

Riparian forest structure and stream geomorphic condition: implications for flood resilience

William S. Keeton, Erin M. Copeland, S. Mažeika P. Sullivan, and Mary C. Watzin

Abstract: Managing riparian corridors for flood resilience requires understanding of linkages between vegetation condition and stream geomorphology. Stream assessment approaches increasingly use channel morphology as an indicator of stream condition, with only cursory examination of riparian vegetation. Our research (i) examines relationships between stream geomorphic condition, as assessed by Rapid Geomorphic Assessment (RGA) scores, and riparian forest structure, and (ii) investigates scale dependencies in the linkages between land cover and stream geomorphology. We sampled vegetation structure and composition and assessed geomorphic condition at 32 stream reaches within the Lake Champlain Basin, USA. RGA scores were modeled as a function of structural attributes using classification and regression trees. Landsat coverages were used to delineate land uses within five nested spatial scales. Generalized linear models (GLM) evaluated relationships between land cover and RGA scores. Standard deviation of basal area partitioned the greatest variability in RGA scores, but dead tree density and basal area (positively) and shrub density (negatively) were also significant predictors. RGA was related to forest and agricultural cover at the two finest scales. Riparian forest structure is highly dynamic in relation to stand development and disturbance history; simple forest cover information does not capture these differences or their influences on stream geomorphic condition.

Key words: stream ecosystems, riparian forest structure, stream geomorphology, watershed management, flood resilience.

Résumé : L'aménagement de corridors riverains pour favoriser la résilience aux inondations exige qu'on comprenne les liens entre l'état de la végétation et la géomorphologie des ruisseaux. Les approches visant à évaluer les cours d'eau font de plus en plus appel à la morphologie du canal en tant qu'indicateur de l'état d'un cours d'eau et se limitent à un examen superficiel de la végétation riveraine. Notre recherche examine (i) les relations entre la géomorphologie d'un cours d'eau, selon les résultats de la technique d'évaluation géomorphologique rapide (EGR), et la structure de la forêt riveraine et (ii) si les liens entre la couverture terrestre et la géomorphologie d'un cours d'eau dépend de l'échelle. Nous avons échantillonné la composition et la structure de la végétation et évalué l'état géomorphologique de 32 tronçons des cours d'eau dans le bassin du lac Champlain, aux États-Unis. Les résultats de l'EGR ont été modélisés en fonction des attributs structuraux à l'aide d'arbres de régression et de classification. La couverture du satellite Landsat a servi à délimiter l'utilisation des terres selon cinq échelles spatiales imbriquées. Des modèles linéaires généralisés ont servi à évaluer les relations entre la couverture terrestre et les résultats de l'EGR. L'écart-type de la surface terrière partageait la plus grande variabilité des résultats de l'EGR, mais la densité et la surface terrière des arbres morts (positivement) ainsi que la densité des arbustes (négativement) étaient aussi des prédicteurs significatifs. L'EGR était reliée au couvert forestier et agricole aux deux échelles les plus fines. La structure de la forêt riveraine est très dynamique relativement au développement et à l'historique des perturbations du peuplement; l'information simple au sujet du couvert forestier ne détecte pas ces différences ou leurs influences sur la géomorphologie d'un cours d'eau. [Traduit par la Rédaction]

Mots-clés : écosystème des cours d'eau, structure de la forêt riveraine, géomorphologie des cours d'eau, aménagement des bassins, résilience aux inondations.

1. Introduction

In the wake of two major weather events within the last five years (Tropical Storm Irene, 2011; Hurricane Sandy, 2012), managing riparian corridors for flood resilience has become a pressing concern in the northeastern United States (US Northeast) and other regions. Developing a better understanding of linkages between vegetation condition and stream channel geomorphology is vital for informing these efforts. Stream condition assessment approaches (both physical and biological) in the US and globally have used channel geomorphology as an indicator of ecological condition (Rowntree and Wadson 2000; Maryland Department of Natural Resources (MDDNR) 2001; Southerland 2003; Sullivan

et al. 2004; Sullivan and Watzin 2008; Sullivan 2012; Valero et al. 2015). While the structure of riparian forest stands is known to influence in-stream aquatic habitat characteristics and energy flows (Warren et al. 2016) through, for instance, the provisioning of shade and organic matter, most empirical studies on this topic in the US have been conducted in the western US (Bilby and Ward 1991; Fetherston et al. 1995; Naiman et al. 1998, 1999; Warren et al. 2013). Recent research has increased our understanding of riparian forest structure and dynamics in stream systems in the US Northeast (e.g., Hughes and Cass 1997; Keeton et al. 2007; Laser et al. 2009; Morris et al. 2010; Bechtold et al. 2016). Riparian forest structure is likely to have important reciprocal relationships with various aspects of stream channel geomorphology and ecological

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condition, influencing the entrainment and distribution of large wood (LW) and rootwads (Gurnell et al. 2005; Warren et al. 2009), bank erosion and sedimentation (Zaimes and Schultz 2015), channel geometry and adjustment (e.g., channel widening, changes in meanders) (Hession et al. 2003; Sullivan et al. 2004; Sweeney et al. 2004), chemical water quality (Souza et al. 2013; Fernandes et al. 2014), and energy dynamics (Gregory et al. 1991; Naiman et al. 1999). Thus, riparian forest condition may represent an indirect (through linkages with geomorphology), though important, control on both in-stream habitat characteristics and stream-flow regimes (Thorne 1990; Johnson et al. 1995; Shields and Gippel 1995; Tabacchi et al. 2000; Rahmeyer et al. 1999). Riparian forest control on stream geomorphology has previously been termed “forced morphology” (Montgomery and Buffington 1997).

Understanding relationships between riparian forest structure and stream condition is particularly important in human-dominated landscapes such as northern New England, where land-use history has dramatically altered forest age-class distributions (Lorimer 2001; Lorimer and White 2003; Nislow 2005), as well as the distribution and structure of forest vegetation (Foster et al. 1998; Cogbill 2000; Fuller et al. 2004). These changes are likely to have altered structure-related riparian forest functions such as organic matter input and storage (Keeton et al. 2007; Warren et al. 2009), flood dispersion (Rahmeyer et al. 1999), sediment retention and transport (Fetherston et al. 1995), and the composition and abundance of riverine biotic communities (Jones et al. 1999; Warren et al. 2016). Interest in these relationships has recently spiked in light of the severe flooding and impacts of Hurricane Irene, a post-tropical, high-precipitation storm that struck portions of Vermont and other states of the US Northeast in late August 2011. Regional interest is thus very high in managing for resilience to extreme weather events, including strategies designed to maintain floodplain integrity and conserve forest cover in sub-watersheds important for flood resiliency (Watson et al. 2016). Our study, employing data collected prior to Hurricane Irene (August 2011), establishes baseline relationships that may help inform studies of the very dramatic perturbations, e.g., mass wasting events and wood inputs into streams, caused by this and future extreme events. We focus on a mixture of streams and small rivers, including lower gradient systems and their associated alluvial floodplains, for which relatively few studies have investigated forest-stream interactions in the US Northeast.

1.1. Stream geomorphic condition

Our research examines relationships between forest structure and stream geomorphic condition using a protocol called Rapid Geomorphic Assessment (RGA, see below). As outlined in Sullivan et al. (2006), stream geomorphic condition represents the deviation of a channel from morphological characteristics of a reference, equilibrium reach based on dominant channel adjustment processes: degradation (incising), widening, aggradation, and planform change. Streams are in a state of dynamic equilibrium when sediment transport (i.e., stream discharge and sediment particle size) equals stream power (e.g., stream flow and slope) (Lane 1955). Equilibrium (also referred to as stream stability) is lost when one of the variables changes, requiring one or more of the other variables to increase or decrease proportionally to maintain equilibrium (Lane and Richards 1997; Sullivan et al. 2004). Such disequilibria, due to the formidable force of water and sediment, can lead to significant changes in stream channel form and structure (Pizzuto et al. 2000; Hession 2001). Streams in equilibrium typically exhibit minimal alteration in course from year to year, move water and sediment load in balance, and are characterized by minor bank changes and natural erosion. Conversely, adjusting streams can change course by metres per year, cut new channels, have large sections of collapsing banks, widen and (or) cut deeper into the channel, and can have heavy silt and sediment deposits in natural pools. To re-equilibrate, channels generally pass through a sequence of stages.

These include incising, widening, and eventually re-stabilizing in a new geometry, as conceptualized in channel evolution models presented by Schumm (1977) and Schumm et al. (1984).

The RGA is a semiquantitative evaluation designed to synthesize channel condition using field indicators related to channel adjustment (e.g., bank erosion, sediment deposition, channel avulsion, entrenchment, connectivity to floodplain, etc.; Vermont Department of Environmental Conservation (VTDEC) 2003; Sullivan et al. 2006) and stage of channel evolution. RGA scores are useful for assessing stream geomorphic condition at the reach scale (typically 10^1 – 10^2 m) and have been shown to be reflective of more quantitative channel evaluations and to help define past and (or) current mechanisms of channel adjustment. Higher RGA scores correlate with more stable channel configurations (VTDEC 2003) and have been shown to be tightly linked to aquatic biota (Sullivan et al. 2004, 2006; Sullivan and Watzin 2008).

The RGA is one of several techniques used to prioritize stream reaches for restoration, protection, and management in the US (MDDNR 2001; VTDEC 2003; Rosgen 1996) and abroad (e.g., Cohen et al. 1996; Rowntree and Wadeson 2000; King and Day 2002). Other methods focus more directly on aquatic biota (e.g., Karr 1981; Davis and Simon 1995; Barbour et al. 1999) rather than on geomorphology. As a reach-scale assessment, the RGA is typically used in conjunction with watershed-scale analyses. While limited by its semiquantitative nature, the RGA is actively used by natural resource agencies because it provides a low cost and efficient assessment tool for linking geomorphic condition with anthropogenic land use (Jokay and Watson 2005). Changes on the landscape have the potential to affect channel evolution, and thereby RGA scores, through the modification of water and sediment yields. Moreover, the RGA is typically used as one of several indicators of stream corridor condition and thus can be combined with other information (e.g., biotic, chemical, etc.) in ecological assessments (Sullivan and Watzin 2008).

1.2. Effects of riparian forests on stream-channel dynamics

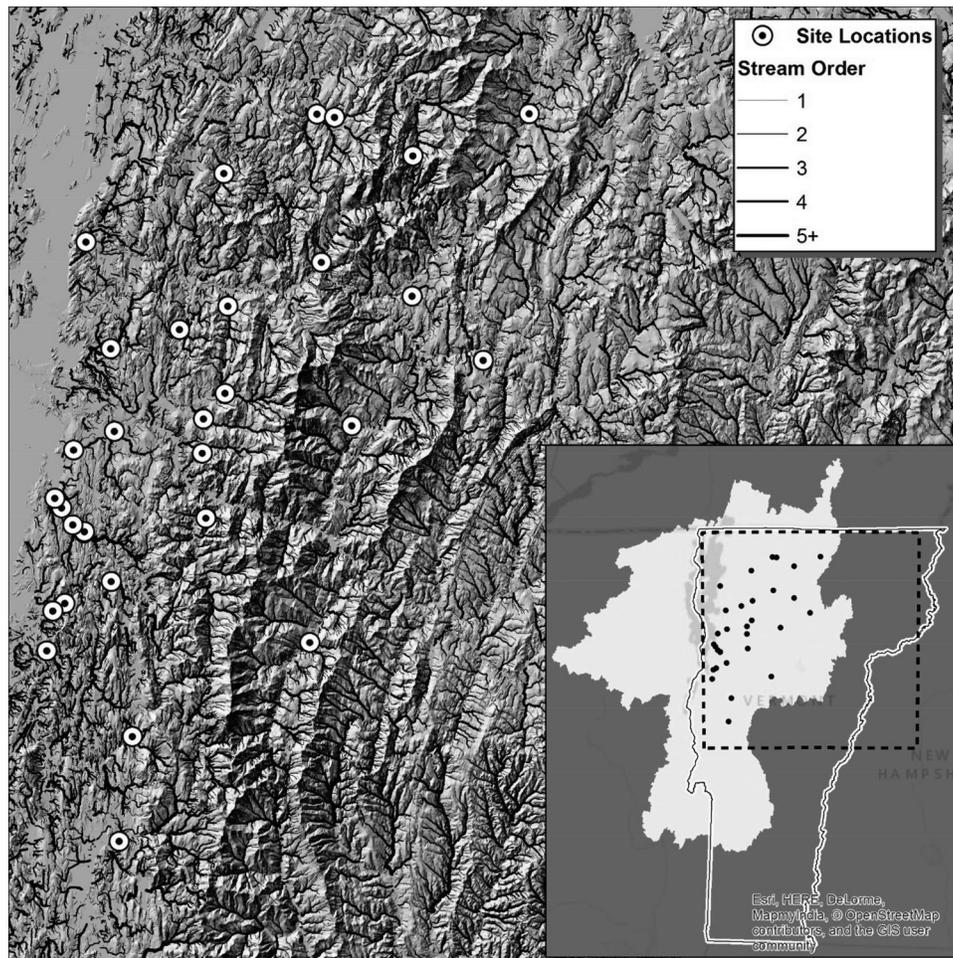
Riparian forests are known to regulate water and sediment movement into stream channels (Endreny 2002; Sweeney et al. 2004). However, research on interactions between vegetation and stream morphology has mostly compared forested streams to un-forested streams (Murgatroyd and Ternan 1983; Sweeney et al. 2004; Anderson et al. 2004; Hession et al. 2003; Allmendinger et al. 2005). Similarly, stream condition assessments often identify presence or absence and extent of riparian forest cover but involve few or no quantitative measurements, e.g., plot-based sampling, of forest structure (Rowntree and Wadeson 2000; MDDNR 2001; VTDEC 2003).

We tested the hypothesis that stream geomorphic condition, as measured by reach-scale RGA scores, in northern hardwood-conifer systems is influenced not by the presence or absence of forest cover alone, but varies with differences in stand structure among reaches. This is likely because stand structure influences coarse root density and thus bank stability (Micheli and Kirchner 2002), water dissipation during flooding (Rahmeyer et al. 1999), and in-stream geomorphic processes related to LW inputs (Bilby and Likens 1980; Montgomery and Buffington 1997; Gurnell et al. 2005; Keeton et al. 2007; Kraft et al. 2011).

1.3. Scale-dependent land cover – stream geomorphology interactions

Stream geomorphic condition scores are often used to prioritize stream reaches for restoration, yet the scale at which land cover and vegetation condition affect geomorphology is not consistently determined. Relationships attributed to proximate effects (i.e., a change within the adjacent riparian area) may reflect upstream or watershed-scale effects or the cumulative effects of processes operating at multiple spatial scales. This has the potential to cause a decoupling between the scale at which restoration

Fig. 1. Location of the 32 stream study reaches within the Lake Champlain Basin (LCB), Vermont, USA. Topography is indicated by shading and stream order is indicated by line thickness (see legend) based on [Strahler \(1952\)](#). Map produced by Dr. Jarlath O'Neil-Dunne, Spatial Analysis Laboratory, University of Vermont.



and conservation activities are conducted and the scales at which deleterious influences occur. With the increasing emphasis and financial expenditure devoted to stream, river, and riparian restoration throughout the US ([Bernhardt et al. 2005](#)) and the use of RGA scores to prioritize restoration projects, it is essential to understand scale dependencies in mechanisms of geomorphic change. Therefore, we tested a second hypothesis that reach-scale RGA scores correlate with forest cover at multiple spatial scales, ranging from 50 m on either side of river reaches to entire watersheds (3.7–509 km² drainage area). This is likely because upstream land use has the potential to alter sediment and water supply, which are important drivers of channel evolution.

2. Methods

2.1. Study area

Our study area encompasses the Vermont, USA, portion of the Lake Champlain Basin ([Fig. 1](#)). It has a depositional history of marine, lake, and large river sediments. These soils are the region's most agriculturally productive soils. The valley has gentle to rolling topography and is bounded to the east by the Green Mountains, a northern extension of the Appalachian Range. Elevations range from 29 m to approximately 550 m above sea level, with annual precipitation averaging 76 cm. Lake Champlain drains five major rivers: the Missisquoi, Lamoille, Winooski, LaPlatte, and Poultney. The Champlain Valley in Vermont has been farmed since the late 1700s; it is 62% forested and 28% agricultural, with

the remainder in wetlands, urban–suburban development, and other land-cover classes ([Meals and Budd 1998](#)).

2.2. Selection of study streams

We sampled 32 third- to fifth-order stream reaches ([Table 1](#)) within the Lake Champlain Valley. Reach drainage areas ranged in size from 3.7 to 509 km², with an average of approximately 110 km². We chose reaches in streams flowing through a range of land-cover types and habitat conditions. Reaches were >10 bankfull channel widths in length and encompassed a range of bed morphologies, including pool-riffle and plane bed, as described by [Montgomery and Buffington \(1997\)](#). Vegetation surrounding the reaches ranged from nonforested (e.g., agricultural or wet meadow) to fully forested (floodplain or upland forest). Forested vegetation in the Champlain Valley is dominated by northern hardwoods and northern hardwood–conifer forest types ([Thompson and Sorenson 2000](#)), although remnant stands of clayplain forest exist (abundant pre-19th century), which include central hardwood species ([Cogbill et al. 2002](#)).

2.3. Data collection

2.3.1. Vegetation inventory

Stream reaches selected for study were delineated on 0.5 m resolution digital orthophoto quadrangles ([Fig. 2](#)). Stream channels were buffered to 50 m on both sides in a geographic information

Table 1. Descriptive information for study reaches.

Reach number	Reach ID	RGA score (%)	Stream geomorphic condition category	Drainage area (km ²)	Bankfull width (m)	50mR		100mR	
						Forest (%)	Agriculture (%)	Forest (%)	Agriculture (%)
1	EPAFR	79	G	36.8	8.4	40	53	20	66
2	EPATB	65	G	43.9	15.8	57	0	17	12
3	EPABG	73	G	32.0	12.3	88	11	61	18
4	EPABB	74	G	30.5	14.5	92	0	56	12
5	EPARB	68	G	16.6	6.7	74	0	60	11
6	EPABR	56	F	52.8	19.8	55	34	12	70
7	EPALR	60	F	34.8	10.8	55	41	20	29
8	EPAMC	61	F	43.7	10.8	60	27	49	30
9	EPAHR	96	R	160.8	22.0	88	0	48	13
10	EPAAB	40	F	27.9	6.6	0	100	0	72
11	EPAMB	60	F	33.4	12.2	72	0	43	36
12	EPALP	59	F	80.9	13.8	37	0	17	55
13	EPALC	84	G	195.6	24.5	81	0	57	8
14	EPALO	66	G	148.2	17.1	85	0	17	58
15	EPANH	64	F	219.5	20.9	77	7	4	57
16	EPAMS	66	G	173.6	25.8	98	0	29	23
17	EPASB	55	F	3.7	10.1	58	0	48	10
18	EPALM	70	G	509.2	35.2	11	89	13	36
19	EPANB	48	F	150.4	26.3	46	39	3	40
20	EPAGR	74	G	139.4	23.7	93	0	47	14
21	EPAWB	44	F	58.7	14.6	14	55	13	49
22	EPAMD	50	F	240.0	33.2	13	85	8	41
23	EPAST	75	G	22.7	7.8	40	52	13	53
24	EPAPB	73	G	15.8	8.3	100	0	58	22
25	EPAMR	66	G	121.4	23.9	56	22	15	40
26	NERCTB	31	P	55.0	29.0	40	60	NA	NA
27	NERCLP2	64	F	111.0	18.0	0	0	NA	NA
28	NERCLP3	77	G	110.0	15.0	60	30	NA	NA
29	NERCLP5	91	R	80.0	16.0	30	10	NA	NA
30	NERCLC2	66	G	200.0	21.0	30	0	NA	NA
31	LPMAZ	85	R	NA	18.6	100	0	NA	NA
32	LCMAZ	76	G	NA	14.7	100	0	NA	NA

Note: Rapid Geomorphic Assessment (RGA) scores are presented as a percentage with higher scores indicating better stream geomorphic condition. Categories for stream geomorphic condition: reference (85–100); G, good (65–84); F, fair (35–64); P, poor (0–34). NA, data not available; 50mR, reach buffered at 50 m on both sides of the stream; 100mR, reach buffered at 100 m on both sides of the stream. Reaches with unavailable data for the 100 m buffer were not included in the GLM analysis for that scale.

system (ESRI ArcMap 8.0). We then stratified within buffered reaches, digitizing polygons by vegetation patch type. Based on orthophoto interpretation and field validation, vegetation patches were classified as upland forest, floodplain forest, floodplain non-forest (wet meadow), agricultural, or agricultural buffer (e.g., unmowed grass). Vegetation classification also incorporated information on landforms. Upland forest (UF) was designated as the forested land extending beyond the first terrace of the river. Floodplain forest (FF) encompassed forests located on a primary floodplain or first terrace and supporting facultative or obligate floodplain tree species. Floodplain nonforest (FNF) was dominated by herbaceous or shrub species; this was always located on a primary floodplain or first terrace adjacent to a river. Vegetation sampling plots were randomly distributed as a proportionate sample of each patch type based on its relative abundance within the buffered area along each reach. This yielded a total of 12–25 plots per reach, depending on the diversity and relative extent of different vegetation types (Shiver and Borders 1996).

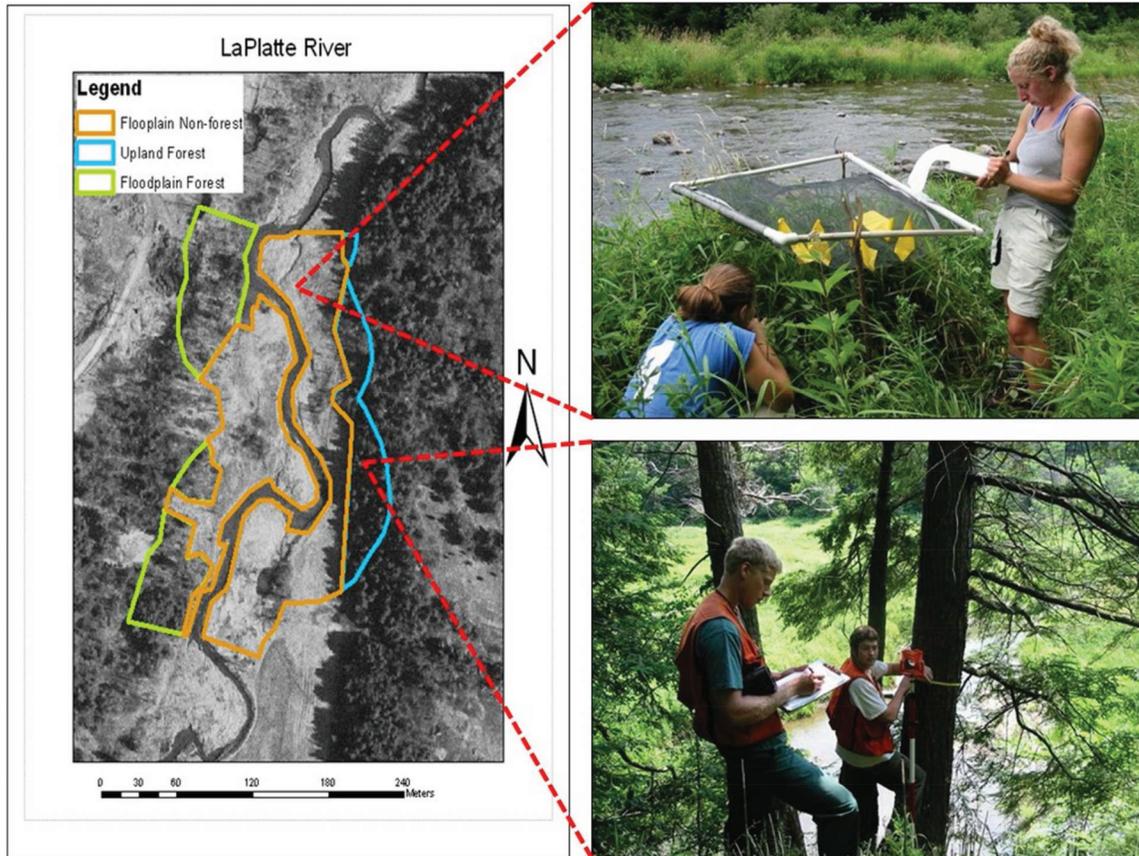
Forest vegetation composition and structure were sampled within variable radius plots, using a 2.3 (metric) basal area factor prism. In each plot, all trees (live and dead) with diameter at breast height (dbh) > 5 cm in were identified, measured at breast height (1.37 m), and assessed for decay class (1 to 7, where 1 represents live and 7 is highly decayed). Tree saplings (>1 m in height, <5 cm dbh) and woody shrubs were inventoried (density by species) using a point-quarter-distance sample centered within each prism plot. LW volume (downed logs ≥ 10 cm diameter at intercept,

≥1 m length) was sampled using a line-intercept method following Warren et al. (2008). LW transects were placed systematically to connect sample plots and were thus of variable length (approx. 30 to 100 m) and orientation, resulting in well-distributed spatial surveys.

2.3.2. Rapid Geomorphic Assessments (RGA)

We used the RGA protocols developed by VTDEC (2003) to assess stream reaches. This protocol is based on evidence of channel adjustment focusing on dominant geomorphic processes: degradation (incision), aggradation (accumulation of sediment), widening (bank erosion), and planform change (channel meander pattern). For each geomorphic adjustment process, a suite of field indicators is used to assign a rating from 0 to 20 (0 represents gross channel instability, 20 represents channel equilibrium). Ratings for the four channel adjustments (degradation, aggradation, widening, change in planform) are summed into a composite value for the stream reach (maximum score = 80). This value is then divided by 80 and multiplied by 100 to yield an overall RGA score, expressed as a percentage. Thresholds within this continuous scale were used to assign stream reaches to discrete condition categories (reference (85–100), good (65–84), fair (35–64), or poor (0–34)) generally following Sullivan et al. (2006). Our dataset included only one site rated “poor,” which limited our ability to determine relationships for this portion of the RGA scale.

Fig. 2. Example of patch type delineation at one of the study sites (EPALP, La Platte River, Vermont), with photographs of vegetation sampling in a floodplain nonforest plot (top right) and an upland forest plot (bottom right). The area sampled extended 50 m to either side and a minimum of 10× channel bankfull width along each stream reach. Each patch was sampled intensively, with the number of plots per patch proportionate to size, yielding a total of 12–25 plots per site.



2.4. Data analysis

2.4.1. Analysis of vegetation structure

Vegetation inventory data were input into the Northeast Decision Model (NED-2; Twery et al. 2005) and spreadsheet-based programs to generate vegetation structural metrics, including metrics indicative of stand stocking and density, tree sizes and variation among size classes, large tree abundance, and dead wood both standing and downed. Coarse root biomass was estimated using species group specific allometric equations from Jenkins et al. (2003). The parameters and equations, developed specifically for coarse roots, use the component ratio method to predict the proportion of total tree biomass in roots based on aboveground live-tree measurements (for the equations, see Jenkins et al. 2003, p. 24). Structural variables were calculated independently for each patch type (FNF, FF, and UF). Reach-specific means were calculated by weighting patch type specific averages by their proportional representation within each site. This resulted in values reflecting the relative degree of influence of each vegetation patch type on stream reach condition. A correlation matrix was generated to reduce the number of variables examined in statistical analyses. When two or more variables were highly correlated ($r > 0.75$) with one another, we selected the variable most indicative of overstory structure, sapling–shrub layers, or LW availability (Table 2).

Classification and regression tree (CART) analyses were run in S-PLUS software (Statistical Sciences, Inc. 2003) to model RGA scores as a function of multiple vegetation structural characteristics (Table 2). CART is a nonparametric test and is able to assess nonlinear relationships and high-order interactions (Breiman et al. 1984; De'ath and Fabricius 2000). CART partitions variance in

a dependent variable through a series of splits based on values of one or more independent variables. Splits are made where threshold values for an independent variable maximally distinguish values of a dependent variable for a subset of stream reaches; the latter become branches on each side of the split. Cost-complexity pruning was used to eliminate nonsignificant nodes ($\alpha = 0.05$).

Linear regression analysis was used to examine potential relationships between the predictor variables selected in CART and RGA scores. This provided confirmation of the CART results but was also complementary because regression evaluates variation across all reaches, whereas CART assesses variation among partitioned subsets of reaches. Riparian LW volume was used as a predictor variable due to its relationship with intermediary mechanisms potentially linking forest structure with stream geomorphic condition (Valett et al. 2002; Gurnell et al. 2005). Riparian LW volume can be strongly correlated with wood recruitment into stream channels (Keeton et al. 2007) and thus provides a useful potential indicator for in-stream LW. Residuals were checked using the Wilk–Shapiro test, confirming assumptions of normality. When nonlinear relationships were evident, we evaluated the relative predictive strength of logarithmic, polynomial, and negative exponential curves fit to the data. One outlier in the dataset was identified using Cook's distance (D) measure.

2.4.2. Analysis of land cover and RGA scores at multiple spatial scales

A logical criticism of attributing channel geomorphic condition to proximate effects at the reach scale is that fluvial geomorphology may reflect an influence from upstream or watershed-scale

Table 2. Vegetation metrics used in the classification and regression tree analysis.

Overstory structure		Sapling–shrub layer	LW availability
Total basal area (m ² ·ha ⁻¹), live and dead trees	Dead tree stem density (stems·ha ⁻¹)	Sapling density (stems·ha ⁻¹)	Downed LW volume (m ³ ·ha ⁻¹)
Standard deviation of total basal area (m ² ·ha ⁻¹)	Large (>50 cm dbh) live tree stem density (stems·ha ⁻¹)	Shrub density (stems·ha ⁻¹)	
Dead tree basal area (m ² ·ha ⁻¹)	Large (>50 cm dbh) dead tree stem density (stems·ha ⁻¹)	Proportion of shrubs sampled that are invasive species (%)	
Stem density (stems·ha ⁻¹)	Quadratic mean diameter (cm)		

Note: LW, large wood; dbh, diameter at breast height.

processes. To examine this question, we delineated five, nested spatial scales in ESRI ArcMap 8.0. The first two scales encompassed the area buffered on either side of each stream reach to 50 m and 100 m. These scales approximate two (50 m buffer) and four (100 m buffer) site potential tree heights, a concept used to scale buffer widths based on functions provided by forest–stream interactions (Gregory 1997). The next three scales encompassed the entire stream network in the 1:5000 Vermont Hydrography dataset (Vermont Center for Geographic Information (VCGI) 2004), including the study reach and all areas upstream. These scales represented (i) buffering to 50 m on both sides of channels, (ii) buffering to 100 m on both sides of channels, and (iii) the entire watershed upstream of the study reach. The five scales were designated as follows: 50 m wide reach (50mR), 100 m wide reach (100mR), 50 m wide, upstream watershed (50mWS), 100 m wide, upstream watershed (100mWS), and entire upstream watershed (WS). For each scale, we used a supervised classification of the 2002 land-cover layer for the state of Vermont, a combination of three 2002 Landsat-7 ETM+ scenes. We calculated area by land-cover type, classified as agriculture, urban, forested, and other for 25 of the reaches (Table 1). This was not performed for seven reaches for which data were unavailable.

Kolmogorov–Smirnov goodness-of-fit tests were used to compare the mean distribution of forest, agricultural, and urban cover at the reach scale (50mR) with the mean land cover at all four larger scales (100mR, 50mWS, 100mWS, and WS). This helped determine if relationships between land cover and RGA scores were truly scale-dependent and not just reflective of differences in cover type distribution at different scales.

To determine the potential effect of spatial scale on RGA scores, we examined models of land use and RGA scores at the five scales described previously. GLMs with the Gaussian link function (normal distribution) were used to model the relationship between RGA scores and multiple predictor variables: proportion of buffer in agricultural, urban, and forested land for each spatial scale. Normality was confirmed for all dependent variables (RGA score at each scale) using the Wilk–Shapiro test. GLMs yield robust predictions when there are potential nonlinear responses in a dependent variable and if heterogeneity of variance is exhibited (Venables 2000). These were of concern for these particular variable combinations.

3. Results

3.1. Reach-scale vegetation structure and RGA scores

The results supported the hypothesis that stream geomorphic condition varies significantly with differences in the forest stand structure and other vegetation characteristics of riparian corridors. When vegetation metrics (Table 2) were included in a CART analysis, four structural variables emerged as important in explaining variation in RGA scores among reaches (Fig. 3): standard deviation of total (live and dead tree) basal area (representing spatial variation within individual reaches), mean total basal area, dead tree stem density, and shrub density. Basal area standard deviation was most predictive of RGA scores.

In general, the CART results indicated that greater levels of forest stand structural complexity (e.g., dead tree density and

basal area) were associated with higher RGA scores (Fig. 3). Higher standard deviations of basal area were associated with greater partitioned values of RGA scores in the CART model. Partitioned RGA scores were highest at reaches with basal area standard deviations greater than 6.0 m²·ha⁻¹ (or highly variable basal area) and shrub densities below 1,373 stems·ha⁻¹ (or relatively low to moderate shrub densities). For reaches with less variation in basal area, partitioned RGA scores were higher above a threshold (33 stems·ha⁻¹) for standard deviation of dead tree density, again suggesting a relationship with aspects of stand structural complexity including horizontal variation in forest density.

Linear regression confirmed that all but one of the variables identified in CART were statistically significant predictors of RGA score across all of the reaches, rather than only for subsets of reaches. Both total basal area ($R^2 = 0.32$, $p < 0.001$) and the standard deviation of basal area ($R^2 = 0.26$, $p = 0.004$) were positively related to RGA score (Fig. 4), but the former emerged as the stronger predictor, which contrasted with the CART results. When an outlier (NERCTB, a reach with an unusually low RGA score; see Table 2) was removed from the dataset, variation explained by basal area increased to 37%. Dead tree density (log transformed) retained a weak ($R^2 = 0.12$) though statistically significant ($p = 0.047$) relationship with RGA score. When examining the total pool of sites, we did not find a significant relationship between shrub density and RGA score using linear regression, signaling that an association with shrub density was restricted to the partitioned subset of sites as modeled in CART.

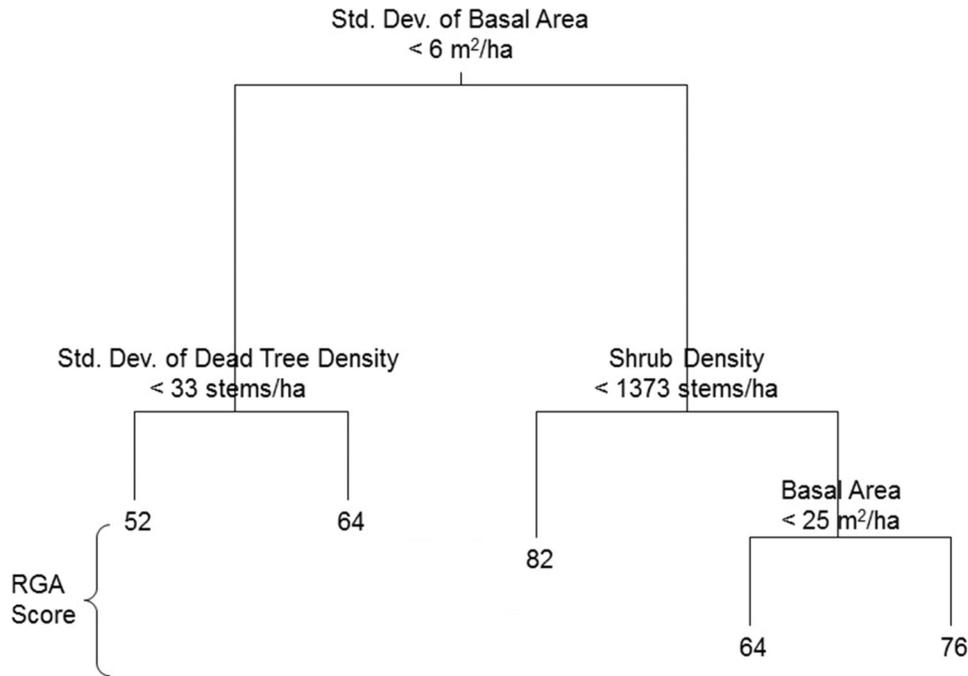
Total basal area was strongly and positively correlated with allometrically estimated coarse root biomass ($R^2 = 0.86$, $p < 0.001$), calculated as an average weighted by the proportion of patch types within each site. Root biomass was, in turn, positively correlated with RGA score ($R^2 = 0.46$, $p < 0.001$). LW volume within 50 m of river banks showed a somewhat weak ($R^2 = 0.20$) though statistically significant ($p = 0.011$) and positive relationship with RGA score. This pattern held when the outlier reach (NERCTB) was removed from the dataset. A logarithmic curve ($y = 0.959\ln(x) - 2.837$) explained the most variation in this relationship.

3.2. Land cover and RGA scores at multiple spatial scales

To assess scale dependencies in relationships between land cover and stream geomorphic condition, it was necessary first to determine if land cover distributions were similar across scales. Goodness-of-fit results (Table 3) showed that percent forest cover within study reaches (50mR) was not significantly different from percent forest at the 100mR. Because of this result, we used the 50mR scale for further comparison against the coarser scales. Percent forest cover within study reaches (50mR) was not significantly different from the watershed scale (WS). However, percent forest within reaches (50mR scales) was different from stream-network scales buffered at both 50mWS scale ($p = 0.015$) and 100mWS scale ($p = 0.015$). Thus, the comparison of 50mR with WS scales was most robust, with comparison with 50mWS and 100mWS less robust due to differences in relative proportions of land-cover types.

Our results did not support the hypothesis that RGA scores are correlated with forest cover across all spatial scales, including watershed scales. Rather significant correlations were found only

Fig. 3. Classification and regression tree (CART), showing independent variables selected, split values, and partitioned mean values (bottom) of the dependent variable (Rapid Geomorphic Assessment (RGA) scores as a percentage value). Basal areas refer to the total of live and dead trees. Length of each vertical line is proportionate to the amount of deviance explained. Independent variables were selected from an initial set of 11. Minimum observations required for each split = 5; minimum deviance = 0.01, $n = 32$. See Table 2 for units of measurement of the independent variables. Std. Dev., standard deviation.



for a subset of the scales that we assessed. Results from the GLMs showed that, at the 50mR scale, RGA score was positively and linearly correlated with percent forest cover ($t = 3.19$, $p < 0.001$) and negatively related to percent agricultural land ($t = -3.409$, $p < 0.001$; Fig. 5). RGA score was also positively related to the percentage of each reach in forest and negatively related to the percentage in agricultural land at the 100mR buffer level (Table 4). There were no significant relationships between land cover and RGA score at any of the larger (upstream watershed) spatial scales (Table 4). Forest and agricultural land cover were inversely correlated at all scales in our dataset. Urban land use surrounding all but one reach represented a comparatively small (mean = 6%) percentage of the study watersheds; the lack of correlation with RGA scores in our dataset may have reflected this lack of variability.

4. Discussion

The geomorphic condition of stream channels is correlated with both riparian forest structure and land cover based on our results. This finding has important implications for our understanding of forest–stream interactions, as well as management intended to maintain the integrity of stream networks including flood resilience. Streams running through riparian forests of greater structural complexity (e.g., greater amounts of, and more spatial variation in, basal area) are more likely to exhibit channels in better geomorphic condition. However, given that we did not test causality in our study, the relationships that we found may be due to an effect of forest structure on channel geomorphology or vice versa (e.g., effects of geomorphic and flood-related disturbances on forest composition and development; Hughes and Cass 1997; Stromberg et al. 2005). There is also the possibility of feedback loops, both positive and negative, between forest structure and dynamic channel processes (Johnson et al. 1995). However, our results are consistent with the limited previous research in the eastern US documenting linkages between the structure of deciduous and mixed deciduous–coniferous forests and in-stream

habitat characteristics (Hedman et al. 1996; Valett et al. 2002; Keeton et al. 2007; Warren et al. 2009). We also present initial evidence that relationships between forest cover and stream geomorphic condition may be scale-dependent. In our study, RGA scores appeared to primarily reflect fine-scale (50mR and 100mR) relationships with forest cover.

4.1. Linkages between riparian forest structure and stream geomorphology

The results support our first hypothesis and point to a relationship between riparian forest structure and stream channel condition in the northern hardwood–conifer systems of our study area. In Vermont’s Champlain Valley, forest cover, basal area, and coarse root biomass were positively and linearly related to geomorphic condition as indicated by RGA scores. Basal area provides a good indication of aggregate structural complexity because it is correlated with elements of both vertical and horizontal complexity (Keeton 2006). Previous research provides some basis for interpreting these results with the caveat that we did not directly investigate mechanistic relationships. Greater structural complexity in riparian forests also enhances sediment retention, limits pollution movement, and regulates stream flow by, for instance, reducing overland flow and dampening the intensity of peak flows (Endreny 2002; Bilby and Ward 1991; Rahmeyer et al. 1999; Tabacchi et al. 2000). Trees and their associated root systems increase tensile strength, soil cohesion, and drainage, thereby increasing bank stability as long as root systems extend to the low-water mark (Thorne 1990). Stand age and stem density also influence stream-bank and in-channel roughness coefficients, which are adjustments in velocity equations for friction (McKenney et al. 1995). Roughness affects mechanisms that influence channel adjustment such as sediment transport and flood or peak flow velocities (Graf 1978; Arcement and Schneider 1989; Bendix and Hupp 2000).

We found that forested stream banks were correlated with channel integrity, as have others (Bilby and Ward 1991; Sweeney

Fig. 4. Results of linear regression analyses predicting Rapid Geomorphic Assessment (RGA) scores (%) as a function of basal area (live and dead, top panel) or the standard deviation of basal area (bottom panel). One outlier (NERCTB) was removed in each of these analyses. With the outlier included, variation explained decreased to 32% for basal area and 24% for its standard deviation. $n = 32$.

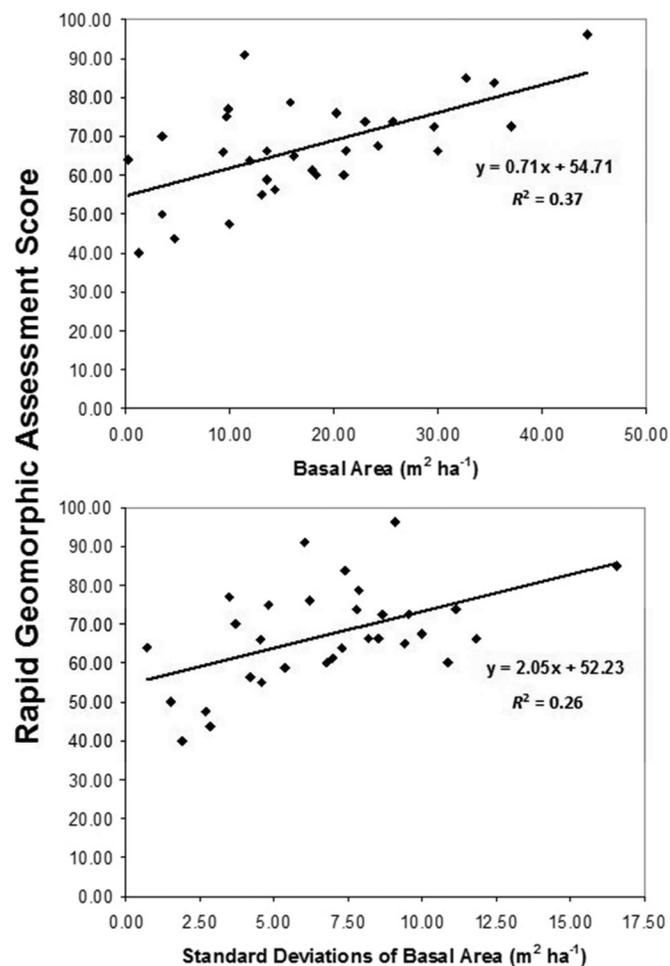


Table 3. Results of goodness-of-fit tests comparing percent forest cover within 50 m of stream reaches with larger spatial scales measured upstream of reach bottoms.

Percent forest cover along reaches compared with:	Kolmogorov–Smirnov value	Significance
Percent forest within 50 m buffering along stream networks	0.44	0.015
Percent forest within 100 m buffering along stream networks	0.44	0.015
Percent forest within entire upstream watersheds	0.28	0.285

et al. 2004; Sullivan et al. 2007). The structural characteristics that we found to be correlated with RGA scores, including basal area, spatial variation in basal area, and dead tree stem density, generally increase with forest stand development into a late-successional condition in northern hardwood–conifer forests (McGee et al. 1999; Ziegler 2000; Burrascano et al. 2013), including riparian systems (Keeton et al. 2007; Curzon and Keeton 2010). For instance, basal-area variation is indicative of horizontal structural development such as shifting gap mosaics, which is a defining characteristic of late-successional temperate forest development (Runkle

2000; Franklin et al. 2002; Franklin and Van Pelt 2004). The canopy disturbances that drive horizontal development play an important role in adding wood to stream channels (Kraft et al. 2002). Thus, while we did not directly investigate whether geomorphic condition is related to late-successional forest structure, our results suggest that this topic is worthy of further study.

LW accumulations in stream channels provide important ecological functions such as debris dam and plunge-pool formation and associated retention of fine sediment (Bilby and Ward 1991; Montgomery et al. 1995; Díez et al. 2000; Valett et al. 2002). In turn, these processes can positively influence channel geometry and stability (Gurnell 1997; Kraft et al. 2011). LW inputs and associated effects on lower order stream geomorphology are strongly correlated with riparian stand age and structure in northern hardwood–conifer systems (Keeton et al. 2007; Warren et al. 2009). It was, therefore, surprising that we only found a relatively weak, though statistically significant, relationship (explaining only 20% of the variation in RGA) between LW volume and channel condition rating along the streams that we studied.

There are several possible explanations for the relatively weak relationships with LW in our dataset. First, we did not measure in-stream LW volume directly, but rather used riparian (or forest floor) LW volume as an indicator of LW input potential. Second, whereas LW has been shown to influence geomorphology in low-gradient river systems in some regions (e.g., Naiman et al. 2000; Wiens 2002), similar relationships have not been well established for mid- to low-gradient systems in the US Northeast (but see Montgomery and Buffington 1997 for Pacific Northwest streams). Our reaches had generally low volumes of riparian LW (mean = 21 m³·ha⁻¹) relative to means reported for riparian forests along low-order stream channels running through mature (86 m³·ha⁻¹) and old-growth (164 m³·ha⁻¹) northern hardwood–conifer forests in the Adirondacks of New York (see Keeton et al. 2007). Lack of old-growth forest structure along our stream reaches may also have played a role. The young to mature and managed forests that dominate the region are known to have lower volumes of LW compared with older and unmanaged forests (McGee et al. 1999; Angers et al. 2005; Keeton et al. 2007). LW volumes and large log frequency are predicted to increase with forest age in the US Northeast (Warren et al. 2009).

The low riparian LW volumes that we observed also may have reflected, in part, the influence of nonforest vegetation (mean = 18% of total cover) at many of our reaches. It is possible that in this region, LW levels are simply too low in proportion to channel size, with wood lengths too short relative to bankfull width, to have a strong effect on channel dynamics (Gregory et al. 2003). LW is less likely to aggregate in debris dams in larger streams (>10 m bankfull width) in the US Northeast compared with intermediate-sized streams (6–10 m bankfull width; Kraft et al. 2011), which may reduce retention period within larger channels. Finally, Vermont's streams and rivers can experience large ice flows in the spring, which frequently dislocate LW from within channels, although re-deposition can occur with high spring flows. Thus, LW may be relatively less influential in the systems that we studied due to a combination of large stream size and disturbance dynamics.

Interestingly, our CART results also showed that stream geomorphic condition was highest at reaches above a certain level of structural complexity (i.e., basal area standard deviation) in forested patches but below a shrub density threshold in nonforest patches. The latter result clearly corresponded with the exceptionally high shrub densities at reaches dominated by open-canopied, primarily nonforest vegetation, which may, in turn, be related to disturbances (e.g., flooding, geomorphic disturbance, cattle grazing, forest clearing, etc.). Higher shrub densities were thus correlated with lower channel stability. A portion of woody shrub stems were exotic, invasive species (7% on average, but ranging from 0% to 45%), particularly Japanese knotweed (*Fallopia japonica* (Houtt.) Ronse Decr.) and shrub honeysuckles (*Lonicera* sp.).

Fig. 5. Significant generalized linear models for Rapid Geomorphic Assessment (RGA) scores vs. 50mR percent forest cover (top left); RGA vs. 50mR percent agriculture cover (top right); RGA vs. 100mR percent forest cover (bottom left); and RGA vs. 100mR percent agriculture cover (bottom right). Tukey test statistic and p values are generated by the models. $n = 25$.

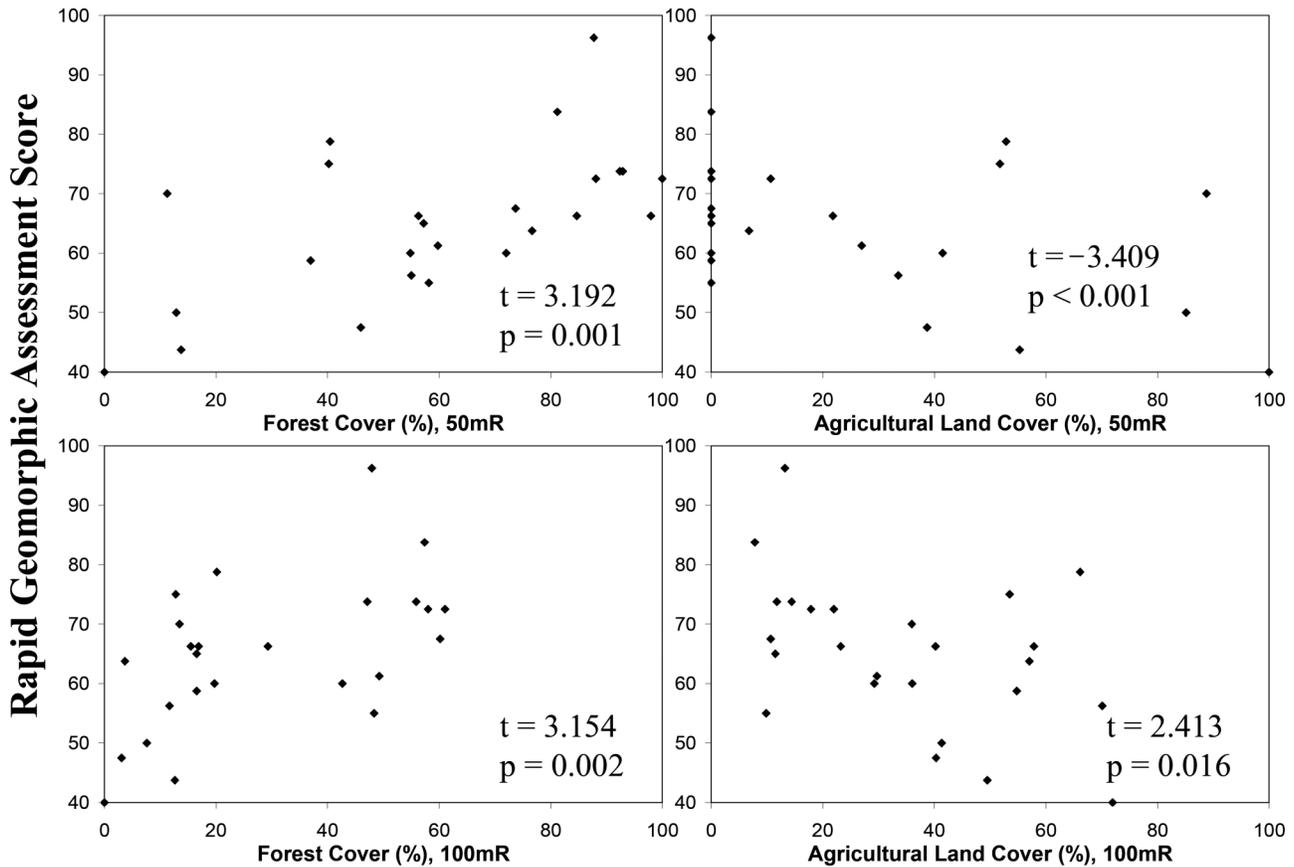


Table 4. Generalized linear modeling results.

Cover (%)	50mR ^a		100mR ^b		50mWS ^c		100mWS ^d		WS ^e	
	t value	p value	t value	p value	t value	p value	t value	p value	t value	p value
Forest	3.19	0.001	3.15	0.002	-0.541	0.589	-0.248	0.804	-0.231	0.817
Agriculture	-3.41	0.001	-2.41	0.016	0.414	0.679	0.243	0.808	0.174	0.862
Urban	NA	NA	-0.46	0.645	-0.419	0.675	-0.665	0.506	-0.014	0.989

Note: RGA score is the dependent variable. Not applicable (NA) indicates instances of zero percent coverage.

^a50mR: reach buffered at 50 m on both sides of the stream.

^b100mR: reach buffered at 100 m on both sides of the stream.

^c50mWS: entire upstream stream network buffered at 50 m on both sides of the stream.

^d100mWS: entire upstream stream network buffered at 100 m on both sides of the stream.

^eWS: entire upstream watershed.

While we did not find a statistically significant relationship between geomorphic condition and invasive shrub density across the full range of sites, several of our sites (identified in CART) with highest invasive densities also had the lowest RGA scores. Spread of invasive shrubs within riparian areas and along floodplains may influence geomorphic condition through reductions in bank stability, an inference also supported by previous research (Hood and Naiman 2000). At the same time, flooding and stream geomorphic disturbances are known to facilitate dispersal and establishment of invasive plant species, creating a possible positive feedback between these processes (Stromberg et al. 2007). Therefore, our findings suggest that further research could help elucidate possible connections between invasive plants and stream geomorphic condition in the Lake Champlain Basin.

Our results showed a positive relationship between forested cover within 100 m of stream channels and geomorphic condition. Forest-stream interactions at this scale are an important consid-

eration for managers interested in riparian buffer design (Gregory 1997). However, our results suggest that forest cover alone does not tell the full story. Rather, it is critical to examine riparian forest structure, as this might be expected to directly influence fluvial geomorphic condition and is highly dynamic and related to stand age, disturbance history, and human manipulation (Hale et al. 1999; McGee et al. 1999; Angers et al. 2005; Keeton 2006). We suggest that direct measures of forest structure are an important consideration for stream condition classification and mapping, particularly for key concerns such as bank stability and roughness.

4.2. Scale-dependent influences of forest structure on channel geomorphology

Expanding the spatial scale of analysis may increase the strength of relationships between vegetation condition and channel condition using the RGA and other geomorphic evaluations (Wiens 2002). For example, it may be necessary to inspect upstream reaches for

sedimentation and flow alterations related to loss or degradation of forest cover (VTDEC 2003). However, while reach-level relationships among forest structure, land cover, and RGA were statistically significant, a similar relationship at larger spatial scales was not evident in our dataset. Nevertheless, forest cover and reach-scale RGA scores appeared closely related at the 50mR and 100mR scales based on our GLM findings (Table 4). The results of the goodness-of-fit tests suggested that the strength of this relationship at the reach rather than watershed scale was not due a difference in percent forest cover; cover was not significantly different between these scales (Table 3).

Channel geomorphology is likely to be affected by land use, and the cover type and condition of vegetation are likely to influence stream geomorphology and hydrology at multiple spatial scales (Ebisemiju 1989; Knox and Hudson 1995; Ruhiman and Nutter 1999). Stream characteristics have been correlated with land cover at both stream reach and coarser scales (Richards et al. 1996; Townsend et al. 1997; Sponseller et al. 2001). For instance, land-cover and vegetation changes at stream-reach scales influence bank stability (Zaimes et al. 2004), while watershed-scale land-use impacts (e.g., percent imperviousness surface) influence timing and intensity of peak flows (Jones and Grant 1996), with corresponding effects on planform adjustment (Allmendinger et al. 2005). However, we infer from both our CART and our GLM results that important forest structure–stream geomorphology interactions occur at within-reach scales and that RGA scores strongly reflect localized (reach scale) land cover, primarily agricultural versus forested land cover.

4.3. Management implications

We recommend that stream assessment approaches could be enhanced by incorporating forest structural indicators at reach scales, rather than relying on vegetation cover alone. This would be useful where a better understanding of riparian corridor condition is desired. Where feasible, these data could be collected either through field sampling, perhaps conducted in conjunction with RGA protocols, or by using high-resolution remote sensing techniques such as light detection and ranging (LIDAR; Goodwin et al. 2006). Data for the latter are now available for most of the Vermont portion of the Lake Champlain Basin.

Incorporation of forest structure indicators into stream assessments would help managers identify and prioritize areas in need of riparian forest restoration or silvicultural treatment, for instance, where these projects would be most likely to help improve channel condition. A pressing management issue is the need to design, restore, and safeguard riverine systems, including location of buildings and infrastructure, in ways that maximize resilience to flooding (Watson et al. 2016). Forest structure is another indicator that agencies and communities can use to assess potential flood resilience and prioritize floodplain and riparian forests most in need of protection. This assumes relationships among riparian forest structure, bank roughness, channel geomorphic condition, and the ability of a riverine system to dissipate flood energy and recover more rapidly following high discharge events (Hession et al. 2003; Thomas and Nisbet 2007; Jones et al. 2009).

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