocks, and other pieces of debris, and CWD with intact root wads is there less likely to move than CWD missing a root wad (Curran 2010). The increased number of pieces of debris with intact root wads at Reference sites may help explain the greater overall concentration of debris at these sites, as those pieces with root wads are less likely to be moved elsewhere, and are also available to trap other pieces of debris.

There is no obvious explanation for the prevalence of debris with root wads at Reference sites, but these reaches are generally located further from human activity, and are by definition subject to less anthropogenic disturbance and activity than Non-Reference sites. When trees fall by natural processes in proximity to a person's property, they frequently remove the trees to use for fuel or lumber, or to avoid the potential hazard the tree may pose to structures. It is likely that at Non-Reference sites, dead and dying trees are removed from the floodplains, reducing the odds that an entire tree, with root wad intact, will enter the channel. This would reduce the proportion of pieces with root wads at these sites relative to those with little to no human disturbance.

Though this study was successful in supporting the hypothesis of a broad association between habitat quality, debris quantity, and a myriad of debris characteristics, it was unable to establish a predictable relationship between these variables utilizing linear regression analyses. For example, given the results above, a land management professional could confidently say that if their property scores above a 0.80 on the SWR Index scale, there is a high probability that it will contain a larger quantity of debris than a property scoring below a 0.80 on the SWR Index scale. However, that same individual is unable to predict precisely the quantity of debris at their site based upon the exact score. This was one of the perceived shortcomings of previously-completed studies in this field, and it continues to be an issue in need of further investigation. It may be that there were not enough sites surveyed for this study, or that those chosen represented too great a degree of variation. Future studies could utilize a larger pool of sites and focus on establishing a more predictable relationship within a site class (i.e., Reference or Non-Reference).

Despite the fact that no predictable mathematical relationship between debris quantity and Reference status was established, there was some success in uncovering a relationship between riparian forest basal area and local debris quantity. This study demonstrated that sites with greater riparian basal area values had greater quantities of debris in the channel than sites with smaller riparian basal area values. This makes sense, as basal area is a direct indicator of local debris supplies, and sites with more in-channel debris should be associated with large local debris supplies. In addition, when analyzed using a linear regression of the number of pieces of debris by the basal area of the associated riparian forest, a relatively robust mathematical relationship was uncovered. These findings indicate that perhaps, instead of relying on reference status, land managers should measure basal area when analyzing debris on their properties, using the relationship between these variables to determine the appropriate amount to include in artificial placements.

Debris Characteristics and Dynamics

Debris dynamics were addressed by the fourth and fifth hypotheses laid out at the beginning of this study. These statements dealt primarily with the relationship between dynamics and habitat quality, but a number of interesting interactions between debris characteristics and dynamics were also highlighted by the results of this study. Prior studies (Curran 2010, Roni et al. 2015) have addressed the manner in which root wad presence/absence influences debris mobility, and these results were replicated here. Data showed that stationary debris was significantly more likely to possess a root wad than mobile debris. The explanatory factors behind this relationship were not investigated in detail for this study, as they have been addressed in the publications noted above, as well as others. To summarize those findings, it has been shown that the root wad increases the overall length of the debris, and also the "roughness" at one end, making it more likely for the debris to be caught on riparian vegetation or other pieces of debris. It is encouraging to find that movement mechanisms at work in other regions operate similarly in the headwater streams of the Mid-Atlantic Region.

Most prior studies indicate that debris length is a critically important, and in some cases the most important, characteristic in determining whether or not a given piece of debris will move (Haschenburger 2012, Dixon and Sear 2014, Roni et al. 2015). The results of this study showed no significant relationship between length and mobility, but did find significant relationships between mobility and both diameter and volume. All of these variables are indicators of debris size, and one would expect them to display similar relationships with mobility. The fact that length did not, though interesting, is likely the result of the pool of debris considered for this study. The studies cited above dealt almost exclusively with debris in undisturbed settings, meaning a majority of the pieces considered was likely from the larger end of the size spectrum in regards to length (Krejčí and Máčka 2012). This study was somewhat unique in its investigation of debris mobility in a developed landscape, and the dominance of smaller debris at these sites may have affected the results concerning the relationship between length and movement. Many branches were considered that, although long, had relatively small diameters, low volumes, and overall diminutive sizes in comparison to the larger trees surveyed. For studies involving debris from across the size spectrum, I recommend considering total volume, and not length, as the best indicator of mobility.

Environmental Characteristics and Debris Dynamics

In addition to the relationship between physical debris characteristics and mobility, this study also addressed the interaction among precipitation event size, site reference status, and debris mobility. It was predicted that at Reference sites, larger precipitation events would be required to spur movement, as the environmental conditions in and around these sites would likely do a great deal to attenuate flood flows and mitigate their ability to transport debris. In stark contrast to this prediction, results demonstrated that on average, less rainfall was required to generate flows that moved debris at Reference than Non-Reference sites. This counterintuitive result could stem from the greater range of debris sizes found at Reference sites versus Non-Reference sites. If Reference sites contain pieces of debris smaller than the smallest pieces found at Non-Reference sites, than it follows that it would likely take less precipitation to initiate movement at these sites than at Non-Reference sites.

It could also be a result of the fact that the channels found at Reference sites were generally of smaller order than the channels found at Non-Reference sites. This means that less rainfall is required to produce flood flows at these sites, potentially mobilizing debris with relatively precipitation in comparison to Non-Reference sites.

This result could also stem from sampling methodologies that were not designed to capture this particular relationship. It has already been shown that debris size differs significantly between Reference and Non-Reference sites. The complex interactions between debris characteristics, channel morphology, landscape variability, and the varying influences of these factors on debris mobility and how precipitation events are manifested in a given channel are well beyond the scope of this study.

Floodplain Characteristics and Habitat Quality

In-stream debris was the focal point of this study, but because riparian systems comprise both channels and their associated floodplains, data on debris-related variables were collected from the areas immediately adjacent to the channels as well. Reference sites not only possessed more channel debris than Non-Reference sites, but also more floodplain debris, and a greater quantity of floodplain snags. These particular relationships have not been investigated in previous studies, and their exploration here is an important step toward a more complete understanding of how debris moves between the floodplain and the channel, and between disturbed and undisturbed systems. The presence of increased numbers of snags and debris on the floodplain at the same sites that contain large quantities of debris in the channel seems to imply two processes are occurring more often at these locations, both related to increased connectivity between the channel and the floodplain during flooding events. The significant difference in Incision Ratio between Reference and Non-Reference sites speaks to this difference in connectivity.

First, debris suspended in flood waters is, upon entering these Reference reaches, more likely to be pushed out of the channel onto the floodplain, where flows are slower, depths are shallower, and surface roughness is increased. A significant portion of this debris then, is likely deposited on the floodplain, increasing the quantity found there. Conversely, as these same flood flows move over the floodplain, some pieces of debris present there are likely transported back into the channel, where they are trapped by pre-existing log jams or larger pieces of debris. This increases the in-stream count of debris at these Reference sites. In addition, snags are continuously being felled by natural processes, providing debris to both the channel and the floodplain and fueling both of the processes outlined above.

Unfortunately, this study did not directly monitor the flux of debris on a Reference floodplain over time. To more accurately capture the dynamics of this process, a long-term study focusing on one or a handful of floodplains should monitor the influx and outflux of debris over time, noting the size of pieces that come and go, and the quantity of precipitation (and accompanying flood depth) that initiates movements.

When studying debris, dead and downed trees are obviously the primary focus, but the composition of the living forest is also of great interest as the source of almost all local debris. Of particular interest is the ratio of conifers to hardwoods, as the debris produced by these two groups has markedly different patterns of decay and mobility (Dixon and Sear 2014). These differential properties influence recruitment, loading, and jam formation in turn.

As has been previously mentioned, of the conifers found in the riparian forests surveyed for this study, Eastern Hemlocks (*Tsuga canadensis*) were by far the most prevalent. This was not surprising because, of the handful of conifer species native to central Pennsylvania, Eastern Hemlock is by far the most common species in floodplain and riparian environments (Lutz 1930). What was perhaps more surprising was the drastic difference in hemlock population counts between Reference and Non-Reference sites, with Non-Reference sites containing significantly ($p < 0.0001$) fewer conifers than Reference sites (due to their overwhelming dominance, hemlock and conifer counts are considered to be equivalent).

When recruiting through natural processes, hemlocks do best in mature interior forests, where their shade-tolerance and relatively slow growth rates lend them a competitive edge over other common species that require more light (e.g., *Quercus* species) (Godman and Lancaster 1990). However, this has not prevented them from entering the horticultural trade as a popular landscaping tree, and they are capable of surviving under more exposed conditions. It was somewhat surprising to find them nearly completely absent from the smaller riparian forests of Non-Reference sites, and indicates that many of these stands were either planted by hand, or have only recently begun to re-establish following past anthropogenic or natural disturbance.

Aside from indicating the presence of mature interior riparian forest habitat and providing conifer-dependent species with necessary conditions, the relatively large proportion of Eastern Hemlocks at Reference sites has a number of implications for debris recruitment and dynamics. Conifer debris is generally less dense than hardwood debris, and is, therefore, often recruited from greater distances from the channel, and is prone to moving greater distances once in the channel (Dixon and Sear 2014). This phenomenon likely contributed, to some degree, to the increased debris loading at Reference sites observed during the course of this study. Future work incorporating a more careful identification of debris to the species level would shed some light on the role that this plays.

In addition, as was mentioned in the Introduction, the increasing prevalence of native pests and diseases will have a dramatic impact on the structure of Mid-Atlantic forests over the next several decades. This is especially true for Eastern Hemlock, which is experiencing widespread mortality as a result of hemlock wooly adelgid (*Adelges tsugae*) (McClure 1991). The prevalence of this species at Reference sites means forests of the type observed at these locations (i.e., mature, interior riparian stands) may be those most affected by invasive species as time progresses. It will be interesting to observe how debris loading and dynamics change at these sites in the future.

Study Limitations

Though this project was successful in demonstrating that many of the previously-established relationships between coarse woody debris and anthropogenic disturbance exist in the Mid-Atlantic Region much as they do elsewhere, no consistent, predictable relationship between variables was uncovered. Establishing such a relationship could be acheived if some of the limitations of this study are addressed. Of primary importance is the acquisition of a larger sample, in several senses. For this study, only 18 sites were utilized, all within the same region, and all surveyed over the same 8-10 month period. This is a limited sample, both physically and temporally, and allows for little variation in debris and landscape characteristics, weather patterns, and environmental change. With an expanded sample size, both temporally and geographically, it is likely that many of the outliers and odd aberrations would become part of a more easily-explained spectrum.

This study is also limited in its quantitative and empirical measurement of many of the variables of importance. Much of the survey procedure is reliant on best professional judgment, which makes the results valid within the study, but difficult to compare between surveys. The development of more objective methods of measurement, while likely increasing the time required to complete the protocol, would make the conclusions significantly more robust.

Similarly, better methods are needed to account for the incredible diversity of land use histories and weather patterns in this region. Both of these factors were coarsely accounted for in this study, but each exerts an enormous influence on the manner in which debris is recruited and moves through an ecosystem of interest. Accounting for these factors in a more detailed and explicit manner in future studies could increase the significance of the results, and render the conclusions more applicable outside the study region.

Monitoring of debris dynamics was one of the principal components of this study, and offers perhaps the greatest opportunity for methodology improvement moving forward. Debris should be chosen from each site randomly in an effort to avoid researcher bias and hopefully give a more accurate idea of how debris characteristics influence mobility. Furthermore, in only two cases were tagged pieces of debris recovered after they moved from their original locations, despite extensive searches both downstream and within the study plots themselves. There are a number of factors that are hypothesized to have negatively influenced recovery rates, including (but not limited to) distances moved, algae growth, leaf litter, sedimentation, and tag removal. Although it was easy to recognize a piece of debris in its original location, it was effectively impossible to do so once it had moved, and the tags utilized were too small to be seen except upon extremely close inspection of the debris. If a movement survey of this nature is undertaken in the future, it is advisable to attach a significantly larger marker to the chosen pieces of debris. If possible, GPS or telemeter tracking should be utilized.

CONCLUSION

This study set out to test five hypotheses, and was successful is gathering data relevant to three of those five. Reference sites were shown to contain significantly larger quantities of coarse woody debris, regardless of whether the metric utilized to measure quantity is volume or a count of the individual number of pieces (1). The debris at Reference sites was shown to have a broader range of sizes than the debris at Non-Reference sites and, in addition, debris found at Reference sites was found to be larger on average (2). Finally, those sites containing the largest pieces of debris were also found to be those providing the most and highest quality ecosystem services, including carbon storage (3). The insignificant difference in decay classes between Reference and Non-Reference sites prevented a more nuanced investigation of this variable, but findings like these will be important in the future as local land managers are increasingly charged to make decisions that positively influence not only their property, but global trends like climate change and ocean acidification.

Though a predictable mathematical relationship between quantity of debris and SWR Index score was not determined, debris count did show a relatively strong correlation with riparian forest basal area. Land managers interested in utilizing debris installations on their properties, or those interested in discouraging agricultural professionals from removing channel debris, would likely do best to survey the floodplain forest and base their use of debris on the results of these surveys.

Unfortunately, few conclusions were drawn regarding debris dynamics and mobility, variables addressed by the remaining two hypotheses (4 & 5). Results did not demonstrate conclusively whether or not debris at Reference sites is less likely to move than debris at Non-

Reference sites, and, if it does move, whether or not this movement will be more or less consistent.

A wealth of future studies could be developed to further shed light on these and other as-yet unanswered questions. Perhaps the most obvious route is the extension of this study, both geographically and temporally. As was noted above, this particular endeavor was somewhat limited in its impact due to the truncated nature of the sampling period and the localized focus inherent in the sample site selection. Future efforts incorporating other ecoregions of the Mid-Atlantic Region over several years would likely avoid many of the issues associated with this study, and would account for and include streams varying in order and slope, watersheds of different sizes, and riparian forests composed of different suites of species. Undertaking larger studies that account that account for these variables would position authors to craft far more widely-applicable statements regarding debris characteristics and dynamics throughout the diverse ecosystems of the Mid-Atlantic.

A more robust characterization of the ecosystems themselves would also aid in the expansion of the conclusions drawn here, and help draw stronger lines of correlation between habitat quality and debris characteristics (perhaps giving an idea of which is more important to the presence of the other). This could involve a more intensive study of forest composition, or a thorough investigation of the land-use history at each of the sites of interest. It could also incorporate a survey of an expanded suite of ecosystem services, as there are a number that are closely associated with coarse woody debris that were not measured for this study. For example, flow velocity, which should decrease within reaches that contain large quantities of debris or debris jams, could be measured directly and utilized as a proxy for a number of ecosystem services, including increased local sedimentation, reduced local scouring, and improved habitat for certain species of flora and fauna.

To this end, there are several ongoing efforts associated with this study that hope to improve the characterization of ecosystem services at a number of the sites studied. Sedimentation disks were placed at each of the sites in an effort to determine how debris quantities and characteristics may be affecting flow velocities and local sedimentation/scour rates. Macroinvertebrates were also collected at 6 sites (3 Reference sites and 3 Non-Reference sites) in an effort to determine how differential debris concentrations may be influencing local macroinvertebrate populations. There are plans to publish the data and analyses from these studies at a later date.

Expanded surveys of the debris itself also has the potential to strengthen connections between concentrations, characteristics, and ecosystem health. One of the areas wherein this study could be expanded significantly is the characterization of the individual pieces of debris. Temporal constraints limited the number of qualities that could be surveyed intensively in the field, but an extended sampling period and a larger budget and/or field team would allow for the collection of a great deal more data. Debris could be classified according to its embeddedness, which influences its mobility (Wohl and Goode 2008). Debris could also be better classified according to species and age, information that would give an improved sense of origin, local recruitment rates, and the differential mobility of different species, old trees versus young trees, etc. Employing remote sensing technology to characterize the amount of debris dispersion along a reach could reveal how this metric is related to channel morphology and flow intensity, and how it influences ecosystem service provisioning. Differential mobility would also be far better monitored through the application of improved debris tracking methods. These were discussed in some detail in the Discussion section, but their importance to potential future studies into debris mobility should not be overlooked.

Future studies of this nature will be critical because, when considered in a nationwide context, the MAR contains one of the most heavily-monitored and managed watersheds, the Susquehanna, and perhaps the most heavily-monitored and managed body of water, the Chesapeake Bay. In spite of this fact, much remains to be done to restore the ecological integrity of this region's water resources. Nutrient and sediment loading continue to be perennial problems in the Bay, and only a careful investigation of upstream processes will generate a solution to these issues (Hassett et al. 2005). In fact, research has demonstrated that watershed deforestation, primarily occurring on tributary rivers and streams, is largely responsible for the increased loads of nutrients and sediments that the Bay experiences today (Langland and Cronin 2003). Given what is known about the beneficial impacts of coarse woody debris, it is reasonable to assume that many of these problems stem from the severely-reduced coarse woody debris load tied to the aforementioned deforestation. Loss of this vital but previously underappreciated piece of ecosystem architecture has had wide-reaching effects throughout the Susquehanna watershed and the Bay itself. Within the past few decades there has been a new understanding regarding the importance of woody debris, but there is still little evidence, particularly for the Mid-Atlantic Region, to demonstrate precisely how anthropogenic disturbance is influencing recruitment and loading. The goal of this study was to not only begin to answer some of the larger questions surrounding these issues, but also to supply land conservation professionals with guidance on how best to manage their properties for CWD. If managers are better able to understand the relationship between CWD and disturbance, then they will perhaps be more well-equipped to make decisions regarding riparian buffers, agricultural practices, and log jam installations. It is hoped this information will be used to improve the ecological quality of the Susquehanna watershed, the Chesapeake Bay, and their tributaries.

APPENDIX A:
SUPPORTING DATA

Table 5. Site-by-Site Tree Metrics.

Site ID	Final Score	Total # Trees	Average DBH	# Trees w/ DBH > 40
234	0.434062119	7	60.00	6
31	0.504554522	1	37.00	0
35	0.516125599	1	73.00	1
35A	0.623620585	20	56.25	11
64	0.635263356	4	52.00	4
230	0.648738874	12	30.75	1
239	0.662933004	17	36.24	6
130	0.685623642	18	42.11	8
18	0.701948064	13	30.00	1
233	0.736442345	23	26.78	2
151	0.778337751	17	36.94	5
24	0.812023936	29	32.69	6
60*	0.834942204	58	42.53	24
23	0.862801303	29	38.1	11
T1	0.906857594	29	30.86	4
19	0.917470397	44	34.77	13
10*#	0.929242541	60	43.62	26
241	0.948142241	35	34.03	7

Table 6. NOAA Weather Station Locations

Name	ID	Latitude	Longitude
Boalsburg	GHCND:US1PACN0013	40.7736	-77.7847
State College 2.4 ENE	GHCND:US1PACN0003	40.8067	-77.8167
State College 2.6 NW	GHCND:US1PACN0005	40.8162	-77.8954
Tyrone	GHCND:USC00369022	40.6645	-78.2191

APPENDIX B
SUPPLEMENTARY PICTURES

Riffles typical of a Non-Reference study site (Site 151). Very little debris present.

Run typical of a Non-Reference study site (Site 234). Very little debris present.

Log jam typical of a Non-Reference study site (Site 18).

Intense algal growth at a Non-Reference site (Site 64). Indicative of high nutrient concentrations and direct sunlight.

Bank scour at a Non-Reference site (Site 233). Indicative of intense flood flows and low channel-floodplain connectivity.

Debris jammed against a farm bridge at a Non-Reference site (Site 234). Residents stated that debris had to be removed frequently to prevent damage.

Log jam typical of a Reference site (Site 10*#). Note the large quantity of debris and the size of the individual pieces comprising the jam.

Channel typical of a Reference site (Site 60*). Note the large quantity of debris and the size of the pieces present.

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