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Mapping the spatial and temporal distributions of woody debris in streams of the Greater Yellowstone Ecosystem, USA

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Abstract

The objectives of this study were: (1) to document spatial and temporal distributions of large woody debris (LWD) at watershed scales and investigate some of the controlling processes; and (2) to judge the potential for mapping LWD accumulations with airborne multispectral imagery. Field surveys were conducted on the Snake River, Soda Butte Creek, and Cache Creek in the Greater Yellowstone Ecosystem, USA. The amount of woody debris per kilometer is highest in 2nd order streams, widely variable in 3rd and 4th order streams, and relatively low in the 6th order system. Floods led to increases in woody debris in 2nd order streams. Floods redistributed the wood in 3rd and 4th order streams, removing it from the channel and stranding it on bars, but appeared to generate little change in the total amount of wood throughout the channel system. The movement of woody debris suggests a system that is the reverse of most sediment transport systems in mountains. In 1st and 2nd order tributaries, the wood is too large to be moved and the system is transport-limited, with floods introducing new material through undercutting, but not removing wood through downstream transport. In the intermediate 3rd and 4th order channels, the system displays characteristics of dynamic equilibrium, where the channel is able to remove the debris at approximately the same rate that it is introduced. The spatial distribution and quantity of wood in 3rd and 4th order reaches varies widely, however, as wood is alternatively stranded on gravel bars or moved downstream during periods of bar mobilization. In the 6th order and larger channels, the system becomes supply-limited, where almost all material in the main stream can be transported out of the central channel by normal stream flows and deposition occurs primarily on banks or in eddy pool environments. Attempts to map woody debris with 1-m resolution digital four-band imagery were generally unsuccessful, primarily because the imagery could not distinguish the narrow logs within a pixel from the surrounding sand and gravel background and due to problems in precisely coregistering imagery and field maps. © 2002 Elsevier Science B.V. All rights reserved.

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1. Introduction

Woody debris plays a key role in the ecology and geomorphology of streams. Woody debris traps coarse

particulate organic matter and sediments (Anderson and Sedell, 1979; Bilby and Likens, 1980; Marston, 1982); provides habitat for aquatic insects (Angermeier and Karr, 1984; Benke et al., 1985); and creates cover in pools and slow water areas (Bisson et al., 1982, 1987; Tschaplinski and Hartman, 1983; Fausch and Northcote, 1992).

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The role of wood in affecting stream morphology is dependent on the size of the stream (Bilby and Ward, 1989). In smaller streams, woody debris can create step pool sequences (Heede, 1972, 1985; Marston, 1982), increase pool area (Murphy and Hall, 1981; Ralph et al., 1994), and reduce sediment transport (Bilby, 1984). Nakamura and Swanson (1993) noted that the importance of woody debris to the morphology of 1st order streams can be limited by the size of the debris, which is often large enough to bridge the channel and not interact with the flow. In this model, woody debris plays a larger role in moderate size streams, because it can enter the channel bottom where it diverts flow and affects erosion and deposition.

Documenting and understanding variations in woody debris distribution is therefore crucial to understanding variations in stream process and form throughout a watershed (Piegay and Marston, 1998). The first part of this study compares field data from 2nd through 6th order streams in the Greater Yellowstone Ecosystem, USA, in order to document variations in wood distributions across different stream scales, discuss the effects of floods on some of these patterns over time, and suggest a broad hypothesis for explaining woody debris distributions in mountain systems. A major impediment to studying woody debris at these watershed scales is the time required to map the wood. The second part of this paper therefore examines the utility of four-band airborne multispectral digital imagery for mapping woody debris.

2. Field area

Data on woody debris distributions were collected in the Snake River on the southern side of the Greater Yellowstone Ecosystem (GYE) and from Cache Creek and Soda Butte Creek at the northern end of the GYE (Fig. 1). Data on the Snake River were obtained between Jackson Lake Dam and the bridge crossing at Moose, Wyoming, a section that lies entirely within Grand Teton National Park (Table 1).

Cache and Soda Butte Creeks drain adjacent watersheds. The Cache Creek basin was severely burned in 1988 (Minshall et al., 1998), but Soda Butte was largely unburned. Both streams are braided to partially braided and have gravel to cobble substrates in the

study reaches. More detailed descriptions of the study streams are included in Colvard (1998), Wright et al. (2000), Meyer (2001) and Table 1.

3. Methods

Woody debris distributions were originally mapped as part of two different and unrelated studies in the Greater Yellowstone Ecosystem. The wood was therefore mapped with different techniques in the Snake River and in the Cache Creek/Soda Butte Creek drainages. We later merged our two data sets to investigate the effects of scale on woody debris distributions.

In the Snake River, five reaches along 42 km of river were identified based on differences in gradient, percent of various channel unit types, sinuosity, floodplain width, and mean bankfull depth. Large woody debris (LWD) accumulations were mapped in 1999. These field surveys documented differences in frequency, size, age, and orientation of wood accumulations from reach-to-reach. Locations were recorded with a global positioning system. In order to be mapped, wood had to be a minimum of 10 cm in diameter and 1 m in length (Platts et al., 1987). The size of each accumulation and the percent of the channel width blocked by each accumulation were determined by direct measurement. Each accumulation was assigned to a relative age class based on presence/absence of green or dead needles and primary/secondary limbs. Streamside vegetation was recorded from existing maps and field observations. Beaver-cut trees were distinguished from trees fallen or trees tilted by bank undercutting. The orientation of each LWD accumulation relative to the thalweg was noted. The percent of the bankfull channel width affected by LWD accumulations was measured by comparing the bankfull width of the channel with the width of the channel blocked by LWD accumulations.

In Soda Butte and Cache Creeks, woody debris was originally mapped to test the ability of 1-m resolution digital imagery to map woody debris of different sizes. Only woody debris larger than 2 m length by 0.3 m diameter was mapped, based on the assumption that this was the minimum size of debris that could significantly affect channel flow and because this debris was probably large enough to be detected by the multispectral imagery. The location and dimensions of

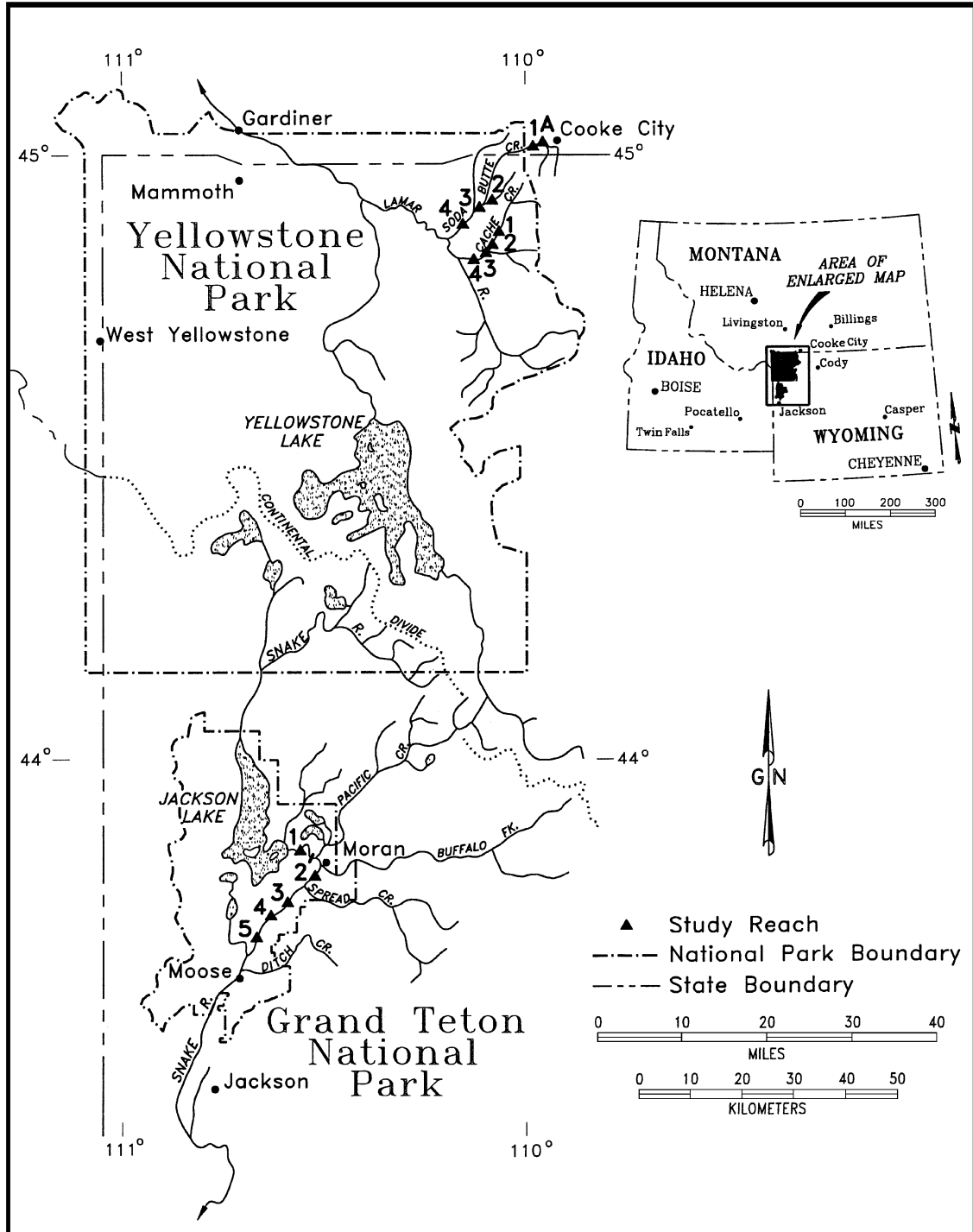


Fig. 1. The study area.

Table 1
 Characteristics of the study reaches in Soda Butte Creek (1999), Cache Creek (1995) and the Snake River (1999)

	Length (km)	Floodplain width (m)	Slope (m/km)	Bankfull depth (m)	Stream order	Basin area (km ²)	Pools (%)	Glides (%)	Riffles (%)	Rapids (%)	Sinuosity
<i>Soda Butte Creek</i>											
Reach A	0.11	11	29.02	0.60	2	14.1	ND	ND	ND	ND	1.43
Reach 1	0.25	46	5.19	0.83	3	47.5	25	15	60	0	1.05
Reach 2	0.33	35	7.01	0.80	3	129.5	ND	ND	ND	0	1.10
Reach 3	0.19	73	3.92	1.00	3	153.3	ND	ND	ND	0	1.05
Reach 4	0.27	135	3.28	1.16	4	242.7	6	26	68	0	1.02
<i>Cache Creek</i>											
Reach 2	0.49	38	14.49	ND	3	120.9	4	25	71	0	1.03
Reach 3	0.20	48	13.89	ND	4	179.8	ND	ND	ND	0	1.09
<i>Snake River</i>											
Reach 1	6.97	290	0.88	3.20	6	ND	58	35	11	0	1.45
Reach 2	6.53	860	1.87	2.10	6	ND	7	82	28	0	2.33
Reach 3	10.40	1230	1.75	2.20	6	ND	4	68	19	0	2.00
Reach 4	6.18	520	2.47	2.00	6	ND	0	69	35	12	1.43
Reach 5	11.90	1040	3.33	2.00	6	ND	0	63	23	2	3.09

ND indicates no data for that variable. Data in Soda Butte and Cache Creek were mapped at scale of 1:100. Location of wood in the Snake River was mapped with GPS, while stream and vegetation variables were mapped to a base map with a scale of 1:24,000.

solitary pieces of wood were mapped, as were the dimensions of debris jams. We did not attempt to measure the size of individual pieces of wood that were part of debris jams, nor did we attempt to count the number of pieces of wood in jams with more than 10 logs.

The Soda Butte and Cache Creek reaches were mapped in 1995. Four of the five reaches in Soda Butte Creek were remapped in 1996 after a significant flood event and one was revisited in 1999. Debris and channel morphology were surveyed using standard compass and tape survey procedures described in detail by Colvard (1998).

Positive Systems acquired the digital imagery in August of 1995 with a spatial scale of approximately 1 m per pixel. Imagery was flown in August because water levels were low, exposing the logs, but there was not yet snow on the ground that would have hidden the woody debris. The eight bit imagery consisted of four bands: blue (0.40–0.48 μm), green (0.46–0.57 μm), red (0.61–0.69 μm), and near infrared (0.78–1.0 μm). Supervised classification of the imagery followed standard procedures, with an additional post-classification step. Pixels that were obvious commission errors were added to the training pixels of their correct class until visually identifiable

commission errors were reduced to a minimum (Colvard, 1998). Image analysis was conducted using ERDAS Imagine.

4. Data

Data on the distribution of woody debris are shown in Tables 2 and 3. Detailed descriptions of the digital data from 1995 are in Colvard (1998), Wright (1998), and Wright et al. (2000). The “freshly undercut trees” data for Soda Butte Creek in Table 2 include only trees along the bank and do not include excavated trees carried into the channel from upstream reaches.

5. Analysis and discussion

5.1. Spatial variations in quantity, sources and transport of LWD in streams of different scale

The greatest amount of wood within the Soda Butte and Snake River systems was present in Reach A of Soda Butte Creek, a 2nd order headwater channel that was the smallest stream we mapped. Much of the wood in this reach consisted of undercut trees with roots still

attached to the bank, bark on the trunk, twigs, or attached needles, all of which indicated relatively recent input to the stream. The amount of LWD of unknown origin increased in 1996 (Table 2), but it was our opinion that most of this wood came from local bank collapse. The origin (fresh or transported from upstream) was difficult to determine with certainty, because the high floods of spring 1996 removed much of the dirt from root balls and undercut already dead trees along the bank, hindering identification of which trees had just entered the stream. The large majority of trees were perpendicular to the bank, however, suggesting that most of the debris jams had their origins in trees collapsing along the banks. The apparent lack of downstream transport of LWD was further indicated by the absence of any accumulations of more than 10 trees (Table 2), suggesting that the wood could not be moved far enough downstream to become ensnared by the next debris jam.

Intermediate amounts of wood in the Soda Butte–Snake River systems were present in Reaches 1 through 4 of Soda Butte Creek, where the stream is a 3rd to 4th order system. The LWD in these reaches was distributed throughout the channel and a much larger proportion was of unknown origin than in the headwater Reach A (Table 2), indicating that a larger proportion of the wood came from upstream transport rather than as inputs due to bank collapse. Reach 2 is the one apparent anomaly in this pattern. The total amount of wood in Reach 2, however, is much larger than Table 2 suggests. One debris jam in Reach 2 was located at a bedrock constriction and contained over 150 pieces of wood. Although it was not mapped in later years, this debris jam was broken up and partially mobilized by floods in 1996 and 1997.

On the Snake River in 1999, a total of 558 LWD accumulations were located and measured (Table 3). More than 80% occur as accumulations of 1–4 pieces. Essentially all fallen and tilted trees along the banks were blue spruce. Beaver-cut trees were found exclusively in cottonwood stands.

Most accumulations were comprised of LWD with some needles still in-place, indicating they were recently added to the river. In general, the age class of LWD accumulations decreased as the percent pools increased. Almost all accumulations were oriented parallel to the thalweg; the exceptions were all located in pools. The positioning of debris in thalweg parallel

positions indicates that the flow volume and depths were sufficient to readily transport all the wood through the main channel of this 6th order stream. Accumulations occurred only when the wood was caught on banks or was stranded in eddy pools.

Examination of data in Table 3 indicates that the frequency of LWD accumulations increased slightly as the frequency of riffles increased ($r=0.37$). Much of this relation, however, may be due to one stream segment, Reach 2, which had many riffles and a great deal of wood. As one would expect, there was a relatively strong positive correlation between the frequency of woody debris and the frequency of fallen or tilted trees ($r=0.60$ for fallen trees; $r=0.72$ for tilted trees). The percent of the bankfull channel width affected by LWD accumulations increased as the percent glides increased ($r=0.89$), and as the frequency of fallen and tilted trees increased ($r=0.66$).

The variability in total sinuosity for each reach was calculated for the 100-year period, 1899–1999 (Table 3). High variability in total sinuosity corresponded to reaches with a large amount of channel shifting. On average, the number of LWD accumulations was highest where channel shifting was minimal ($r=0.72$), although there was significant variability about the general trends. Without channel shifting, LWD accumulations grow in size as additional debris is snagged on existing jams. In more dynamic channels, these jams are mobilized on a more frequent basis, preventing the buildup of materials at any one site.

5.2. Flood-driven variations in woody debris distributions

In Soda Butte Creek, basin-wide floods with approximately 100-year recurrence intervals occurred in both 1996 and 1997, as determined from gage data at the lower end of Soda Butte Creek and regional flood frequency curves (Omang et al., 1986). The last natural flood of this magnitude or greater occurred in 1918 (Meyer, 2001). A 1950 tailings impoundment collapse created a flood an order of magnitude greater than a 100-year flood in headwaters near Reach A, with the flood level attenuating to 100-year levels near Reach 4 in Soda Butte Creek (Marcus et al., 2001). The Soda Butte data for 1995, 1996 and 1999 thus provide a portrait of flood effects on wood transport in a system that had not experienced similar magnitude floods or

Table 2
Downstream distribution of woody debris in Soda Butte Creek before and after floods and in the Snake River in 1999

	Number of jams /km with logs greater than 2 m				Origin of Woody Debris in jams/km:			Number of jams/km:				
	1–4	5–10	> 10	Total	Beaver cut	Freshly undercut	Unknown	On bars	On willows	Parallel and on bank	Perpendicular and attached to bank	In-channel
<i>Reach A</i>												
1995	109	18	0	127	0	100	18	0	0	18	100	9
1996	173	36	0	209	0	136	73	9	0	73	109	18
<i>Reach 1</i>												
1995	92	44	12	148	0	12	136	84	36	16	12	0
1996	88	20	32	140	0	16	124	76	28	16	8	12
1999	104	36	24	164	0	ND	ND	ND	ND	ND	ND	ND
<i>Reach 2</i>												
1995	24	3	6	33	0	6	27	6	0	3	0	24
<i>Reach 3</i>												
1995	58	16	21	95	0	0	95	53	0	26	0	16
1996	95	32	16	142	0	5	137	121	0	11	5	5
<i>Reach 4</i>												
1995	63	15	0	78	0	4	74	44	15	11	4	4
1996	74	11	0	85	0	4	81	81	0	0	4	0
<i>Snake River, 1999</i>												
Reach 1	0	0	0	0	0	0	0	ND	ND	0	ND	ND
Reach 2	28.9	5.2	3.2	37.4	2.9	12.2	22.3	ND	ND	34.4	ND	ND
Reach 3	10.7	0.6	0.6	11.8	4.8	1.2	5.9	ND	ND	9.9	ND	ND
Reach 4	7.4	0.3	0.6	8.4	2.5	4.1	1.8	ND	ND	6.8	ND	ND
Reach 5	10.0	0.8	0.9	11.7	2.4	1.4	8.0	ND	ND	10.9	ND	ND

ND indicates no data for that variable.

Table 3
Woody debris and morphology along the Snake River, 1999

Variables	Snake River channel reach					All five sections
	1	2	3	4	5	
Start (km)	0	6.97	13.5	23.91	30.09	0
End (km)	6.97	13.5	23.91	30.09	42.00	42.00
Length (km)	6.97	6.53	10.41	6.18	11.91	42.00
Floodplain width (m)	290	860	1230	520	1040	790
Average gradient (m/km)	0.88	1.87	1.75	2.47	3.33	2.18
Bankfull depth (m)	3.20	2.10	2.20	2.00	2.00	2.20
Percent pools	58	7	4	0	0	12
Percent glides	35	82	68	69	63	63
Percent riffles	11	28	19	35	23	22
Percent rapids	0	0	0	12	2	2
Total sinuosity 1999	1.45	2.33	2.00	1.43	3.09	2.21
Variation in total sinuosity, 1899–1999	0.37	1.34	1.33	0.40	1.91	0.92
Mean total sinuosity, 1899–1999	1.38	1.96	1.99	1.38	1.97	1.77
Streamside vegetation						
Percent blue spruce	23.6	83	32.6	48.4	21.8	49.1
Percent cottonwood	0.4	12.3	53.0	42.2	63.5	32.7
Percent lodgepole pine	40.0	0	0.2	0	0	5.1
Percent unidentified	36.0	4.7	14.2	9.4	14.7	13.1
Fallen trees per kilometer (tree at least partially in-channel)	46.6	90.2	46.7	55.0	31.9	50.5
Tilted trees per kilometer (tree not in channel)	6.9	42.3	10.9	18.3	5.8	13.5
In-channel LWD						
Percent beaver cut	0	7.8	40.3	29.5	20.4	19.5
Percent bank undercut	18.6	32.6	9.9	49.3	11.6	25.4
Percent unknown origin	81.4	59.6	49.8	21.2	68.0	55.1
Jams with 1–4 pieces	0	189	111	46	119	465
Jams with 5–10 pieces	0	34	6	2	9	51
Jams with >10 pieces	0	21	6	4	11	42
Total number of jams	0	244	123	52	139	558
Total jams per kilometer	0	37.4	11.8	8.4	11.7	13.3
Mean age class	0	2.60	3.22	3.09	2.56	2.78
Mean channel width in jams	0	11	3	44	11	12
Mean %BFW in jams	0	15	6	7	8	9
Percent jams parallel to flow	0	92	84	81	93	89

potential mobilization of wood in the previous half century.

Although detailed mapping of approximately 2.2 km of stream length was conducted, the total amount of wood was not large enough to determine whether changes in wood quantity after the floods were statistically significant. The following analysis is therefore descriptive in nature and does not provide statistical analysis of pre- and post-flood wood quantities.

In the relatively small 2nd order Reach A, very little of the 1995 wood was moved by the 1996 flood, as was discussed in the previous section. The total amount of debris did increase, however, due to undercutting of trees and the accumulation of piles of smaller logs and branches (Table 2).

Downstream of Reach A, pre- and post-flood maps showed that almost all wood moved significantly in Reaches 1, 3 and 4, with the occasional exception of bank-attached trees or the most massive debris jams containing many more than 10 logs. In Reach 1, decreases in the number of intermediate size wood clusters after the 1996 flood were offset by increases in larger debris piles (Table 2), suggesting that clumps broke up only to reform further downstream in the braided system. The subsequent 1999 Reach 1 data show fewer large clumps (>10 pieces), but more small and intermediate size accumulations. The overall quantities and channel locations of LWD in Reach 1 thus remained similar before and after the floods, despite the movement of almost all wood within the reach.

In the larger downstream channels of Reaches 3 and 4, the floods increased the number of individual logs and small clumps of debris, but either broke up or did not affect the number of large clusters with more than 10 logs (Table 2). Most of the small debris ended up on bars, where it was stranded on the receding limb of the flood. The increase in small debris stranded on bars appeared to be a function of both new debris entering the system and of the redistribution of debris as it was washed from the active channel, lifted off of bank-parallel locations, or mobilized out of disintegrating wood clusters.

The floods thus led to wood accumulation in the relatively small 2nd order Reach A, but mostly acted to mobilize and redistribute wood in the larger 3rd and 4th channels of Reaches 1, 3, and 4. The total wood in the 3rd and 4th order portions of the stream system thus appears to be approximately constant. Although the 4-year duration of our sample is too short to determine whether the system is in equilibrium, it seems likely that major changes, if they were to occur, would show up in the data from before and after the 100-year floods. The fact that there were no large changes in the quantity of wood (despite major channel changes) suggests equal inputs and outputs of wood to the 3rd and 4th order reaches.

5.3. *A conceptual model for woody debris transport and distribution*

Our good fortune in being able to map LWD distribution before and after major floods, coupled with the large range of river orders mapped by independent studies, provides a rare opportunity to comment on mechanisms controlling LWD distributions over time across a broad range of spatial scales. At the same time, however, we believe our data set does not cover a long enough time period or provide sufficient spatial detail to reach firm conclusions regarding basin-wide controls on LWD distribution. The reader should therefore view the following presentation as a conceptual model requiring further testing rather than as a proven theory.

The distribution of wood in the Soda Butte and Snake River systems and its movement after floods suggests a system that is the reverse of most sediment transport systems in mountains. Sediment transport in mountain streams is typically supply-limited in head-

water reaches, where sporadic sediment inputs provide relatively little fine grained sediment, most of which is removed by the high gradient streams (Montgomery and Buffington, 1997). Headwater mountain streams therefore often have cobble and boulder substrates, with relatively few sediments of gravel size and smaller. Farther downstream, streams with plane bed to riffle/pool morphology tend towards an equilibrium state, where sediment inputs equal sediment outputs. Farther downstream, the supply of finer grained sediments increases and the stream cannot flush all the sediments from the system. The downstream portions of mountain stream systems are thus often transport-limited, containing many more finer grained sediments than headwaters.

In contrast, our data suggests that LWD is transport-limited in headwaters and supply-limited in downstream reaches (Fig. 2). In the 2nd order headwaters of Soda Butte Creek (Reach A), the wood is too large to be moved and the system is transport-limited, with floods introducing new material through undercutting, but not being able to move the wood, which is snared by the narrow channels. In the intermediate size 3rd and 4th order channels (Reaches 1, 3 and 4), the system displays characteristics of dynamic equilibrium, where the channel is able move the debris at approximately the same rate that it is introduced, although wood will accumulate locally before being dispersed by subsequent flows. In the 6th order channels of the Snake River, the system appears to be supply-limited, having sufficient flow depth and energy to transport the wood down the channel, except in eddy pools or along banks and bars where it is deposited during receding flows.

Although the data in Fig. 2 appear to define a general linear trend between width and total wood, it would be a mistake to model this trend with regressions at scales ranging from 2nd to 6th order streams. Regressions imply a linear relation between variables, whereas we believe the data are better explained by thresholds between transport-limited, equilibrium, and supply-limited portions of the stream, with different width–LWD relations within each segment. In headwater channels where the channel width is often less than the height of trees, any logs falling “in” will span much of the channel and probably not be transported farther downstream. The quantity of LWD in these reaches is therefore largely supply-driven and will not

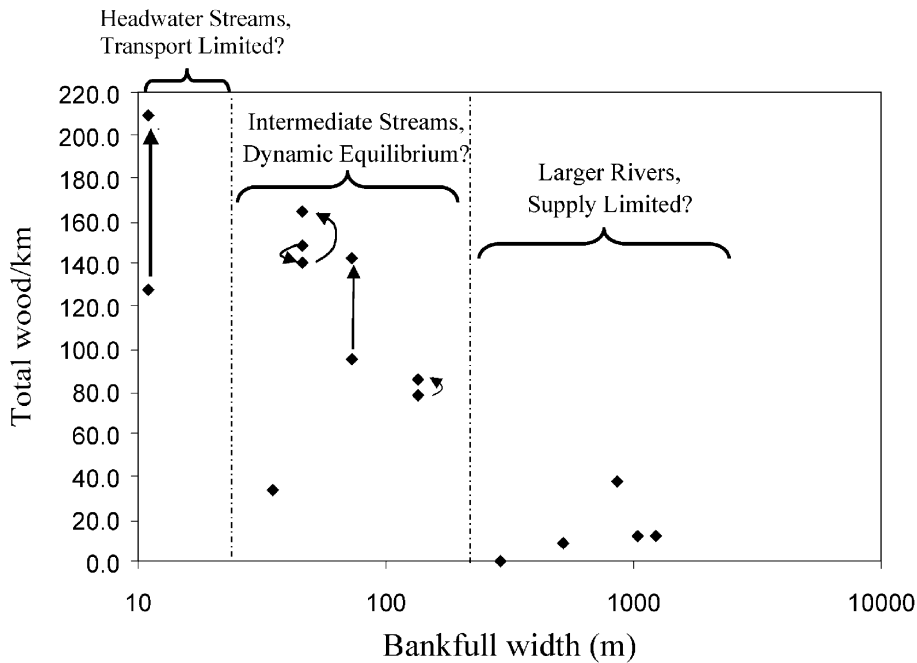


Fig. 2. Wood and morphometric data from Soda Butte Creek (1995, 1996, 1999) and the Snake River (1999). Arrows indicate change in wood amounts in Soda Butte Creek after floods. No pre- or post-flood wood data are available for the Snake River. We speculate that the high amount of wood in headwaters indicates a supply-rich, transport-limited system where wood hangs up in narrow, relatively shallow channels. Floods therefore introduce wood through undercutting, but cannot transport the wood out of the system. In intermediate streams, the variable amounts of wood and variable directions of change after flooding may indicate a pulsing equilibrium system, where wood introduced to the streams is moved downstream and redistributed on a sporadic basis by high flows. Low wood amounts in the larger streams suggests a supply-limited system, where the stream is able to remove most wood from the system under a wide range of flow conditions.

vary with width. Whether the width is 1/4 or 1/2 or 3/4 of the tree height makes no difference, since very few if any of the trees can move downstream. In contrast, once the width exceeds a certain size, all trees will be transported. There is therefore no linear relation between width and LWD in a system the size of the Snake River, with accumulations being more dependent on local bank phenomena and eddy currents. Only in the potential equilibrium reaches is there likely to be a relation between width and amount of LWD. Similar arguments hold for other morphologic control variables such as depth.

This suggests that a conceptual woody debris transport model could parallel those for sediment transport, with factors controlling debris input (disease, drought, fires, logging, lateral erosion) and transport (particularly channel width and depth relative to tree size and shape) providing guides to channel segments where debris could be expected to

be in equilibrium, accumulate, or move downstream. Braudrick et al. (1997) and Braudrick and Grant (2000) have made significant progress towards developing wood transport models based on flume studies, but the applications of these models to real world settings and the development of wood supply models for streams are still in their infancy. Integrated supply-transport models could provide valuable management tools for guiding stream restoration and identifying reaches sensitive to disturbance in the riparian zone, much as Montgomery and Buffington (1997) have outlined for mountain rivers.

5.4. Mapping woody debris with digital imagery

The ability of digital imagery to map woody debris was tested in Reaches 2 and 3 of Cache Creek. Visual analysis of the four-band digital imagery indicates that band 1 (blue) is reflected highly by both LWD and

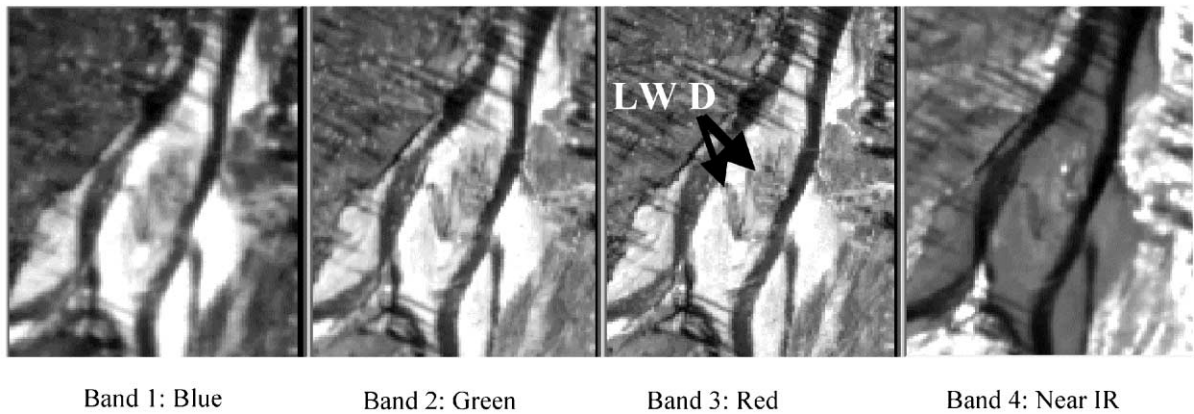


Fig. 3. Comparison of blue, green, red and near infrared spectral resolution. Blue band is blurred due to atmospheric scattering. Slight blurriness in the other images is due to the spatial resolution of the imagery and the instrument focus and is not a function of the quality of the figure. Appearance of large woody debris on the images is highlighted by location arrow on the red band image.

bare soil and rock (Fig. 3). Much of the non-wetted area within the permanent stream channels of Cache Creek is sand, gravel, and cobbles, so the blue band offers poor discrimination between woody debris and its background. Blue light is also scattered to a greater extent than longer wavelengths, which accounts for the relatively fuzzy definition of features in band 1 (Fig. 3).

Band 2 (green) offers high reflectance from woody debris with slightly more definition of woody debris than band 1. Individual logs are best distinguished from sand/gravel with band 3 (red) and individual logs are sometimes visible within larger log jams. Woody debris reflectance is low in band 4, but appears brighter than water in the imagery.

Viewed in “true color” mode (bands 3, 2 and 1), wood debris appears bright white, as one expects from logs missing their bark. In false color mode (bands 4, 3 and 2), wood has a signature resembling bare soil and is harder to distinguish.

The visual analysis and transformed divergence statistics, which indicate the degree of separability between spectral signatures of features (Jensen, 1996), indicate that four-band imagery should effectively classify and map woody debris (Colvard, 1998) (Fig. 4). A supervised classification, however, yields poor results for woody debris, with a user’s accuracy of 45% and a producer’s accuracy of only 17% (Table 4 and Fig. 5).

The poor classification results occurred primarily because the size of most woody debris is smaller than the individual pixels. This leads to poor spectral resolution of the wood relative to its background and to problems in accurately aligning imagery with the wood.

Problems with spectral resolution occurred because individual logs and logs sticking out of debris jams were typically only 30 to 60 cm in diameter, although

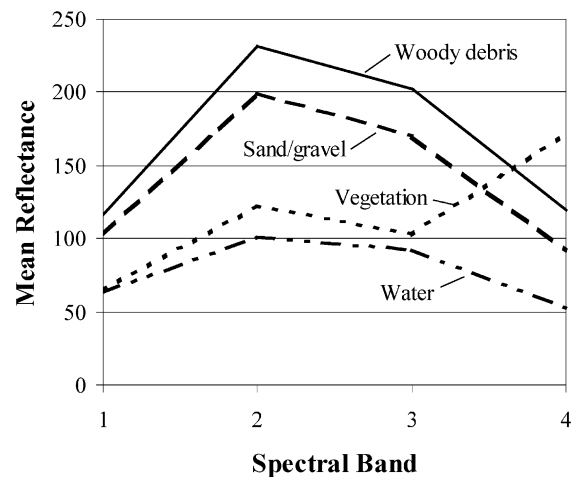


Fig. 4. Comparison of the spectral responses of wood, sand, water and vegetation. Wood is easily differentiated from water and vegetation, but can be confused with sand and gravel when pixel size is large enough to include mixtures of both components.

Table 4
Accuracy assessment of supervised classification results

Class	Number of sites mapped in field	Number of sites classified as that type of feature	Number correct	Producer's accuracy (%)	User's accuracy (%)
Water	57	69	56	98.3	81.2
Sand/gravel	60	63	44	73.3	69.8
Vegetation	31	48	28	90.3	58.3
Woody debris	52	20	9	17.3	45.0

they were often 10 m or more in length. As a result, the wood often only covered a small portion of an individual 1×1 m pixel. The standard rule of thumb with multispectral (as opposed to hyperspectral) imagery is that the spatial resolution of the imagery should be half the size of the feature being classified (Woodcock and Strahler, 1987), e.g., 1-m pixels should be used for features that are 2×2 m in size. Our results suggest that trying to capture features that are only 0.3 to 0.6 m in width on multispectral imagery is problematic, because the woody debris signature is often overwhelmed by the spectral signature of its background. Either finer spatial resolution and/or hyperspectral imagery that enables subpixel identification are required for mapping of individual pieces or small piles of woody debris. It is also possible that different

classification algorithms, particularly those that make use of pattern recognition, might provide better results with the existing imagery.

As noted by Wright et al. (2000), problems with coregistering the imagery and the field maps also occurs with features as small as individual logs, which leads to misclassification of features. The remote sensing classification process we used overlaid field-mapped features onto the multiband imagery to determine which pixels corresponded to a given feature. With logs that are as small as 0.3 in width and pixels that are 1 m in size, relatively small coregistration errors of less 1 m can lead to a feature being located in the wrong pixel. An error of 0.5 m in matching up the map and the image, for example, may therefore place a mapped log on top of image pixel 1, which is all sand, when in

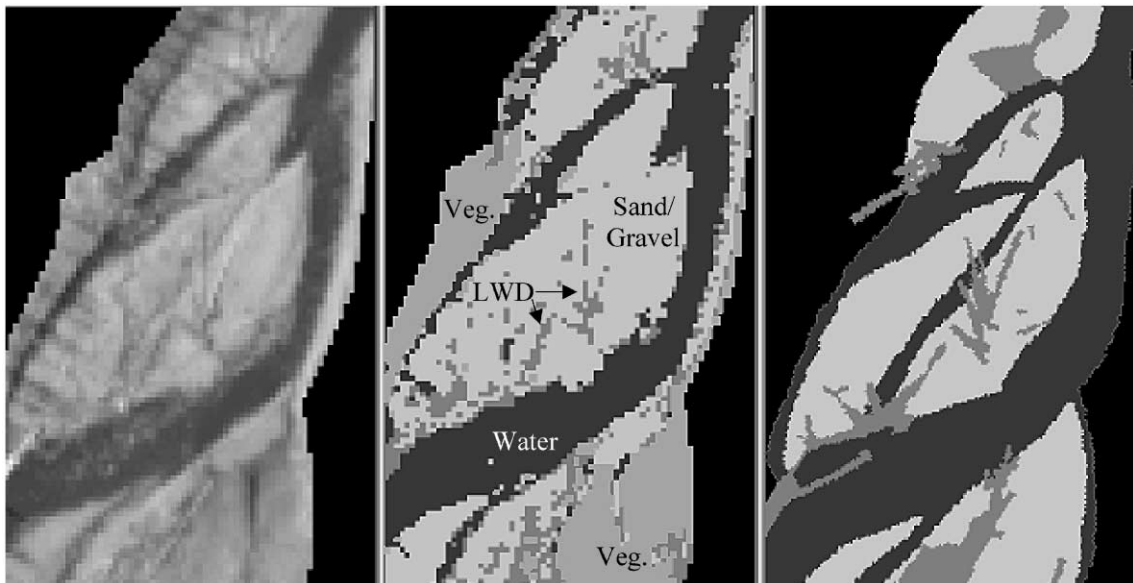


Fig. 5. A comparison of a three band composite image showing woody debris in the stream, a supervised classification of woody debris locations, and a map of actual woody debris classifications. Although the supervised classification shows the general location of major woody debris piles, it often mixes up woody debris and sand when both are located in a pixel, resulting in a low overall classification accuracy.

fact the log should be located in adjacent pixel 2. In this case, the image may correctly classify pixel 2 as wood, but our field map tells us that the wood is in pixel 1, leading us to believe that the image has misclassified pixel 2. Unfortunately, precise coregistration of the image and the field validation map is very difficult with features as fine scale as individual logs. If at all possible, it would be preferable to map the field validation sites for wood directly to the imagery to insure coregistration of mapped features and image pixels. If accurate coregistration and better spectral resolution cannot be obtained, then one would do better to fall back on classical methods and map directly to high resolution aerial photos or false-color composite printouts of high resolution multiband imagery.

6. Conclusions

The frequency, size, age, and orientation of LWD accumulations at the reach scale are related to channel unit types, total sinuosity, and characteristics of streamside vegetation. Floods led to increases in woody debris in 2nd order streams, but had little effect on distributions in 3rd and 4th order streams, acting to redistribute the wood within the channel rather than change the overall quantity. We conclude from the pre- and post-flood data from Soda Butte Creek coupled with data on the spatial distributions of LWD along the Snake River that the movement of woody debris through the system is transport-limited in the headwaters and supply-limited in lower reaches, with equilibrium transport occurring in intermediate reaches. Attempts to map woody debris with airborne digital multispectral imagery were generally unsuccessful, primarily because the imagery could not distinguish the narrow logs within a pixel from the surrounding sand and gravel background, and because of problems in accurately coregistering imagery and field maps at the fine spatial resolution required for individual pieces of woody debris.

The data set used to develop the conceptual model does not cover a broad enough range of stream environments to validate the model. Although the model is intuitively appealing, we can envision circumstances where it might not apply. For example, headwater streams might not be transport-limited with regard to woody debris in places where all wood is small and

brushy and can move within the channel, or in areas where debris flows frequently scour 1st to 2nd order streams. Likewise, equilibrium transport in intermediate order streams may not apply in braided rivers with multiple small channels and areas where wood can be stranded on bars. Finally, a supply-limited model for downstream reaches might be inappropriate in semi-arid to arid exotic streams where flows decrease downstream. A true testing of this model requires that rivers and their woody debris be examined across a wide range of geographic regions and river types.

Our findings that four-band 1-m resolution imagery is not effective for mapping woody debris are discouraging. It is unclear from our work, however, whether the major problems in distinguishing woody debris derive from insufficient spectral bands or from problems in coregistration of imagery and field maps at this fine spatial resolution. Future work should focus on evaluating the potential of digital imagery to map wood using both hyperspectral imagery and field maps that are very precisely coregistered to the imagery.

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