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DISSERTATION

ALTERATION OF FOREST STRUCTURE AND ECOSYSTEM FUNCTION ALONG THE YAMPA RIVER, COLORADO

Submitted by

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In partial fulfillment of the requirements

for the degree of Doctor of Philosophy

Colorado State University

Fort Collins, Colorado

Spring 1999

COLORADO STATE UNIVERSITY

January 30, 1998

WE HEREBY RECOMMEND THAT THE DISSERTATION PREPARED UNDER OUR SUPERVISION BY HOLLY E. RICHTER ENTITLED ALTERATION OF FOREST STRUCTURE AND ECOSYSTEM FUNCTION ALONG THE YAMPA RIVER, COLORADO BE ACCEPTED AS FULFILLING IN PART REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY.

Committee on Graduate Work

Adviser

Department Head/Director

ALTERATION OF FOREST STRUCTURE AND ECOSYSTEM FUNCTION ALONG THE YAMPA RIVER, COLORADO

The hydrologic regime of the Yampa River remains relatively unaltered, supporting some of the finest examples of riparian community types left in the Upper Colorado River Basin. However, GIS analyses suggest that the existing stands of riparian vegetation represent only a fraction of that which likely spread across the Yampa's floodplain only a century before. Anglo settlement has resulted in clearing of riparian plant communities for agricultural uses, and in extensive thinning and fragmentation of the remaining stands of forest. Previously thinned forests were found to exhibit a mixed-age stand structure as a result of subsequent asexual reproduction by *Populus angustifolia*.

This research examines the complex interactions between natural hydrologic and geomorphic processes and vegetation patterns within the floodplain ecosystem through the use of an ecological model. To effectively conserve the biodiversity represented within particular ecosystems, ecologists need to develop a better understanding of natural ecosystem function and the ways in which human-induced stresses have altered these systems. The model provided a tool by which biotic, hydrologic, and geomorphic data could be integrated to create testable hypotheses regarding ecosystem dynamics. Interpretation of modeling results suggests that in the vicinity of the study site, the Yampa River may be especially vulnerable to human alteration due to its geomorphic and

hydrologic characteristics. In recent decades, both increases in floodpeak variability, and human clearing of riparian forest cover that has decreased streambank stability, have likely contributed toward changing trends in ecosystem function and the regeneration of riparian communities.

Model development not only led to the formation of hypotheses regarding the complex interactions between ecosystem structure and function (including complex feedback mechanisms), but also helped to define preliminary site conservation goals. An adaptive management approach will be used to test the hypotheses suggested by this model in the future. Finally, a strategy for maximizing the asexual reproduction of *Populus angustifolia* along the Yampa River was developed as a critical first step toward the development of a larger ecosystem restoration program.

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CHAPTER 1

INTRODUCTION

STUDY GOALS AND OBJECTIVES

Human interaction with riparian ecosystems has been widespread across the western U.S. during the past century. Unfortunately, water diversions, reservoir construction, channel stabilization practices, and other human impacts have altered natural streamflow processes and adversely affected riparian plant communities along most western rivers during this time period (Kauffman *et al.* 1997). Many studies within the past decade have clearly elucidated the strong dependency of these systems upon natural hydrologic and geomorphic regimes (Nilsson *et al.* 1991, Stromberg *et al.* 1993, Auble *et al.* 1994, Rood *et al.* 1995, Friedman *et al.* 1996, Scott *et al.* 1996, Scott *et al.* 1997).

Currently, riparian systems are being altered, impacted, or destroyed at a greater rate than any time in history (National Research Council 1992). For the southwestern United States, the estimated losses of riparian ecosystems range from 70% to more than 95% (Johnson and Haight 1984, National Research Council 1992). In addition, the remaining fragments of some riparian forests are also highly vulnerable to some of the slower, less obvious processes of environmental degradation such as the invasion of aggressive exotic plant species, and poorly managed livestock grazing (Braatne *et al.* 1996).

However, riparian areas significantly contribute to local and regional biodiversity. Less than 1% of the western North American landscape is covered by riparian vegetation, yet it provides habitats for more species of birds than all other vegetation types combined (Knopf *et al.* 1988). In northern Colorado for example, eighty-two percent of all breeding bird species occur within riparian vegetation (Knopf 1985). Furthermore, researchers have found that the disproportionately high importance of riparian habitat extends to other vertebrate species as well (Brode and Bury 1984, Cross 1985).

Fortunately, the hydrologic regime of the Yampa River in northwestern Colorado remains relatively unaltered, supporting some of the finest examples of riparian community types left in the upper Colorado River Basin. The globally rare *Acer negundo-Populus angustifolia Cornus sericea* community found along the Yampa is one of the primary targets for protection by the Colorado Program of The Nature Conservancy. The majority of high-quality occurrences of this community is found along a 64-kilometer stretch of the Yampa River between Craig and Milner, Colorado. Land acquisition and protection efforts by the Conservancy began in 1986 in the area and still continue today with the purchase of the Carpenter Ranch in 1996.

Unfortunately, the existing stands of riparian forest along the Yampa River represent only a fraction of the original riparian forest which spread across the floodplain only a century before. Clearing of riparian vegetation in the Yampa valley was probably most extensive during the late 1800s similar to vegetation trends in adjacent valleys of the region (Athearn 1988). However, in recent decades the continued clearing of vegetation for agriculture has reduced the average percent of the floodplain with riparian forest

cover, decreased the average forest patch size, and increased the number of forest patches within the corridor (Noble 1993). The Conservancy plans to work cooperatively with local landowners to launch an ambitious restoration initiative along selected reaches of the Yampa. However, before undertaking any restoration measures, it is highly desirable to have a thorough understanding of the influence that both historic human land uses, and abiotic processes have had on vegetation dynamics.

To address this need, the first objective of this study was to determine the impacts that historic land management practices, such as tree harvesting and livestock grazing, may have had on the remaining stands of riparian forest. Whereas previous studies have documented the overall reduction of riparian forest cover along the Yampa during the past century (Noble 1993), little is known regarding the influences of previous land uses on the successional trends of the remaining remnant forest stands. This research component is discussed in Chapter Two.

The next objective of this study, and perhaps the most important one, was to develop an ecological model to generate hypotheses regarding the functional relationships between hydrologic and geomorphic processes and the patch types that comprise the overall riparian mosaic. This objective also included identification of the ways in which human influences may have altered these natural processes and their functional relationships to ecological patterns. Model development provided an essential component of this research project by providing a tool with which biotic, hydrologic, and geomorphic data could be integrated to provide testable hypotheses regarding ecosystem dynamics. Chapter Three provides a summary of ecological model development.

Finally, Chapter Four provides preliminary restoration strategies which address the hydrology, geomorphology, and biotic components of the ecosystem. The strategies developed in this chapter are based upon hypotheses generated in Chapters Two and Three. Chapter Five provides a summary of the findings associated with this research project and suggests future ecosystem management goals.

STUDY AREA

Physical Setting

The study site is located in the upper Colorado River Basin, encompassing approximately 18.7 km of the Yampa River upstream from the town of Hayden, Colorado. Within this stretch of the river, elevation ranges from 1926 to 1951 m, with an average channel gradient of 1.3 m/km (i.e., slope=.0013). The recent alluvial sediments range from 3-7 m in thickness; alluvial width varies from 150-1600 m along the study reach (Madole 1989).

Precipitation occurring near Craig, Colorado (25 km downstream of this site) is approximately 34 cm annually. River flow in the Yampa typically peaks in late-May to early-June in response to snow melt runoff from the river's headwaters on the western slope of the Rocky Mountains. Flow levels gradually recede during June-August, with occasional minor surges attributable to summer rainfall events. The mean January temperature is -7.7 C°, while the mean July temperature is 19.4 C°. Surrounding uplands are dominated by Wyoming big sagebrush (*Artemisia tridentata* ssp. *wyomingensis*) with a

diverse understory of herbaceous species such as: prairie junegrass (*Koeleria macrantha*), blue grama (*Bouteloua gracilis*), Indian ricegrass (*Oryzopsis hymenoides*), Great Basin wildrye (*Elymus cinereus*) and arrow-leaf balsamroot (*Balsamorhiza sagittata*). The study site lies within the North-Central Highlands Section of the Southern Rocky Mountain Ecoregion Province (Bailey *et al.* 1994).

Fluvial Processes

At the landscape scale, riparian communities occur along the Yampa River as a result of hydrologic processes operating in various geologic settings within the watershed. Within the study site, two different geologic settings along the stream channel have created substantially different floodplain environments. Broad valley settings occur where the channel cuts through either the Lance Formation or Lewis Shale Residuum. In these areas, the low-gradient stream channel meanders across relatively wide valley floors, as in the Morgan Bottoms area (Figure 1). Narrow, confined valleys occur where the channel cuts through Mesaverde Group Residuum, a relatively resistant geologic unit capable of forming massive sandstone cliffs and steep valley sides (Madole 1989). In these settings, the stream gradient is higher and the channel straighter, such as at the Yampa River Preserve (Figure 2).

These two settings differ in the operative geomorphic processes that shape fluvial landforms, and therefore initiate plant succession. Other studies have confirmed that differences in factors such as local bedrock, or geologic history, can result in two nearby reaches of the same stream being dominated by different fluvial processes (Scott *et*

Figure 1. A wide valley setting on the Yampa River in Morgan Bottoms just upstream of Hayden, Colorado.

Figure 2. A narrow valley (confined) setting of the Yampa River near the U.S. Highway 40 bridge, 3 km upstream of the area shown in Figure 1. An abrupt transition in floodplain width has occurred, most likely as a result of a change in geology.

al. 1996). The variation in fluvial processes between these reaches may also result in different spatial and temporal patterns of riparian tree species over the long-term (Scott *et al.* 1996). In the broad valley settings along the Yampa River, lateral channel migration creates depositional point bars where *Populus angustifolia* seedlings can germinate and establish. Another important geomorphic process, meander cut-off, occurs in these broad valleys when a segment of the main stream channel is abandoned during a large flood and a new channel segment is activated, usually cutting across a meander bend and straightening the channel in the process. Channel abandonment allows the development of wetland plant associations in the old abandoned channels or "oxbows." These wetland plant associations are found only in the broad valley settings, and they substantially contribute to beta (between habitat) diversity within the overall riparian corridor. The ecological model developed during this study applies only to vegetation dynamics within these wide valley settings.

In contrast, a different suite of geomorphic processes influence the riparian landscape in confined, narrow valley settings. Although alternate, lateral gravel bars may form along the channel in narrow valley settings, they are quite small in area compared to the point bars found in wider alluvial valley settings. *Populus* regeneration on these bars is generally not successful because these sites are frequently reworked by the river. Successful recruitment in these areas is most likely associated only with the largest of floods, wherein the straight stream channel widens at the peak of the event and subsequently narrows, creating depositional surfaces along either side that can be

colonized by vegetation (Scott *et al.* 1997). Meander cut-off does not occur in these settings, due to the inherent lack of channel sinuosity.

The geomorphic processes operating in both floodplain settings are, however, entirely dependent upon hydrologic processes operating at the watershed scale. In particular, natural variability in streamflow drives the geomorphic processes that shape the riparian landscape. Therefore, a hydrologic regime retaining natural variability is necessary to produce the full array of geomorphic possibilities in the landscape that sustain the beta diversity of plant associations, as well as the associated wildlife species, within the riparian mosaic (Scott *et al.* 1997).

In summary, the synergy of hydrology and geomorphology, along with the biotic response of riparian plant associations, results in a rich mosaic of dynamic habitats along the Yampa River. Even though these plant associations or "patch types" may shift spatially and temporally as a result of flood-induced stand destruction and stand initiation events, the long-term dynamics can be conceptualized as a "shifting-mosaic steady state", as described by Bormann and Likens (1979), if the processes driving ecosystem dynamics approach a long-term equilibrium. Under such conditions, drastic fluctuations in patch type abundance may occur at a local scale over shorter time periods, but a steady state persists at the larger ecosystem scale, because rates of community regeneration are balanced with degenerative disturbance processes (Noss and Harris 1986). However, the rates and magnitudes of fluctuation in patch type abundance can have substantial influences on local biodiversity. Landscape ecologists have found that the structure of

patch mosaics (e.g. patch density, distance between patches, and patch size distribution) is important to both plant and animal species (Forman and Godron 1986).

REVIEW OF PREVIOUS MODELING EFFORTS

A number of computerized "forest ecosystem models" have been developed by ecologists during the past decades. Some of these models were originally developed for terrestrial forest systems (e.g. "JABOWA"- Botkin *et al.* 1972; "FORET"- Shugart and West 1977) and later adapted by others for use in forested wetland environments in the Southeast (i.e., "FORFLO"- Pearlstine *et al.* 1985 for Santee River, South Carolina; "SWAMP"- Phipps 1979 for White River, Arkansas). Other ecosystem models have been designed for site-specific riparian ecosystem applications, such as the modeling work performed by Franz and Bazzaz (1977) on the Sangamon River in Illinois, by Auble *et al.* (1991) on the Gunnison River in Colorado, and by Johnson (1992) on the Missouri River in North Dakota. Table 1 is a summary of these riparian ecosystem modeling studies.

The riparian or floodplain forest modeling efforts noted above have all (with the exception of Johnson 1992) been based upon the assumption that the topography of the study site remains essentially unchanged for the simulation period. For many, if not most of the sites which have been modeled, this assumption may have been acceptable for the time periods simulated. The rates of river migration and floodplain sedimentation in the low-gradient, southeastern Coastal Plain rivers are generally orders of magnitude less than those characteristic of meandering western rivers, such as the Yampa. Although the FORFLO (Pearlstine *et al.* 1985) and SWAMP (Phipps 1979) models simulate the

Table 1. Summary of riparian ecosystem modeling studies.

Study Site	Time Step	Unit Modeled	Regeneration Simulation	Growth Simulation	Mortality Simulation	Field Data Requirements	Citation
White River, Arkansas	annual	trees	explicit; depends on hydrologic conditions, crowding, shading	explicit; depends on growth rates	explicit; depends on growth rates	1) streamflow 2) topographical surveys 3) vegetation sampling 4) tree ring data 5) depth to water	Phipps 1979
Sangamon River, Illinois	instant equilibration	trees	implicit; direct gradient with hydroperiod	none	implicit; direct gradient with hydroperiod	1) reservoir stage 2) topographical surveys 3) vegetation sampling	Franz and Bazzaz 1977
Santee River, South Carolina	15 days	trees	explicit; depends on hydrologic conditions, soils	explicit; depends on crowding, temperature, shading, depth to water	explicit; depends on growth rates	1) streamflow 2) topographic surveys	Pearlstine et al. 1985
Gunnison River, Colorado	instant equilibration	vegetation cover types	Implicit; direct gradient with hydroperiod	none	implicit; direct gradient with hydroperiod	1) streamflow 2) topographic surveys 3) vegetation sampling	Auble et al. 1991
Missouri River, North Dakota	annual	5 patch types	implicit; averaged succession rates	none	implicit; averaged succession rates	1) streamflow 2) tree ring data 3) groundtruthing of aerial photos	Johnson 1992

recruitment, growth, and mortality of species according to time-varying hydrologic and biotic conditions, they cannot presently accommodate changing floodplain elevations and shifting channel positions and would, therefore, require substantial modifications to enable their application to geomorphically-dynamic western rivers. These two models were developed to simulate changing forest composition (i.e., tree species) in response to hydrologic variation in geomorphically stable environments. However, these models were not designed to simulate geomorphically-driven patch dynamics such as the establishment of emergent wetlands in recently abandoned channels.

The modeling efforts of Auble *et al.* (1991) on the Gunnison River in Colorado were also based on the assumption of a static floodplain cross-section. This was an appropriate modeling approach within the bedrock-confined channel of their Black Canyon study area. The potency of the assumption of static topography is that it greatly simplifies a modeling strategy. It enabled these previous investigators to develop models that rely heavily upon a relationship between the elevation of the site and the hydrologic gradients (e.g. hydroperiod) associated with that elevation. However, the assumption of a static geomorphic environment is clearly not appropriate for actively meandering, alluvial reaches of the Yampa, suggesting that a new or substantially modified modeling approach is needed for these types of western riparian ecosystems.

Johnson's (1992) work on the Missouri River is probably most similar to the model described herein for the Yampa River (see Figure 3). This relates to the fact that the Yampa, like the Missouri River, is a meandering river where lateral channel migration is an

important geomorphic process driving biotic succession. Alluvial deposits located on the inside of meander bends provide ideal seedbeds for the germination of *Populus* seedlings (Bradley and Smith 1986). Subsequent transitional and terminal stands form through biotic succession. In addition, all vegetation types are potentially subject to eventual destruction by flood flows that once again result in the formation of bare alluvium. The development of a patch dynamics model for the Yampa expands the modeling approach employed by Johnson (1992) by also addressing the geomorphic process of channel abandonment, and the formation of resulting patch types. Perhaps the strongest argument for the development of a new modeling strategy for the Yampa River is the relatively high

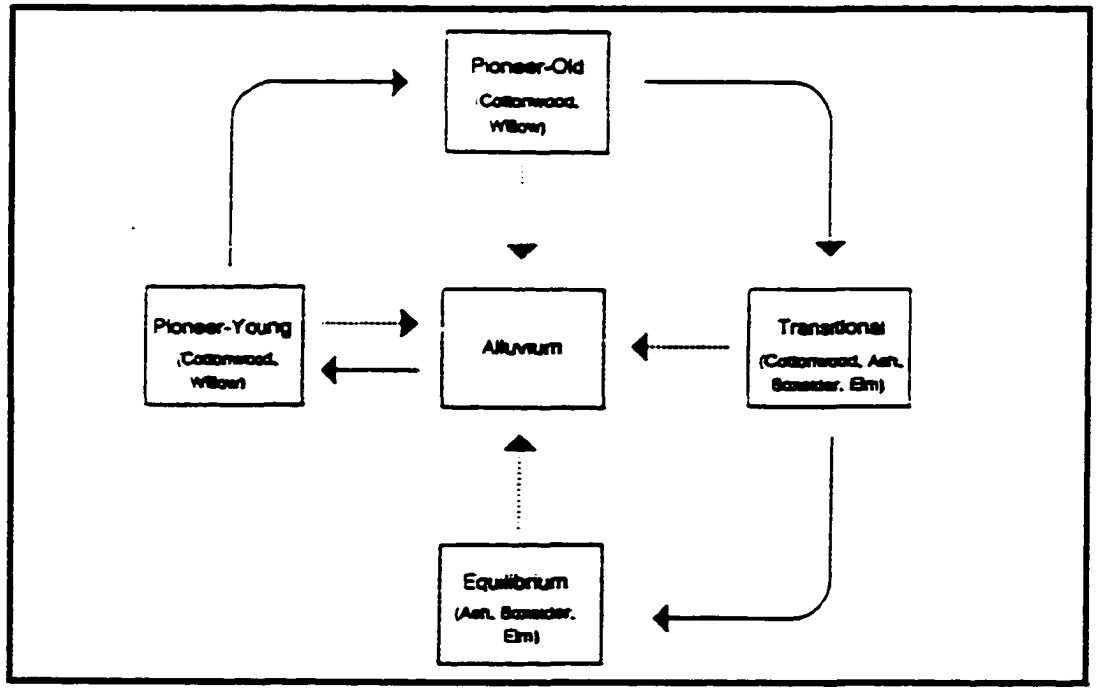

Figure 3. Vegetation simulation model developed by Johnson (1992). Dashed arrows represent erosion losses to the alluvium compartment and solid arrows represent successional pathways among forest types.

diversity of patch types that occur within this riparian mosaic and the Conservancy's interest in conserving this (beta) diversity. Conservation efforts at this site will not only be aimed at protection of the dominant mature *Populus* forest, and its keystone species, *Populus angustifolia*, but also at protection of the full riparian mosaic, of which the *Populus* forest is a dominant element. Therefore, model construction in this study was based on a higher hierarchical scale than the species level, addressing the flux of patch types that comprise the overall riparian mosaic.

The diverse fluvial landforms found along meandering rivers such as the Yampa include floodplain terraces, point bars, abandoned channels and oxbow lakes. The river is constantly reworking, altering, destroying and modifying these landforms. Each landform type supports a plant community or riparian patch type adapted to the distinctive hydrologic and edaphic conditions characteristic of the landform, and these patches change over time in response to allogenic forces and autogenic succession. Direct gradient analysis between simple hydrologic gradients (such as hydroperiod) and floodplain vegetation will generally not yield a high level of predictive capability in such environments, because much variability of other physical attributes within each of these hydrologic settings may exist (such as sediment texture, exposure to flood flow hydraulics, etc.) which may also exert substantial influence on plant species composition.

The development of new predictive tools that are capable of simulating the response of complex riparian mosaics to changing biotic and abiotic conditions in geomorphically active floodplains over time is greatly needed to guide conservation efforts. The modeling strategy required for these rivers will need to accommodate time,

geomorphic and hydrologic change, and the relatively high diversity of riparian patch types that are represented within the shifting mosaic.

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CHAPTER 2

HISTORIC LAND USE IMPACTS ON THE REMAINING STANDS OF RIPARIAN FOREST ALONG THE YAMPA RIVER

INTRODUCTION

Study Goal

Similar to other riparian areas in the semi-arid western United States, the Yampa River Valley has attracted human inhabitants for at least 10,000 years (Athearn 1982). Located in the upper Colorado River Basin in northwestern Colorado, the Yampa River floodplain provides an abundance of water, lush vegetation, and wildlife within the semi-desert shrub-dominated matrix of the regional landscape. This riparian corridor serves as a critical interface between terrestrial and aquatic systems.

The globally rare *Acer negundo-Populus angustifolia/Cornus sericea* plant community found along the Yampa near Hayden, Colorado, is one of the primary biodiversity conservation targets in this region (The Nature Conservancy 1996). Unfortunately, the existing stands of this riparian forest type represent only a fraction of its original extent. Presumably, most human alteration of riparian vegetation has occurred since Anglo settlement began in the 1870's, primarily due to clearing for agricultural uses. Athearn (1988) states that along the White River, in the watershed south of the Yampa

River, cottonwood forests had almost completely disappeared by the 1890s, being cut for use as lumber or firewood.

Unfortunately, no aerial photographs are available of the area until 1938. Noble (1993) used a Geographic Information System (GIS) to describe changes in riparian vegetation cover along the Yampa River from the Town of Hayden, Colorado to a point approximately 18.7 kilometers upstream during 1938-1989. She reported that the average patch size of mature *Populus* forest stands declined by 62%, and the number of patches increased by 91% during this period. Mejia-Navarro (1996) generated GIS transition matrices to calculate the average percentage of both mature *Populus* forest and wetlands associated with abandoned channels along the Yampa that were cleared each year. The average annual clearing rates have increased since 1938, particularly for wetlands in old abandoned channels, suggesting increasing development pressure on the riparian corridor (see Appendix A).

Whereas these previous studies have quantified the loss of riparian vegetation cover along the Yampa River for approximately a 50 year period, the goal of this study was to identify the impacts that historic land uses may have had on the remaining stands of riparian forest. Based on initial field observations, the majority of the mature riparian forest stands within the Yampa River study area appear to consist of mixed-aged stands of trees, unlike the distinct, even-aged cohorts of cottonwood typically described of undisturbed riparian forests (Everitt 1968, Noble 1979). Development of hypotheses that describe the effects of previous land management practices on successional trends of the

forest is an important first step towards defining restoration needs within the riparian corridor.

Historical Background

Prior to European settlement, the northwest corner of Colorado was historically populated by three indigenous tribes: the Utes, the Arapaho, and the Shoshoni. Of these groups, the largest was the Ute who were nomadic hunters that used the river valleys for shelter during winter (Athearn 1982). Little is known regarding the composition, structure, or abundance of riparian vegetation along the Yampa River prior to European exploration of the area.

The first recorded non-indigenous people visited the area in 1776. They were Spanish exploring new routes to California from New Mexico. European fur trappers were also active in this region from the 1820's to the 1840's, after which the fur trade declined since most of the prime pelts had been trapped out, and furs had lost popularity.

By 1871, the first cattle were driven into northwestern Colorado, including the Yampa and Little Snake Valleys (Athearn 1982). Although there were few detailed historical accounts of the natural vegetation that existed within the Yampa River's floodplain prior to extensive settlement, the Ferdinand Hayden surveys (1877) mentioned the presence of vast riparian forests. In 1876, S.F. Emmons described:

> "Along the waters of most of the streams are alluvial bottoms, which on the Yampa River itself afford considerable stretches of arable land, sometimes nearly a mile in width and which support a growth of fine large cottonwood trees".

Only 22 years later, in 1898, A.L. Fellows made a general reconnaissance in northwestern Colorado in order to obtain data concerning the flow of streams useful for irrigation. In a 1899 US Geological Survey Report he described:

> "Nearly all the people in the vicinity of Craig, as well as those of Routt County in general, are stock growers and apparently prosperous"

And:

> "On the morning of September 17 we left (Craig) for Steamboat Springs, situated on the Yampa River about 45 miles above or east of Craig. The road winds along the river side, sometimes on the edge of the mesas and sometimes along the river bottom, through beautiful, well-cultivated ranches. The principal products of the irrigated lands are hay and grain for the winter feed of stock. Improved ranches with water rights are held at high figures. About noon we passed through the little town of Hayden, which is nearly in the center of the best cultivated part of the Yampa Valley."

The 1880's, 1890's, and early 1900's were the height of the open range cattle industry in northwestern Colorado. Cattle were put out on the range year-round, and in winter they depended upon native forage for survival; in some years this was a profitable venture, while in others the hard winters took terrible tolls on the herds (Athearn 1982).

By 1904, the value of cattle in Routt County (which then included present-day Moffat County) was estimated at more than half the county's total assessed value. An extremely important influence on the local economy occurred in 1909 when rail service reached Steamboat Springs. This transportation system enabled Steamboat Springs to become the largest cattle shipper in Colorado's northwest corner. In fact, at one point Steamboat Springs was the greatest cattle shipping point in the United States (Burroughs 1974).

In addition to the improved transportation system, a second factor may have also enhanced the success of the cattle industry in northwestern Colorado during this time. By the late 1890's and early 1900's ranchers in the Yampa Valley began to harvest top-quality wild hay to feed cattle during the long winters, allowing for both higher winter survival rates, as well as higher market prices (Fellows 1899, Athearn 1982). However, conflicts between cattlemen, sheep herders, and homesteaders were common in the area until the 1920's when the open range cattle industry ended. The cattle industry of northwestern Colorado no longer remained the mainstay of the economy by the 1920's when coal, oil, and sheep threatened to overtake that industry. The Depression of the 1930's, coupled with an unprecedented drought, caused the failure of many agricultural enterprises in the region. The upper Yampa Valley fell into deep economic depression from the 1920's until the 1940's (Athearn 1982).

It is difficult to assess the impacts that livestock may have had on riparian plant communities along the Yampa River during the height of open range livestock grazing. We do know, however, that riparian ecosystems offer more forage of higher quality (i.e., a higher proportion of green to dead plant material and a higher proportion of leaves to stems) and greater amounts of shade, water, and thermal cover than do upland ecosystems (Briggs 1996). Such characteristics tend to attract and concentrate livestock, and as a result riparian areas often receive a disproportionate amount of use in comparison to their size (Briggs 1996). For instance, one study found that although streamside vegetation makes up only about 10% of the total vegetation found in meadows in northern California, it provides about 90% of the usable forage for livestock (Svejcar 1989).

Today, the Yampa River Valley still supports livestock grazing and hay production, although livestock management practices are much different than when open range, year-long grazing occurred. In addition, recreational, residential, and commercial land uses are becoming increasingly important in the region. Lastly, the Yampa River ecosystem has recently been recognized for the many important biodiversity values that merit conservation (The Nature Conservancy 1996).

METHODS

Tree age dating and tree excavation were used to define the age structure of the dominant tree species and forest successional trends. From this information, hypotheses were formed regarding how previous land uses may have influenced the current age and physical structure of riparian forests that are observed along the Yampa River today. Analyses of historic streamflow records and observations of historic aerial photography were also used to help refine these hypotheses and interpret results.

Tree Age Dating

Tree cores were collected from 100 *Populus angustifolia* and 18 *Acer negundo* trees, from 10 macroplots (that were 15 m x 25 m) located within mature cottonwood forest, using 40 and 75 cm increment borers.

The tree core data from these plots were used to detect the timing or lack of recruitment patterns over the past century. In addition, data from three of the macroplots were also more closely examined for age variability within plots.

The total number of trees to be sampled was determined by time constraints and labor available for sample collection within one field season. An effort was made to collect samples throughout the study area, but access was restricted to a limited number of sites. Therefore, the stands that were sampled were subjectively located according to access restrictions. Because all stands that were sampled typically contained a large range of stem sizes, the trees to be sampled were randomly selected within broad size classes (saplings 0-1 m tall, juvenile trees over 1 m tall ≤ 25 cm dbh, mature trees ≥ 25 cm dbh) within each stand so that the samples represented the range of variability of stem sizes that were present. In addition, a few of the largest diameter stems within the stands were also subjectively selected for sampling to obtain a reasonable estimate of minimum stand ages. Cores were obtained from as close to the ground surface as possible.

Multiple samples were collected when necessary so that the core hit or very nearly hit the center ring. Cores were air dried, mounted in grooved wooden blocks (Phipps 1985) and sanded with a random orbit sander using progressively finer grit sandpaper (150, 220, down to 30 micron grit). Tree rings were counted under a dissecting scope.

Trunk cross-sections were also collected from individuals too small to core (i.e., younger saplings) or from trees recently felled by beaver. The smaller cross sections were mounted on wooden boards after drying and sanded as were the cores. Multiple cross sections (2-4) were prepared for each of the smaller saplings so that the location of the true root collar could be determined (the one possessing the most rings). The root collar of saplings growing within the understory of these mature forest stands was typically at

the elevation of the ground surface. However, if saplings were buried by a few centimeters of sediment they were excavated down to the root collar for collection of cross sections. Cores or slabs were collected from a total of 118 trees.

Because tree age data were to be used to define general successional relationships and the approximate timing of land use impacts, the absolute dates of all of the specimens were not required and cross-dating techniques were not deemed necessary for this study.

Tree Excavation

Populus angustifolia has the capability to reproduce asexually from root sprouts (Rood *et al.* 1994), as well as sexually from seed germination. Without relying on genetic information, the only practical way to determine the reproductive origin of individual trees in the field is by excavation of the root system. Tree excavation was used in this study as a means of determining the method of reproduction of younger *Populus* trees. Twenty saplings were excavated within mixed-aged stands of trees to determine method of reproduction. Root structure of younger individuals is often quite revealing: asexual ramets obviously originate from a horizontal root, while sexually-derived individuals possess one or a few tap roots that descend vertically.

The excavation of ten older mature *Populus* trees also served to verify that the original root collar of these trees was not far below the present ground surface. Therefore, coring trees near the elevation of the current ground surface provided a reasonably accurate estimate of the tree's true age, due to the proximity of the root collar. Excavation of trees to the establishment surface decreases by as much as an order of magnitude the

number of trees that can be sampled per unit time (Scott *et al.* 1997). Scott (1997) estimates that dating cottonwoods at the ground surface results in a mean underestimate of 5.1 years, although considerable variation exists.

Hydrologic Analyses

The Index of Hydrologic Alteration (IHA) methodology was used to determine if the Yampa River's flood regime had changed significantly during 1905-1925, as compared to subsequent years (1926-1997). Because streamflow records were not available for the study area before 1938, data from the Steamboat Springs streamgauge were used. Little *Populus* recruitment was found to have occurred between 1904-1925 (see results section) and this analysis was performed to determine if a lack of flooding during this period could be responsible for reduced recruitment rates. The results of Richter's analysis can be found in Figure 29 in Appendix B.

RESULTS

Tree age data collected from mature *Populus* stands within the study area exhibited two surprising characteristics. First, the age variability within individual stands of trees was large. Even-aged stands of mature cottonwood were not typically observed in the study area, as is commonly described in the ecological literature (Everitt 1968, Noble 1979). While many different sources of error are present in the collection of tree cores and interpretation of tree core data, the age variability within individual macroplots was on the order of 90-110 years and cannot be solely attributed to sampling error (Table 2).

Table 2. The ranges of ages of *Populus angustifolia* within three different macroplots that were sampled along the Yampa River, 1993.

	Macroplot One	Macroplot Two	Macroplot Three
Number of trees cored or slabbed	17	17	7
Mean age of trees sampled (years)	27	21.5	47.7
Estimated standard error	5.2	5.6	14.1
Range of tree ages within the stand (years)	90	103	110

Secondly, when combining the data from all macroplots that were sampled within the study area, an obvious gap appears to have occurred in the regeneration of *Populus* along the Yampa between 69 and 90 years ago (i.e., 1904-1925). None of the 100 *Populus* or 18 *Acer* that were sampled had become established during this period (Figure 4). The length of the "regeneration gap" (21 years) is sufficient such that the younger post-settlement era recruits (less than 69 years old) can be clearly distinguished from the older remnant trees (exceeding 90 years old), even by visual observation in the field. Of the 100 *Populus* trees age-dated, 32 established before the regeneration gap (the period between 1904-1925) and 68 established after it (Table 3).

For all of the trees cored, the range in tree ages spanned from 9 to 161 years. The distribution of tree age data shown in Figure 4 suggest that age distribution is not evenly distributed between all ages, but that trees established more successfully during certain years than others. It is difficult to determine if these successful recruitment years were

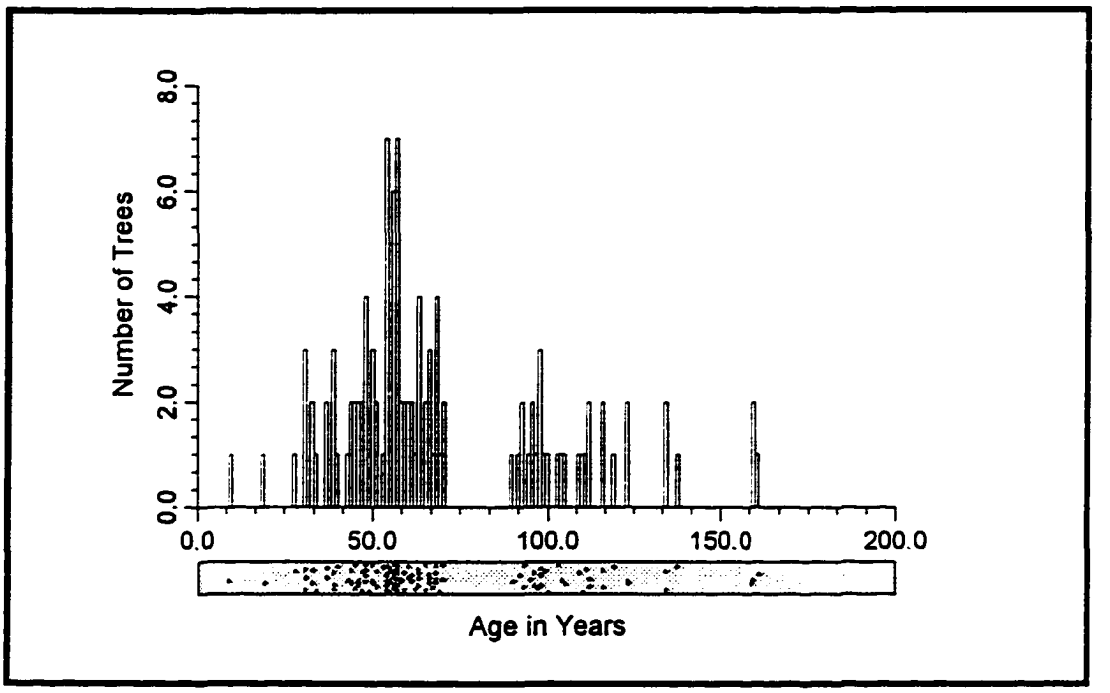

Figure 4. Histogram of ages of 118 trees that were cored or slabbed along the Yampa River, 1993.

Table 3. Descriptive statistics of the 118 trees that were cored or slabbed (within stands dominated by mature trees) along the Yampa River, 1993.

	All *Populus* trees sampled	*Populus* trees that established during the pre-settlement period	*Populus* trees that established during the post-settlement period	All *Acer negundo* sampled
Number of trees cored or slabbed	100	32	68	18
Mean age (years)	72	112	53	50
Estimated standard error	3.1	3.5	1.4	3.0
Maximum / minimum tree age (years)	161/9	161/90	69/9	70/28[1]

[1]The minimum age for *Acer negundo* individuals reflects sampling biases. Young *Acer* saplings were not age-dated as *Populus* saplings were.

closely correlated with floods due to the error associated with tree core data, and a lack of stream gauge data for the study site before 1937. However, only 9 % of these trees originated within ±5 years of the four largest floods that occurred between 1938-1989. Based on this broad range in tree ages, it is evident that although tree coring occurred exclusively within stands dominated by mature trees (≥25 cm dbh), not all trees within these stands may be considered mature individuals.

Excavation of the youngest individuals within mixed-aged *Populus* stands revealed that root sprouting had occurred, as evidenced by the root morphology of these individuals (Figure 5). However, the root morphology of older individuals did not always clearly define reproductive origin. This may be partially attributable to the decay of older

Figure 5. *Populus* saplings were excavated to determine their origin. This asexual ramet sprouted from a relatively slender root.

parental roots over longer periods of time, after the ramets have established their own independent root system.

However, the root collar of the majority of trees within the mixed-aged stands was typically positioned near the elevation of the present soil surface, indicating that little deposition of alluvium had occurred since the establishment of these trees. This may also serve as a good indicator of asexual reproduction, because sexually derived *Populus* seedlings typically experience high sedimentation rates during the first few years after their establishment (Rood and Mahoney 1990, Mahoney and Rood 1992, Johnson 1994, Brattne *et al.* 1996).

DISCUSSION

The diverse age structure of *Populus* stands along the Yampa River is quite atypical for floodplain forests such as these. Previous research that has focused on the sexual regeneration of other closely related *Populus* species, including *Populus deltoides* and *Populus fremontii*, has determined that reproduction occurs episodically along rivers of the western U.S. when high flood flows create fresh, wet sediment deposits, providing ideal germination sites with minimal interspecific competition (Bradley and Smith 1986, Braatne *et al.* 1996, Stromberg *et al.* 1991, Scott *et al.* 1996). The production of extensive *Populus* seedling cohorts, therefore, usually coincides with the years of higher streamflows and deposition of alluvium. On meandering rivers such as the Yampa, *Populus* stands typically originate on point bars developed during lateral channel migration. Thus, episodic lateral migration of the channel and point bar extension produces a series of parallel,

arcuate stands of even-aged trees. By age dating through tree coring, investigators have mapped the ages of *Populus* stands in floodplains of meandering rivers and developed "isochrones," or contour lines, reflecting stand ages (Everitt 1968).

Based on these previous studies, one would have logically expected the tree age data collected along the Yampa to identify even-aged cohorts of *Populus* trees as well, with cohorts increasing in age with increasing distance from the stream channel. Instead, tree age data from the Yampa macroplots indicate that at least some forest stands may exhibit age variability that is as great within stands as amongst different stands. Additional data collection is merited to determine how prevalent mixed-aged stands are along the riparian corridor.

Observation of aerial photography reveals that many of the stands of mature *Populus* forest that remained by 1938 (the earliest available set of photographs) had evidently been thinned. The crowns of individual trees appear much more widely spaced in areas that received the most intense human uses (such as near town sites) in the 1938 photos, as compared to more remote or physically isolated stands, such as those located on islands. In addition, there appears to be a further decrease in canopy cover in heavily used areas when comparing the 1938 photos to the 1954 photos. Therefore, not only did fragmentation occur between individual stands of forest, but the structure of the forest canopy within stands may have also been altered as a result of human land uses. Clearing the shrubby understory (which is characteristic of undisturbed stands) undoubtedly improved human access, while thinning of the forest canopy most likely improved forage

for livestock beneath the trees by allowing shade-intolerant grasses to become established on these moist, rich soils.

Figure 6 illustrates the alteration of forest structure along approximately one km of the Yampa River during 1954 (six years after the nearby Mount Harris mine was abandoned). The developed area shown above the river was the residential town of Mount Harris; below the river is the location of the present-day Yampa River Preserve

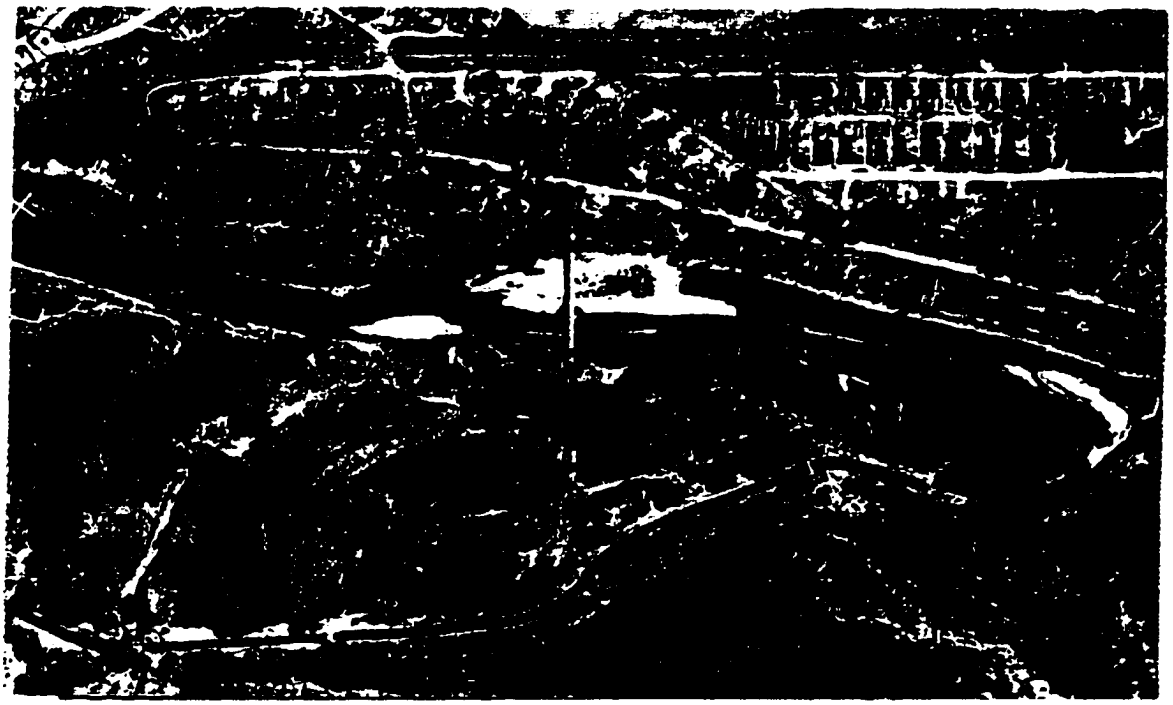

Figure 6. The upper end of the Yampa River Preserve showing the discontinuous forest canopy in 1954, shortly after the Mount Harris mine and associated town site was abandoned. The Yampa River flows from right to left (east to west) in this picture.

owned by The Nature Conservancy. During the 45 years since mine abandonment, much of the fragmented forest canopy has "infilled" with additional trees within the protected area of the Yampa River Preserve. Similar trends can be observed within many other forest stands along the Yampa (particularly those that are most inaccessible to livestock)

indicating that forest thinning by the early Anglo settlers may have been fairly widespread, and could have potentially played an important role in the development of mixed-aged stands of trees that are present today.

Excavation of the root systems of the younger individuals within these mixed-aged stands indicated that asexual reproduction has been an important reproductive mechanism operating within these stands in recent years. A likely hypothesis regarding the origin of the younger individuals within the mature forest along the Yampa River is that adventitious shoots originated from preexisting parental roots. This observation is consistent with the findings of Rood *et al.* (1994) who determined that 52% of the cottonwood began as seedlings in the Oldman River Basin while 48% originated through clonal mechanisms, of which 30% (of the total) were root suckers.

Forest thinning may have had an important effect on the structure of contemporary forests along the Yampa. The reduced density of *Populus* trees within thinned forest stands and the associated reduction of forest canopy cover likely played an important role in promoting root suckering. Previous research (Shaw 1991) has determined that root suckering favors unshaded sites. However, the increase in light availability from thinning most likely varied among stands, according to the percent of forest canopy that was actually removed. Stands where there was little canopy reduction would probably respond solely by reclosure of the canopy through canopy expansion of the remaining trees (Oliver and Larson 1996). Along the Yampa this would result in larger, more widely spaced mature *Populus* trees than found in unthinned stands, with few root sprouts in the understory due to shading. Those stands where canopy cover was more drastically

reduced could allow for more prolific root sprouting on the forest floor, in addition to canopy expansion by the remaining mature trees. Stands where only isolated trees were left frequently exhibit water sprouts along the trunks of the remaining trees. Water sprouts are new shoots that arise along old stems from dormant buds (epicormic sprouts) in response to disturbance events (Oliver and Larson 1996).

As previously mentioned, fragmentation of forest stands has also been documented to have occurred within the study area (Noble 1993) and may also be an important influence on the age structure of the remaining forest fragments. Fragmentation has increased the number of individual forest patches and, therefore, the abundance of forest edges. This increase in forest edge also influences microclimate conditions within forest stands. Other studies have found that microclimate amelioration may influence the vegetation structure within forest stands 15-120 m from the forest edge (Franklin and Forman 1987, Ranney *et al.* 1981). The increased light availability along the edges of riparian stands may promote *Populus* root sprouting in these stands, especially in stands where the forest canopy remains otherwise in tact, and light availability is a limiting factor. Root sprouting along the Yampa was frequently observed adjacent to the outer edge of forest stands within cleared agricultural fields.

In these areas parental roots are present, light availability is high, and soil moisture is commonly increased through flood irrigation. The increase in soil moisture close to the soil surface from flood irrigation practices may "mimic" one of the important prerequisites (a high water table throughout much of the growing season) that have been found to favor root sprouting along the Yampa (Richter 1999). Agricultural practices such as discing,

clearing, or grading may also scarify the shallow root systems, and further promote root sprouting.

Trees growing from root sprouts have been found to have advantages over trees of the same species growing from seed. Shoots from root sprouts generally have faster initial height growth because their preestablished root systems and food reserves allow growth to be concentrated in the stem (Oliver and Larson 1996). Root connectivity of *Populus* ramets with previously established parental trees may be an effective strategy that enables the young trees to effectively compete with aggressive herbaceous species, such as introduced rhizomatous pastures grasses, during establishment. Excavation of shallow *Populus* roots that extend out from mature forest stands into agricultural pastures along the Yampa River revealed that *Populus* sprout and produce ramets as far as 25-30 m from the forest edge (Richter 1999). In most locations, these young ramets are annually harvested with the hay crop or grazed by livestock.

It is difficult to determine how extensive asexual reproduction might have been along the Yampa prior to Anglo settlement and associated forest thinning and fragmentation. However, Rood and Mahoney (1993) hypothesized that asexual reproduction of *Populus angustifolia* may be extensive, and perhaps the dominant form of reproduction in foothill rivers that are relatively clear streams with coarse substrates. They also determined that within a site, saplings near the river's edge were commonly sexually derived, whereas saplings further from the river were commonly root suckers. A similar analysis along the Yampa River is merited to fully understand current recruitment patterns and mechanisms.

Populus trees that were not felled during initial Anglo settlement at the turn of the century most likely began producing root suckers immediately after clearing and thinning of the stands. However, this method of clonal reproduction does not appear to have been largely successful until after 1924, a date that closely coincides with the time at which the open range cattle industry ended along the Yampa River (Athearn 1982).

Since the area had been documented to be one of the largest cattle shipping points in the United States, enough livestock herbivory may have occurred along the Yampa to greatly reduce both root sprouting and sexual recruitment of seedlings on point bar sites. The combination of large numbers of livestock in combination with open range cattle grazing, which would have allowed livestock to congregate along the lush riparian corridor, may have been an important factor that resulted in the cottonwood "regeneration gap" between 1904-1925.

A second, alternative hypothesis regarding the reduction in *Populus* regeneration during this period is that the sexual recruitment of this species may have been limited by insufficient floodpeaks necessary for the creation of fresh alluvium for germination to occur. However, IHA analysis of the historic streamflow records at the Steamboat Springs streamgauge indicate that the one-day maximum floodpeaks during the period of 1905-1925 were higher than in subsequent years (1926-1997)(Figure 29). In theory, higher floodpeaks would have increased the amount of alluvium produced, and the *Populus* recruitment sites available. Therefore, the hypothesis that lack of flooding could be responsible for the reduction in *Populus* recruitment during this period does not appear likely.

Acer negundo regeneration may have also been "released" in response to a possible reduction of grazing pressure during the 1920's. The recruitment of *Acer* since that time appears to have been fairly constant and still occurs today beneath the canopy of mature *Populus*. Because no *Acer* trees sampled predate 1924, additional age dating of the oldest remaining *Acer* along the Yampa River is merited to determine whether *Acer* was a common component of these riparian forest stands before Anglo settlement.

CONCLUSIONS

It is apparent along the Yampa River that mixed-aged stands of *Populus angustifolia* have now replaced many of the previously thinned stands of trees that were present in the earlier part of this century. However, it may be impossible to determine the primary method of *Populus* reproduction prior to 1904. Clonal recruitment may eventually restore the presettlement canopy cover to the remaining riparian forest stands, and enlarge the size of forest fragments, but at the cost of reduced genetic variability. Over the long-term, this loss of genetic variability may result in reduced adaptability to changing environmental conditions such as climate change or pathogen outbreaks (Rood *et al.* 1994).

Other studies (Oliver and Larson 1996) suggest that forests fragmented by human land uses may reduce the ability of animals and plants to migrate to suitable forest habitats, and that human activities result in different proportions of habitat types than previously occurred. However, along the Yampa structural restoration of canopy cover in the riparian forest stands may allow for the subsequent recolonization of shade tolerant understory

plant species (such as *Cornus sericea)* typical of the presettlement era, and benefit many animal species that are forest interior specialists.

While some researchers have highlighted the importance of asexual reproduction of *Populus angustifolia* (Rood *et al.* 1994), no reference to extensive mixed-aged stands of this species could be found in the literature. Along the Yampa River it is hypothesized that mixed-aged stands occur from the interaction of four factors: (1) the ability of *Populus angustifolia* to form adventitious shoots from preexisting roots; (2) the presence of hydrologic conditions favoring root sprouting (relatively shallow water table); (3) previous forest thinning and fragmentation that has increased light availability within and around existing stands; and (4) limited grazing pressure enabling the survival of young shoots.

Future research and monitoring efforts are merited to further address the following related issues: (1) determination of the relative importance of asexual versus sexual recruitment mechanisms for *Populus angustifolia* within the overall riparian corridor and if these recruitment mechanisms continue to be altered through human land uses such as forest clearing, thinning, and grazing (2) more precise definitions of the biotic prerequisites and environmental conditions required for successful clonal reproduction of *Populus angustifolia.*

The Yampa River riparian ecosystem has displayed remarkable ecological resiliency and the ability to reverse the effects of direct human perturbations within a relatively short time frame. Future ecological restoration efforts should strive to optimize

these natural successional trends that have already begun to reverse the forest fragmentation that has resulted from intensive human land uses.

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CHAPTER 3

DEVELOPMENT OF AN ECOLOGICAL MODEL TO ASSESS RIPARIAN ECOSYSTEM FUNCTION

INTRODUCTION

Ecosystem responses to human perturbations are complex, and in many cases still poorly understood due to many site-specific factors. To conserve the biodiversity represented within particular ecosystems, ecologists need to develop a better understanding of natural ecosystem function and the ways in which human-induced stresses have altered these systems. Empirical models that enable us to simulate the ecological responses to be expected from hydrologic and geomorphic alterations can greatly influence land and water management decisions and conservation activities in riparian systems. The riparian ecosystem model described here was developed for such use on the Yampa River near Hayden, Colorado. This computerized ecological simulation model predicts vegetation dynamics as driven by hydrologic variation, fluvial erosion and deposition, and biotic succession.

Riparian corridors have been described as the most diverse, dynamic and complex biophysical habitats on the terrestrial portion of the earth (Naiman *et al.* 1993). Because complex ecosystem processes and patterns are not easily understood or predicted, it is

usually desirable to adduce multiple lines of evidence from which to draw hypotheses. Ecological simulation modeling can be used as a means of integrating diverse data sources to develop a more comprehensive understanding of ecosystem dynamics. Data derived from historical aerial photography, as well as hydrologic and botanical records, all provide important sources of information that describe ecosystem dynamics during the past century. To date, very few models have integrated both the biotic and abiotic components of western riparian ecosystems, despite widespread recognition that such integration of information sources is vital to effective resource management.

The Yampa River's hydrologic regime remains relatively unaltered, supporting some of the finest examples of native riparian community types left within the upper Colorado River watershed in Colorado, Utah, and Wyoming. The globally rare *Acer negundo-Populus angustifolia Cornus sericea* plant community found along the Yampa is one of the primary biodiversity conservation targets in this region (The Nature Conservancy 1996). Unfortunately, the existing stands of this riparian forest type represent only a fraction of its original extent. Clearing for agricultural uses has removed much of the forest. To enable effective stewardship and restoration activities, land managers such as The Nature Conservancy are interested in gaining a better understanding of the role of hydrologic and geomorphic processes in sustaining the character of this and other associated riparian communities along the Yampa.

The goal of this research was to develop an ecological simulation model that could generate testable hypotheses for future research, monitoring, and experimental studies,

ultimately leading to a more comprehensive understanding of this complex and dynamic fluvial ecosystem.

Specifically, the goals for development of the ecological model were to:

1) Generate hypotheses regarding functional relationships between hydrologic and geomorphic processes and the patch types that comprise the riparian mosaic.

2) Identify the ways in which human influences may have altered these functional relationships, and the resulting ecological patterns.

STUDY AREA

The study site is located in the upper Colorado River basin, encompassing approximately 18.7 km of the Yampa River upstream from the town of Hayden, Colorado (Figure 7). Within this stretch of river the elevation ranges from 1926 to 1951 m. The alluvial sediments range from 3-7 m in thickness, and vary in width from 150-1600 m along the study reach (Madole 1989).

Annual precipitation occurring near Craig, Colorado (25 km downstream of this site) is approximately 34 cm annually. Streamflow in the Yampa typically peaks in late-May to early-June in response to snowmelt runoff from the river's headwaters in the Rocky Mountains of western Colorado. Flow levels gradually recede during June-August, with occasional minor surges attributable to summer rainfall events. The mean January temperature is -7.7°C, while the mean July temperature is 19.4°C. The surrounding uplands are dominated by Wyoming big sagebrush (*Artemisia tridentata* ssp. *wyomingensis*) with a diverse understory of herbaceous species. The study site

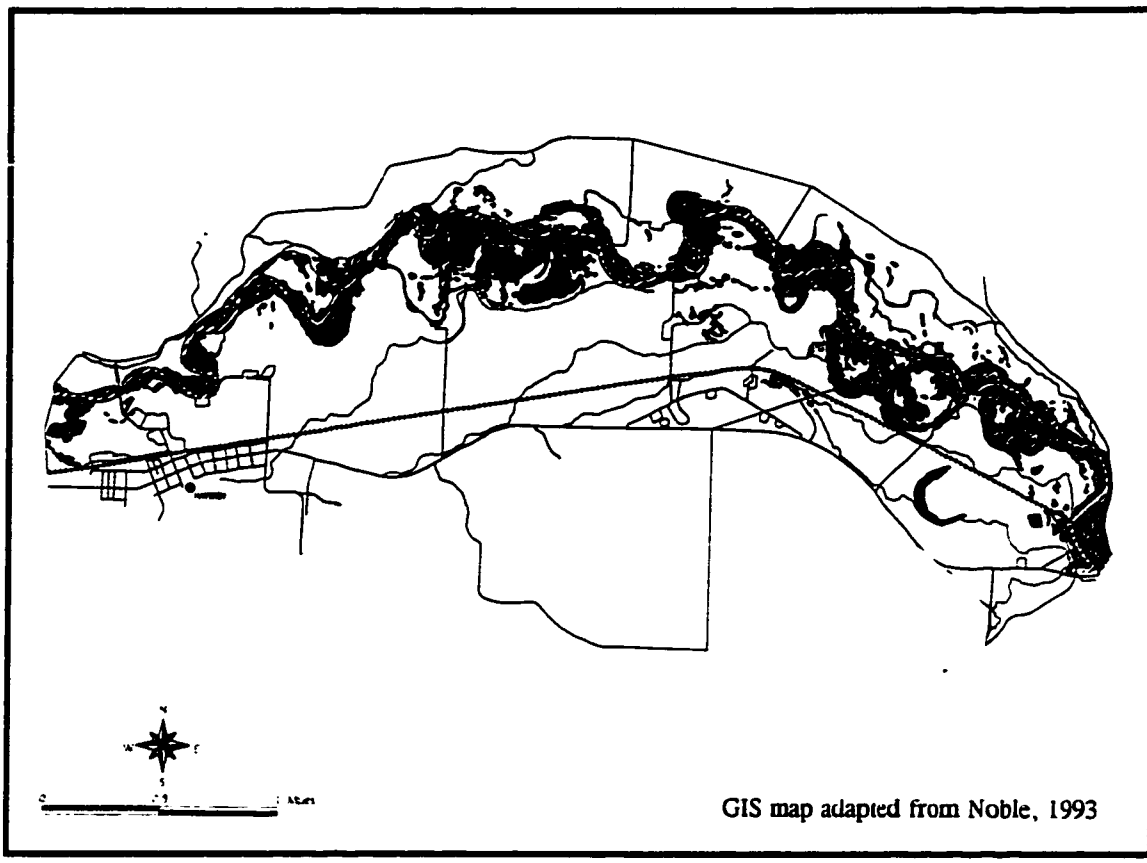

Figure 7. The area where the ecological model was developed for the Yampa River, Colorado. The Town of Hayden lies at the west end of the simulation area. Riparian communities are represented by shaded areas.

lies within the North-Central Highlands Section of the Southern Rocky Mountain Ecoregion Province (Bailey *et al.* 1994).

METHODS

Important data sources for model construction and calibration included: Geographic Information System (GIS) mapping from aerial photography, analysis of streamflow records, calculation of geomorphic process rates, sampling of vegetation composition and structure, and tree age dating.

GIS Mapping

Black and white aerial photographs of the study area at a scale of 1:4800 were acquired for the years 1954, 1969, 1980 and 1989 for the Yampa River corridor from the Town of Hayden, Colorado to a point 18.7 km upstream. Additional photographs taken in 1938 at a scale of 1:31,680 were enlarged to a scale of 1:7920. Noble (1993) used these aerial photo sets to map the current (1989) and historical (1938) riparian vegetation communities. She ground-truthed the 1989 map and entered the data into a GIS. Noble (1993) describes the sources of error associated with GIS mapping for this project.

I subsequently reclassified the polygons in these maps to reflect vegetation "patch type" categories used in the ecological simulation model. See Appendix E for a description of these patch types. I also groundtruthed these patch types in the field for the 1989 GIS data layer where access to the site was possible. Unfortunately, it was not possible to groundtruth patch types for the 1938 data layer. The 1938 GIS database was used to estimate the initial abundance of each patch type in modeling simulations, while the 1989 database provided a means for calibrating the model and testing model assumptions. Observation of the entire aerial photography sequence also aided in the establishment of successional relationships between patch types that were required to create the overall model structure. Transition matrices were computed from the GIS database by Mejia-Navarro (1996) to quantify transitions between patch type categories using the 1938, 1969, 1980 and 1989 vegetation maps. Table 8 in Appendix A is an example of these matrices. GIS data were also used to examine geomorphic processes, such as the rates at which new depositional surfaces are formed.

Hydrologic and Geomorphic Records and Data Analysis

Streamflow records were used to predict rates of geomorphic processes, such as lateral channel migration and channel abandonment, within the simulation model. The U.S. Geological Survey operated a streamgauge (Yampa River near Hayden) within the study area during 1966-1986. Richter and Powell (1996) used these data to develop regression equations capable of estimating daily mean streamflow values at this gauge location for the periods 1938-1965 and 1987-1993, based on other gauges operating in the watershed. By combining actual streamflow records with those synthesized by Richter and Powell (1996), mean daily streamflow estimates from 1938-1993 were developed for use by the ecological model.

A trend analysis of annual flood peaks (Richter 1992) determined that although a numerically small decline in annual flood peaks had occurred since the construction of several small reservoirs in the headwaters of the Yampa, this decline was not statistically significant ($p \geq .05$). However, it is possible that as more years of data accumulate since the construction of Stagecoach Reservoir in 1987, which is the largest reservoir, we may begin to detect significant changes in annual flood peaks. Figure 28 in Appendix B contains Richter's (1992) results. To determine if floodpeaks have become more variable in recent years, I used a two-tailed variance ratio test (Zar 1974) to determine if a change in the variance of the highest annual mean daily streamflows had occurred between the periods of: 1937-1956 and 1957-1993.

Ostendorf (1995) used GIS information taken from the five sets of aerial photos to develop statistical relationships between the creation of new alluvial surfaces and

streamflow variables for the study site from 1938-1989. She developed a regression equation using the total number of days at or above 125% of the bankfull discharge as the independent variable to predict the area of fresh alluvial surfaces created adjacent to the stream channel from one aerial photo date to the next (y=2208120.92*(% of days each year at or above 125% of bankfull discharge) + 4865.979) (r^2= .75, p= 0038). Bankfull discharge for the Yampa River at the study area had been previously determined by Andrews (1980) as 167 m^3/s. The ecological model developed in my study uses this geomorphic rate equation to predict rates at which bare alluvium is created in response to various levels of flooding.

I also developed a regression equation using the highest mean daily flood flow for each year to predict the area of abandoned channel produced for any given year. The accurate prediction of channel avulsion events is problematic, partly due to the fact that these events are somewhat stochastic. For example, the formation of large debris dams may be very important in driving individual channel avulsion events. Highest mean daily flood flow for each year appeared to be the most logical predictor for predicting avulsion rates for the Yampa River since channel avulsion only occurred within the study area between 1938-1989 when peak flows exceeded 12,000 cfs. This equation (y=-3.33+(0.00051*peak daily flow of the year)) was developed through calibration of the ecological model. The regression equation used to estimate channel abandonment rates was calibrated by comparing model output with the actual rates of channel abandonment reported through the aerial photo sequence and GIS database.

Ostendorf (1995) also used the GIS database to calculate the average channel sinuosity (channel length/straight-line valley length) and channel width during the period of 1938-1989. See Figures 30 and 31 in Appendix C to reference important components of Ostendorf's work.

Vegetation Sampling

Vegetation composition and structure were examined in 45 macroplots located along 13 sampling transects. These transects were subjectively located according to land ownership and access limitations and were aligned perpendicular to the river's course, spanning the width of the floodplain. The goal of macroplot sampling was to characterize the typical vegetation of each naturally occurring patch type that contributes to the overall riparian mosaic. Patch types were defined for this project as repetitious assemblages of plant species within the riparian landscape that exhibit similar species composition, and physiognomic and age structure, and occur within similar geomorphic settings of the fluvial environment.

Macroplots were established along the transects whenever the composition or structure of vegetation noticeably varied. Plots were not located in areas where vegetation had been subject to recent human disturbances, or in locations close to the edge of the vegetation patch. An effort was made to sample multiple examples of each of the existing floodplain patch types. Plot sizes varied from approximately 100 m^2 to 375 m^2, according to vegetation structure as suggested by The Nature Conservancy's (1988) Community Survey Handbook. The long axis of the plot was placed parallel to the river whenever

possible. The canopy cover of each species within each plot was estimated using seven cover classes (0-1%, 1-5%, 5-25%, 25-50%, 50-75%, 75-95%, 95-100%). In addition, for species that occupied multiple strata within stands (e.g. canopy, subcanopy, tall shrub, low shrub), cover was estimated separately for each strata that the species occupied as described by The Nature Conservancy (1988). Appendix D contains the vegetation data collected from macroplot sampling. Although no statistical analysis, such as ordination or classification, was used to partition plots according to floristic variability for this study, a general description of Yampa River patch types, along with a listing of representative macroplots is contained in Appendix E.

Tree Age Dating

Age dating of trees helped to define successional relationships between species occurring within the same stands, as well as the time required for biotic succession to occur between different patch types. Because tree age data were to be used to define general successional relationships, the absolute dates of all of the specimens were not required and cross dating techniques were not deemed necessary for this study.

Tree cores were collected from 100 *Populus angustifolia* and 18 *Acer negundo* trees (the two dominant tree species occurring in the study area), using 40 and 75 cm increment borers. The number of trees to be sampled was determined by the limited time and labor available for sample collection within one field season. An effort was made to collect samples throughout the study area, but, access was restricted to a limited number of sites. Therefore, the stands that were sampled were subjectively located according to

access restrictions. Since all stands that were sampled typically contained a large range of stem sizes, the trees to be sampled were randomly selected within broad size classes (saplings 0-1 m tall, juvenile trees over 1 m tall - 25 cm dbh, mature trees ≥ 25 cm dbh) in each stand so that the samples represented the broad range of variability of stem sizes that were present. In addition, a few of the largest diameter stems within the stands were also subjectively selected for sampling to obtain a reasonable estimate of minimum stand ages. Cores were obtained from as close to the ground surface as possible; the root collar of most trees was within two decimeters of the ground surface. Multiple samples were collected when necessary so that the core hit or very nearly hit the center ring. Cores were air dried, mounted in grooved wooden blocks and sanded with a random orbit sander using progressively finer grit sandpaper (150, 220, down to 30 micron grit). Tree rings were counted under a dissecting scope. Trunk cross-sections were also collected when possible from trees recently felled by beaver.

A total of 17 *Populus* seedlings that had been sexually derived were also randomly collected within the study area. These seedlings were excavated and their root morphology was examined to verify that they were produced from sexual reproduction, as opposed to asexual root sprouting. Seedlings were collected from two different types of geomorphic settings: well-developed point bars on the inside of meander bends (n=7), and mid-channel islands and lateral, alternate bars along the channel (n=10). The intent of harvesting seedlings was to compare the recruitment years and/or growth rates of seedlings between these two different geomorphic settings. After seedlings had air-dried, cross sections of the stems were cut and mounted on wooden boards. Multiple cross sections were

prepared for each seedling so that the location of the true root collar could be determined (i.e., the one possessing the most rings). The ring widths were then measured in units of 0.01 mm using a University Model Increment Measuring Machine (obtained from Curt Zahn, formerly Fred C. Hanson and Company). The TRIMS version 1.2 software system from Madera software was used to facilitate data capture from the sliding stage. Appendix F contains seedling stem size data (Table 22) and tree age data (Table 23).

Ecological Model Construction

State variables used in the model are the patch types that comprise the Yampa's riparian mosaic (Figure 8). Patch types, as defined for this project, are discrete spatial patterns typical of specific geomorphic landforms that exhibit relatively homogeneous, predictable structural and compositional vegetation characteristics. For example, the emergent marsh patch type is typically located within abandoned channels and the vegetation consists of almost pure stands of *Typha latifolia*, with very few other abundant species. Patch type descriptions are provided in Appendix E.

The Yampa ecological model simulates changes in the proportional area of each patch type (% of the riparian area occupied) over time. The initial values for the proportional area occupied by each patch type at the beginning of the model simulation was derived from the 1938 GIS map. Fluxes among state variables (represented by arrows in Figure 8) correspond to shifts in the proportional area of each patch type in the riparian area. The model is designed such that the sum of all patch types always equals 100% of the total riparian area. The total riparian area may be defined as all parts of the floodplain

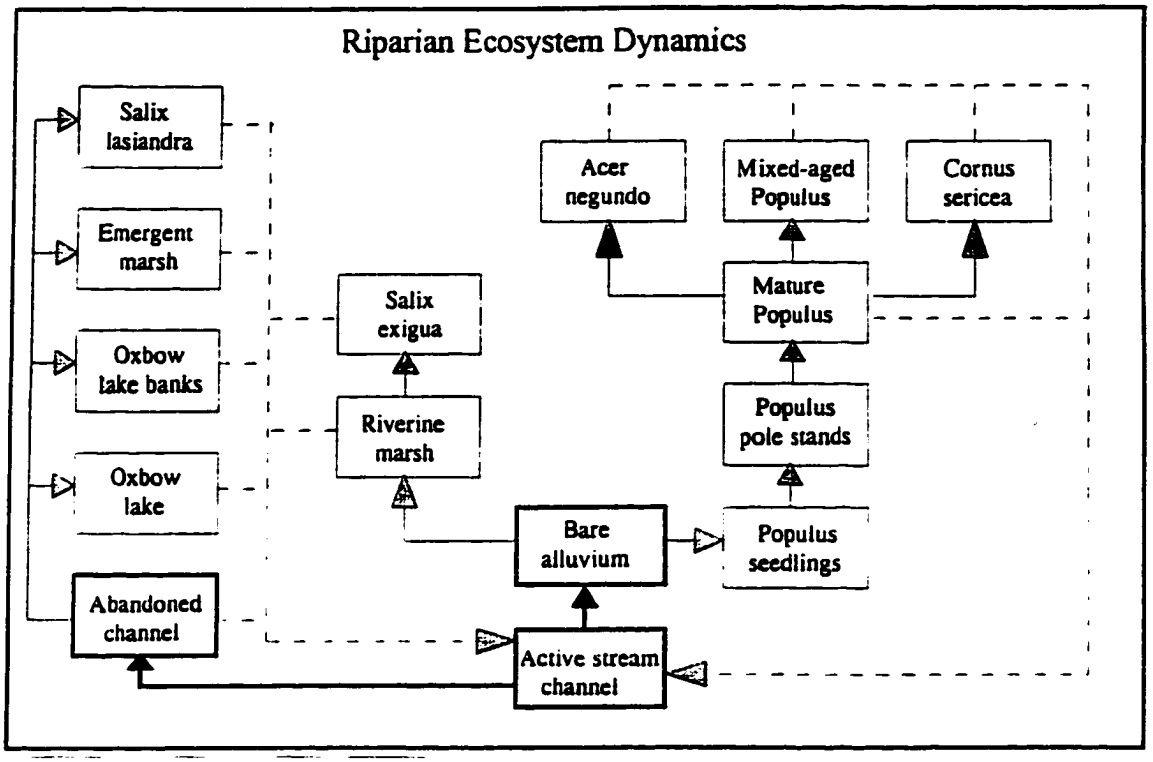

Figure 8. The overall structure of the ecological model. Boxes represent state variables (patch types). Arrows indicate changes that can occur as a result of point bar formation or channel abandonment (bold arrows), biotic succession (solid lines), or patch type destruction from erosion (dashed arrows). The mixed-aged *Populus* patch type was included with mature *Populus* for model simulation runs.

that contain natural vegetation, or geomorphic landforms such as the active stream channel or bare alluvial surfaces. However, cleared agricultural fields were excluded from modeling efforts. The fluxes among state variables are computed in the model by sets of difference equations that are updated during annual time steps (see Appendix G). These equations represent the rates at which patch type creation and destruction is expected to occur within the floodplain based on various levels of streamflow, as well as changes in patch types that are predicted due to plant succession. Patch type abundances at the end of the simulation period (1938-1989) were then compared to the 1989 GIS map.

Area-flow models of this type have been used to simulate forest succession by others (e.g. Shugart *et al.* 1973; Johnson and Sharpe 1976; Johnson 1977,1992). The structure of Johnson's (1992) model for the Missouri is most similar to the model constructed for the Yampa River. However, Johnson's model of the Missouri River riparian forest only addresses creation and destruction of patch types associated with lateral channel migration processes, and does not address meander cut-off or channel abandonment processes and the associated patch types.

The two different successional trajectories of the Yampa model are shown in Figure 8. The trajectory that is initiated by channel abandonment is shown on the left half of the model, while the trajectory initiated by lateral channel migration is shown on the right half of the model. The short trajectory in the center of the model (containing riverine marsh and *Salix exigua* patch types) is also driven by lateral channel migration processes, but these patch types initiate on geomorphic surfaces with fine-textured alluvium, as opposed to coarse point bar gravels where *Populus* seedlings typically germinate. Therefore, in the Yampa model, the patch types whose successional trajectories are initiated by lateral channel migration are: *Populus* seedlings, *Populus* pole stands (i.e., young *Populus*), mature *Populus*, mixed-age *Populus*, *Acer negundo*, *Cornus sericea*, riverine marsh and *Salix exigua*.

Alluvial deposits located on point bars on the inside of meander bends provide ideal seedbeds for the germination of *Populus* seedlings; subsequent transitional and terminal patch types form through biotic succession. To reflect these dynamics, the model first estimates the amount of bare alluvium created by lateral channel migration each year

using historic streamflow records and the geomorphic rate equation developed by Ostendorf (1995). The model then estimates the seral replacement of one patch by another by taking the reciprocal of the average time required for replacement; this is then used as the annual probability of replacement. For example, the transition from a *Populus* seedling patch to a young *Populus* patch takes an average of 8 years to occur. Therefore, the average percent of *Populus* seedling patches that are changing into young *Populus* patches during any given year is 1/8 of the total, or 12.5%. Estimates of the number of years required for biotic succession to occur were calibrated from tree age data collected in the field, and observation of the aerial photograph sequence. This method of calculation provides long-term averages, as opposed to accurate year-to-year estimates of successional change.

In the long-term, all patch types are potentially subject to erosion by lateral channel migration that converts them back into bare alluvial surfaces. The model uses a simple regression equation to estimate the amount of lateral channel movement that is likely to occur in a given simulation year, based on the number of days that year at or above 125% of bankfull flow. This regression equation was calibrated by Ostendorf (1995) using historic streamflow records, aerial photography, and GIS analysis.

In addition, the model was constructed under the assumption that the total area of the floodplain that is eroded by lateral channel migration approximately equals the total area of new floodplain created by the deposition of alluvium along the channel. The FORTRAN code written for the model was structured to reflect this quasi-equilibrium between overall erosion and deposition rates.

Patch types associated with meander cut-off (channel abandonment) include: oxbow lakes, emergent (*Typha latifolia*) marsh, *Salix lasiandra* sloughs, and oxbow lake banks. Succession in recently abandoned channels does not closely resemble the facilitation model, but instead appears to involve an initial partitioning of habitat between relatively persistent patch types. The longevity of these patch types probably reflects the relatively stable environmental conditions that characterize these sites, as compared to sites produced by lateral channel migration.

The model first calculates the amount of abandoned channel that has been created each year with a regression equation that uses the highest mean daily flood flow for that year as the independent variable (based on historic streamflow records). Then, recently abandoned channels are partitioned among the appropriate patch types (oxbow lake, oxbow lake banks, emergent marsh and *Salix lasiandra*) by the model. The proportion of recently abandoned channels that transition into each of these four patch types was calibrated by examination of the aerial photograph series.

The intention behind development of an ecological model was that it could suggest emergent properties regarding ecosystem function, or information about the behavior of the system that was not obvious from the behavior of the parts, leading to new testable hypotheses. Once a basic model was designed, the model itself was used to check the data and assumptions that went into making the model, by comparing model behavior to that of the natural system. When the model and the real world disagree, then one or the other or both are imperfectly known, and tracing such errors increases our understanding of the real world or the model system (Hall and Day 1977). Calibration of the model was not

aimed at simply producing output that replicated the trends observed during the study period (1938-1989). This is an important clarification to make because ecological models can erroneously be calibrated to predict the "right" or expected outcome, although they are based on insufficient data sets, erroneous logic, or faulty ecological theory.

A sensitivity analysis of the model was performed by creating a subroutine in the code that allowed for randomization of the 52 years of highest annual mean daily streamflow values. The model simulation period was then extended to 200 years to better understand how the model would respond to alteration of key process rate equations over longer periods of time. Output from the sensitivity analysis can be found in Appendix G.

The computer program for this patch dynamics model was developed in FORTRAN (program "SUCCESS") on a personal computer. The program code along with input files, driver files, output, and sensitivity analysis, is provided in Appendix G. The model was not validated, because no independent data set was available for this purpose. However, future aerial photographs could be employed for this purpose.

RESULTS AND DISCUSSION

Comparison of Ecological Model Results and GIS Data

The GIS database revealed that the area occupied by patch types derived from lateral channel migration processes (right side of Figure 8) declined between 1938-1989 from an occupancy value of approximately 64% of the total riparian area to 56%. However, the model output predicted only a very slight decrease (1%) in the abundance of these patch types (see Table 4 for a comparison of model output with GIS data) during the

Table 4. Relative percentages of actual (based on Noble 1993), and predicted riparian patch type occupancy within the study area.

Patch types within the riparian mosaic	Actual percent floodplain occupied in 1938	Actual percent floodplain occupied in 1989	Percent of riparian area occupied as predicted by ecological model in 1989	Difference between actual area occupied in 1989 and model results
Active stream channel (ASC)	16	15	16	+1%
Bare alluvium (BAA)	6	9	0[2]	-9%
Patch types derived from lateral channel migration:				
Populus seedlings (CSE)	4	2	8	+6%
Young Populus (YCO)	4	4	11	+7%
Mature Populus (MCO)	43	38	29	-9%
Acer negundo (BOX)	9	8	8	0%
Cornus sericea (COR)	2	2	2	0%
Riverine marsh (RIV)	1	1	3	+2%
Salix exigua (WIL)	1	1	2	+1%
TOTALS:	64	56	63	
Patch types derived from channel abandonment:				
Oxbow lakes (OXL)	1	6	5	-1%
Oxbow lake banks (OXB)	11	13	12	-1%
Emergent Marsh (HMA)	1	2	2	0%
Salix lasiandra slough (SLS)	1	2	2	0%
TOTALS:	14	23	21	

[2]Model assumes that freshly deposited alluvium is suitable for *Populus* colonization or establishment of riverine marshes, therefore, no alluvium remains uncolonized for long.

same time period. It is especially interesting to compare the estimated actual abundance of *Populus* seedlings with predictions from the model (Figure 9). While the model predicted seedlings to increase by approximately 131% during the simulation period, GIS data suggest a decline of approximately 34% during this time period. GIS data suggests that bare alluvium increased in abundance from 6% to 9% of the total riparian area, whereas the model predicted that essentially no bare alluvium would remain uncolonized by 1989.

The patch types associated with abandoned channels, on the other hand, increased in abundance during the simulation period from 14% of the total riparian area to 23% according to GIS data (Table 4). Most noticeable is the abrupt increase in the occupancy of abandoned channels (i.e., oxbow lakes) during this time period from only 1% of the riparian area to 6%.

The discrepancy between the predictions of the ecological model and GIS data estimating the actual abundance of patch types revealed one of the most interesting shortcomings in our understanding of this riparian ecosystem. The geomorphic rate equation developed by Ostendorf (1995) determines the rate of creation of bare alluvium in the model, and this in turn determines establishment rates for *Populus* seedling cohorts. Because the Yampa was thought to be a typical meandering river, the model was constructed with the assumption that alluvium produced adjacent to the stream channel was located on point bar sites, suitable for the establishment of *Populus* seedlings. This assumption is widely supported by ecological and geomorphic literature (Bradley and Smith 1986, Everitt 1968, Noble 1979, Scott *et al.* 1996, Scott *et al.* 1997 among others) describing *Populus* recruitment in meandering river systems. However, while the GIS

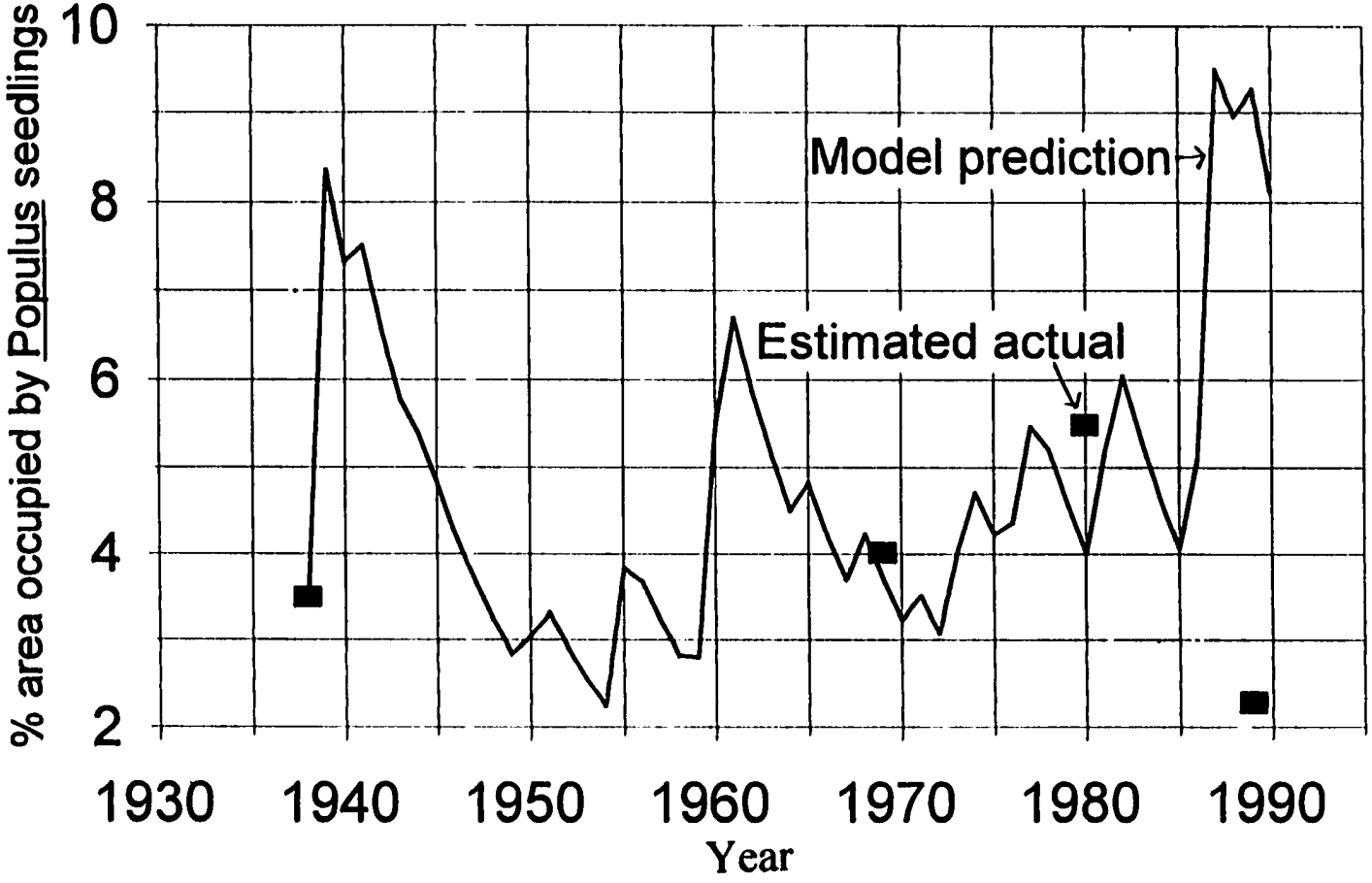

Figure 9. Actual abundance of *Populus* seedlings along the Yampa River compared to ecological model predictions.

database shows that the abundance of bare alluvium within the floodplain has substantially increased during the simulation period (from 6% to 9% of the total riparian area), *Populus* seedlings have not successfully colonized these surfaces, as the model assumes.

Closer observation of aerial photography revealed that very little of the bare alluvium that has been produced in recent years has been located on point bar sites. Rather, the alluvium is located on lateral, alternate gravel bars along the channel and on unstable mid-channel islands. This alluvium is being frequently reworked by the river, resulting in an intense disturbance regime. Mechanical injury from both ice scour and flood flows most likely leads to high rates of seedling mortality at these sites. In addition, because these sites are typically lower in elevation than point bars, they remain inundated for longer periods during the beginning of the growing season, delaying spring growth (Figure 10). In contrast, typical point bar recruitment sites experience a progressive reduction in the intensity and frequency of flood disturbance. They become increasingly distant from the active stream channel due to lateral channel migration, and sedimentation elevates these sites above the active channel (Bradley and Smith 1986) (Figure 11).

All *Populus* seedlings that were collected from the field were found to have originated around the date of the 1983 and 1984 floods (Table 22), which were some of the largest floods during the period of record. Very limited sexual recruitment appears to have occurred within the study area since that time. Radial growth rates were measured from *Populus* seedling stems in these two different geomorphic settings to determine if significant differences in productivity occurred between the sites. Growth rates of the seedling's stems differed among point bar sites and mid-channel island and bar sites as

Figure 10. A typical alternate bar and island recruitment site. Notice that the seedlings are still submerged after they have leafed out for the growing season, as spring run-off continues.

Figure 11. A typical point bar recruitment site allowing the regeneration of *Populus*. Notice the progressively older cohorts of trees as the distance away from the channel increases. This photo was taken during the same week as the photo in Figure 10, however, these seedlings no longer remain inundated by runoff due to their location on an elevated point bar surface.

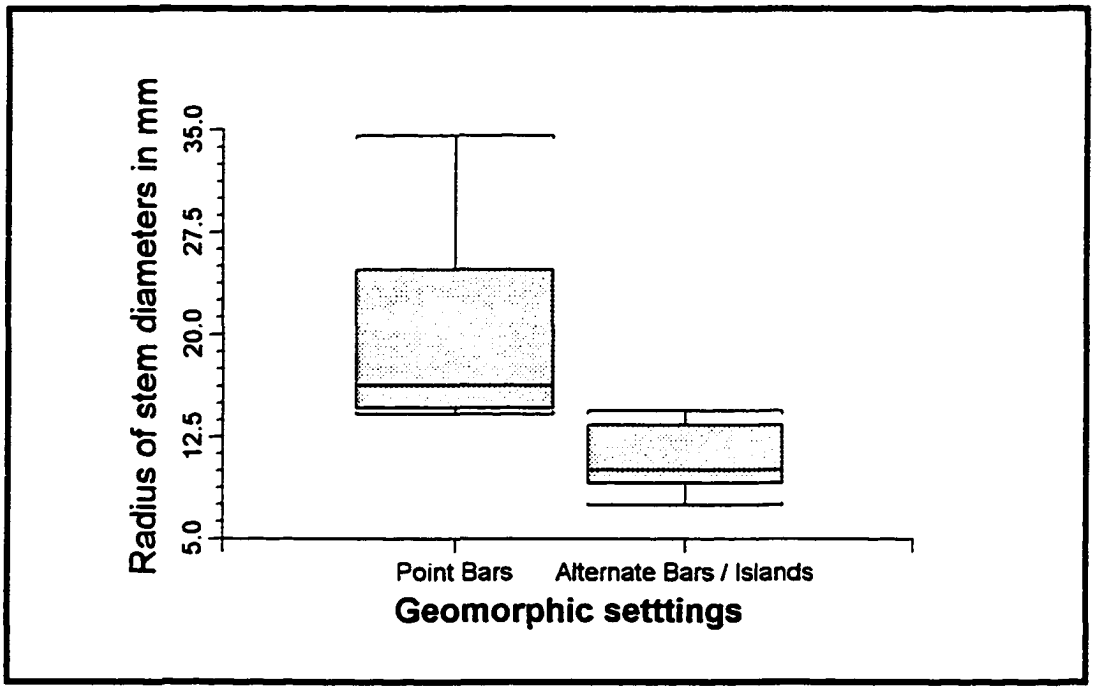

Figure 12. Boxplots comparing the radial growth of *Populus* seedlings from two different geomorphic settings: point bars (n=10), and alternate bars and islands (n=7). The shaded boxes represent interquartile range, and the lines within the boxes are medians.

shown in Figure 12. An analysis of variance of the stem sizes of the seedlings, grouped by the geomorphic setting in which they were collected, showed a significant difference ($p \leq .05$) between groups. Clearly, the point bar sites support faster growth rates for young *Populus* than alternate bars and mid-channel islands.

Age dating of these seedlings indicate that they all established between 1983-1989 (Table 22 in Appendix F). Many of these seedlings may have established soon after the 1983 and 1984 floods. However, both beaver herbivory, and mechanical damage from flooding and ice scour, may have subsequently cut some of the original stems of these seedlings at or near the ground surface, resulting in increased age variability of the existing stems. It is interesting to note that the seedlings on the point bar sites are an average of 2

years older than those on the lateral bar and island sites, although this relationship is not statistically significant at $p \leq .05$. Perhaps the age of the seedlings from the alternate bars and mid-channel islands is biased as a result of the higher probability of mechanical injury that likely occurs in these sites. Further research is merited to better understand the implications of these different geomorphic settings on *Populus* seedling establishment along the Yampa River.

Violation of Model Assumptions- Instability of Ecosystem Processes

The discrepancy between model output and GIS data (reflecting the actual abundance of patch types) suggests that some of the assumptions that went into model construction had been violated. Specifically, the assumption that the majority of the depositional surfaces along the Yampa River were created by the lateral channel migration of meander bends, resulting in the deposition of bare alluvium at point bar sites, does not appear to currently hold true. Reevaluation of this assumption revealed that bare alluvial surfaces were being produced primarily through channel widening and subsequent narrowing, but not as a result of true lateral channel migration processes. Other researchers have found that channel narrowing is an important mechanism leading to lateral deposition, especially for streams subject to large fluctuations in width (Scott *et al.* 1996), such as braided streams (Schumm 1969).

One of the implicit assumptions of models that simulate long-term ecological dynamics is that rate equations and relationships between state variables remain relatively stable throughout the simulation period. The modeling results led me to suspect that this

assumption had not held true for the Yampa River, and caused me to more closely scrutinize the geomorphic trends of the river during recent history.

As described earlier, Ostendorf (1995) had found that the best hydrologic variable to predict the amount of new alluvium produced between successive aerial photos was the number of days at or above 125% bankfull flow. The relationship between these two variables is shown in Figure 13. For the periods between 1938-1954, 1954-1969, and 1969-1980 the amount of alluvium produced appears to have decreased as the number of bankfull days increased. This is the inverse of what would be expected to occur in meandering streams. Then, the final data point, reflecting the amount of alluvium produced between 1980-1989, shows a dramatic increase. The temporal sequence

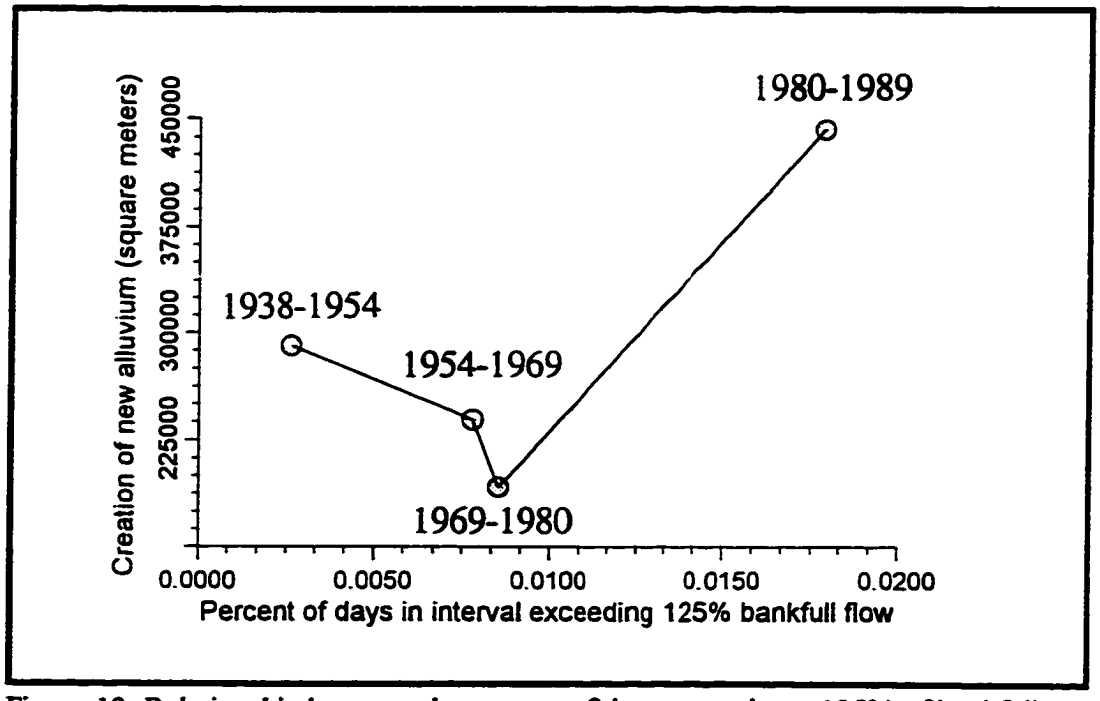

Figure 13. Relationship between the percent of days at or above 125% of bankfull flow and the amount of alluvium created between successive aerial photographs (from Ostendorf 1995).

of these data points suggests that alluvium creation processes were unstable over this period. Further observation of the aerial photograph sequence suggests that alluvium deposition in the early period (1938-1954) was largely located on well-defined point bars, but increasingly, as channel sinuosity declined, the overwhelming majority of alluvium produced during later periods was located on mid-channel islands and alternate bars along the channel.

The channel also made an abrupt adjustment by widening some time between 1969-1980, before the flood of record occurred in 1984 (see Figure 31 in Appendix C). The average width of the channel within the study area increased from an average of 39 m to an average of 57 m during this period. The abundant alluvium present at the end of the simulation period was created as a result of the subsequent channel narrowing that had occurred between 1980 and 1989 (the channel narrowed back to an average of 40 m in width).

Therefore, it appears that the amount of alluvium created by meandering has decreased during the study period, while the amount of bare alluvium created by channel widening and subsequent narrowing has increased. It is interesting to note that channel widening occurred before 1980, and that the channel subsequently narrowed during the period within which the largest flood of record for the Yampa River occurred (in 1984). The result of channel widening has been an overall increase in the abundance of bare alluvium within the floodplain, without a concomitant increase in *Populus* recruitment (in fact a decrease has occurred).

Using data derived from the GIS transition matrices, Figure 14 compares the relative proportion of "colonized" alluvium with "non-productive" alluvium over the simulation period. Non-productive alluvium is defined as the alluvium that is either eroded by the stream channel or remains uncolonized by vegetation from one aerial photo set to the next. "Colonized" alluvium develops into either cohorts of *Populus* or *Salix* seedlings, or older forest types, from one aerial photograph set to the next. The ratio of colonized

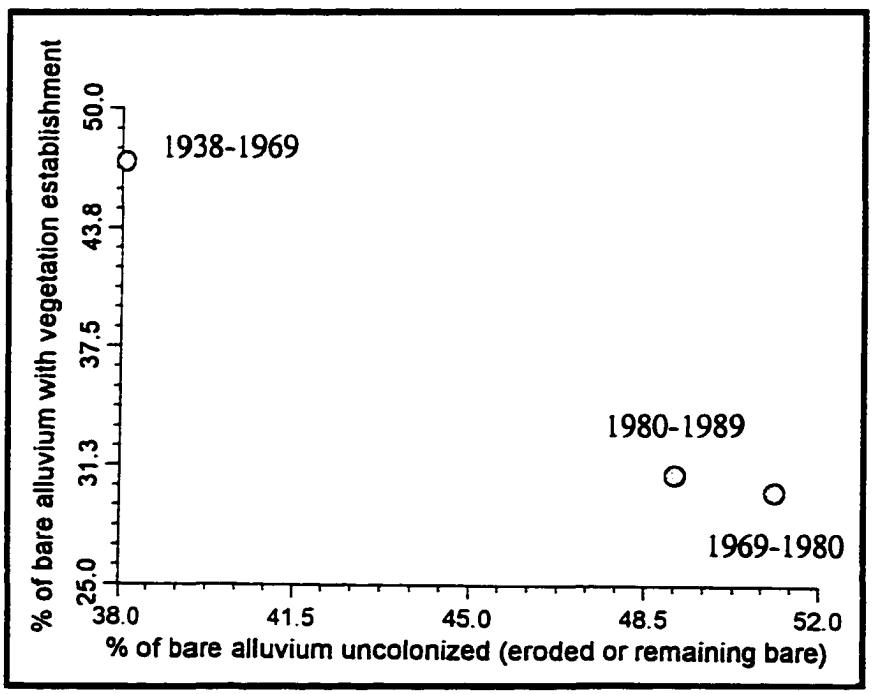

Figure 14. Relationship between the amount of bare alluvium where *Populus* seedlings or trees have colonized and the bare alluvium that remains uncolonized and/or is eroded by the stream channel from one aerial photograph to the next.

versus non-productive alluvium is probably directly correlated to the ratio of alluvium located on point bar sites versus that located on mid-channel islands and alternate bars. These data also support the hypothesis that the fluvial system may be in the process of

crossing a geomorphic threshold into a braided (as opposed to meandering) channel pattern, and that proportionately less of the alluvium is providing productive recruitment sites for *Populus* seedlings.

Probable Causes for Ecosystem Change

The preservation of natural systems involves a paradox: we seek to preserve systems that change (White and Bratton 1980). Equilibrium at a local scale, even over long time periods, is rarely reached, and in the context of constant change through time it is difficult to define what is disturbance and what is normal change (Sousa 1984). Successful site conservation efforts involving dynamic ecosystems such as riparian areas, therefore, necessitate an understanding of landscape patch structure and dynamics at appropriate temporal and spatial scales. In addition, it is important to distinguish between human-induced changes in ecosystem function and natural variability resulting in change. The changes in geomorphic characteristics that have been recognized along the Yampa River as a result of ecological modeling may have resulted from an array of factors. It is impossible to definitively identify a single cause for the geomorphic trends that we have observed in recent history, and most likely these trends result from the combined effects of several variables.

Geomorphologists classify river channel patterns into three general categories: meandering, straight and braided channels (Leopold and Wolman 1957, Leopold *et al.* 1992). These different channel patterns are thought to result from the interaction of several factors, however, slope and discharge are thought to be primary determinants.

Leopold and Wolman (1957) differentiated between meandering and braided channel patterns based upon a slope / bankfull discharge relationship. Interestingly, the Yampa River falls close to the threshold between these two channel patterns within the study site, based upon these two criteria (see Figure 32 in Appendix C). Therefore, this system could have been intrinsically predisposed to crossing a threshold from a meandering to a braided channel. Even small changes in other contributing factors such as increased variability of floodpeaks, and decreased bank stability, may be enough to cause significant changes in this system.

A consistent increase in the variability of floodpeaks has occurred during recent years (Figure 15). A significant difference was found between the variance of floodpeaks in the 1937-1956 period compared to the variance for 1957-1993 ($p \leq .05$). A box plot diagram (Figure 16) comparing the range of floodpeak values from 1938-1957 with 1958-1994 illustrates the difference in the dispersion of data during these two periods.

A number of researchers have shown that the buffering capacity of natural systems may be reduced by anthropogenic influences, resulting in increased variation in natural system functions. Along the Yampa, changes in either watershed functions, or climatic variability, or both, may play important roles in the trend toward increased floodpeak variability.

From a species level, increased floodpeak variability may be detrimental for the establishment of *Populus* seedling cohorts along the river. Drought years would favor seedling establishment in areas with moist soils in close proximity to the main channel, while subsequent years with large floodpeaks would likely destroy these young plants near

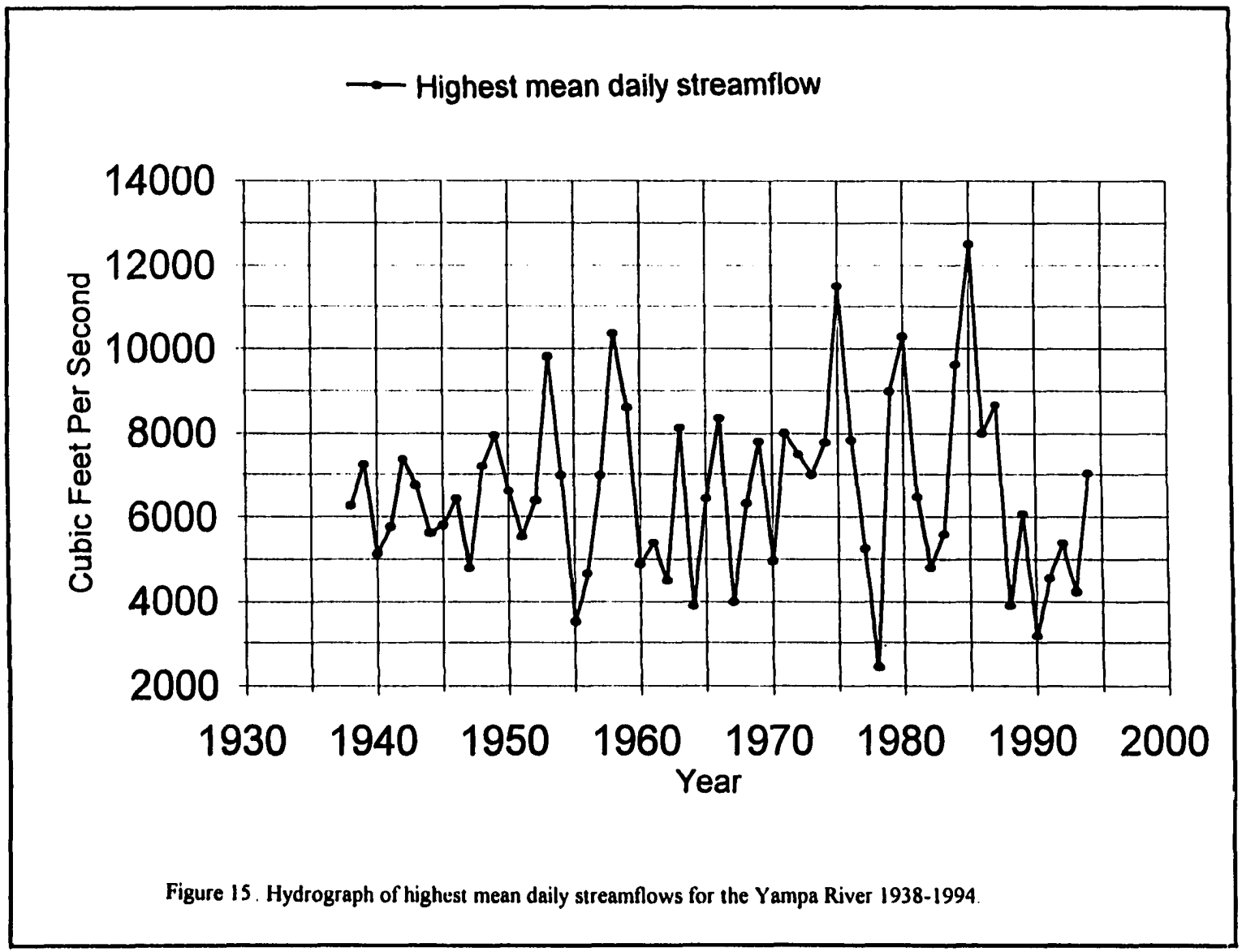

Figure 15. Hydrograph of highest mean daily streamflows for the Yampa River 1938-1994.

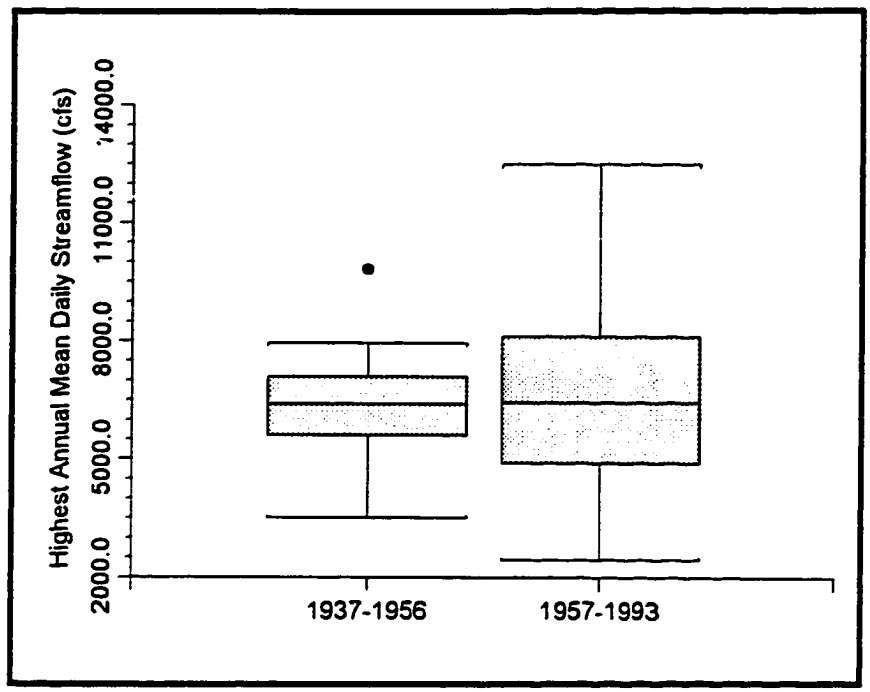

Figure 16. The apparent increase in the variability of floodpeaks of the Yampa River after approximately 1957 is illustrated by these boxplots. The shaded boxes represent the interquartile range, the lines within the boxes are medians. An outlier is shown as a solid dot.

the channel (Braatne *et al.* 1996). Conversely, the establishment sites for seedlings associated with years that exhibit large floodpeaks would be located on higher elevation, protected surfaces farther from the stream thalweg. These seedlings would not fare well during subsequent severe droughts.

Some of the possible factors that may have contributed to the increased floodpeak variability from 1938-1994 include:

1) Decreased infiltration rates and increased surface runoff and sediment delivery from timber harvest, deforestation, road construction, or increases in urban land uses within the watershed.

2) Reduction of surface water storage within the floodplains of the upper watershed tributaries, resulting from reduced beaver populations and less frequent beaver dam construction, that could produce higher floodpeaks and lower base flows.

3) Increases in year to year climatic (precipitation) variability within the watershed.

In addition, another human impact upon the system, the reduction in bank stability along the stream channel associated with the removal of native vegetation, could have also contributed to pushing this system toward a more braided condition. The maintenance of a meandering channel depends on the availability of sufficient energy for bank erosion and sediment transfer; however, banks must be sufficiently resistant to maintain a sinuous course and prevent overwidening (Knighton 1984). Smith (1976) found that the presence of tree roots could increase bank strength by a factor of 20,000, encouraging narrower, deeper and more stable channels. Excessive bank erosion on a meandering river may result in wide, shallow channels which lead to braiding. Bank stability is thus an important criterion for separating meandering versus braided channel patterns.

Within the study area, GIS analyses indicate that approximately 25% of the stream banks have been cleared of native woody riparian vegetation and are instead dominated by exotic pasture grasses. Stretches of channel with primarily forested banks appear to have remained sinuous, and point bar formation continues on these reaches as does *Populus* recruitment (Figure 17). Other reaches subjected to predominantly agricultural uses possess only herbaceous cover and have experienced obvious channel straightening, lack of point bar formation, and little or no successful *Populus* recruitment (Figure 18).

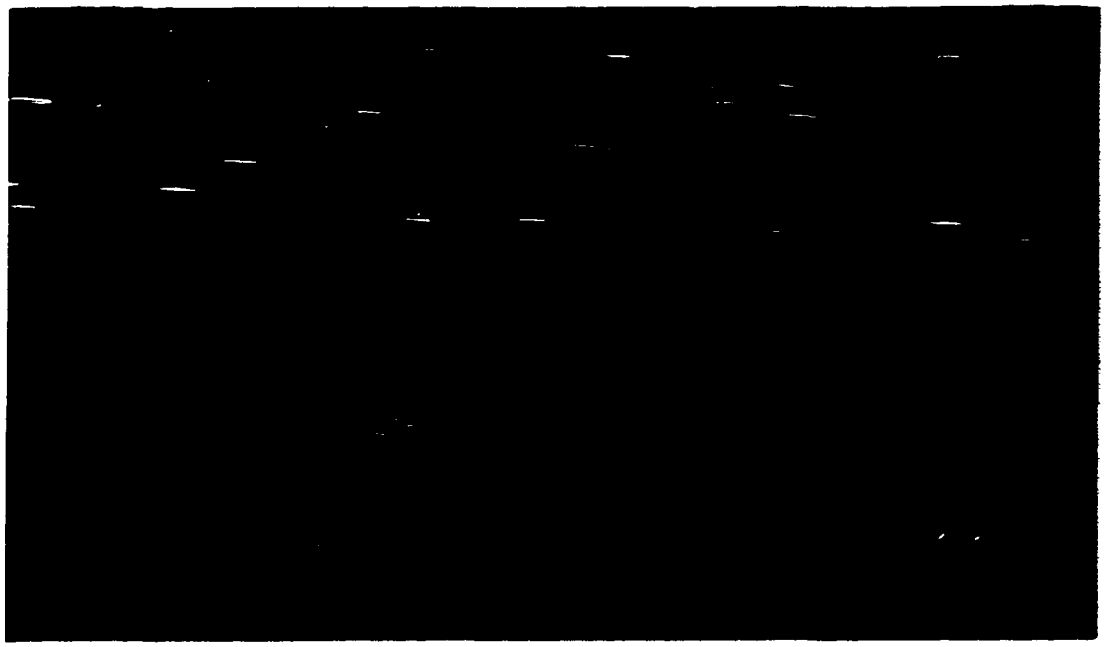

Figure 17. An aerial photograph taken during 1995 of the Yampa River not far upstream of the town of Craig where forested banks may have played a critical role in retaining the sinuous character of the channel.

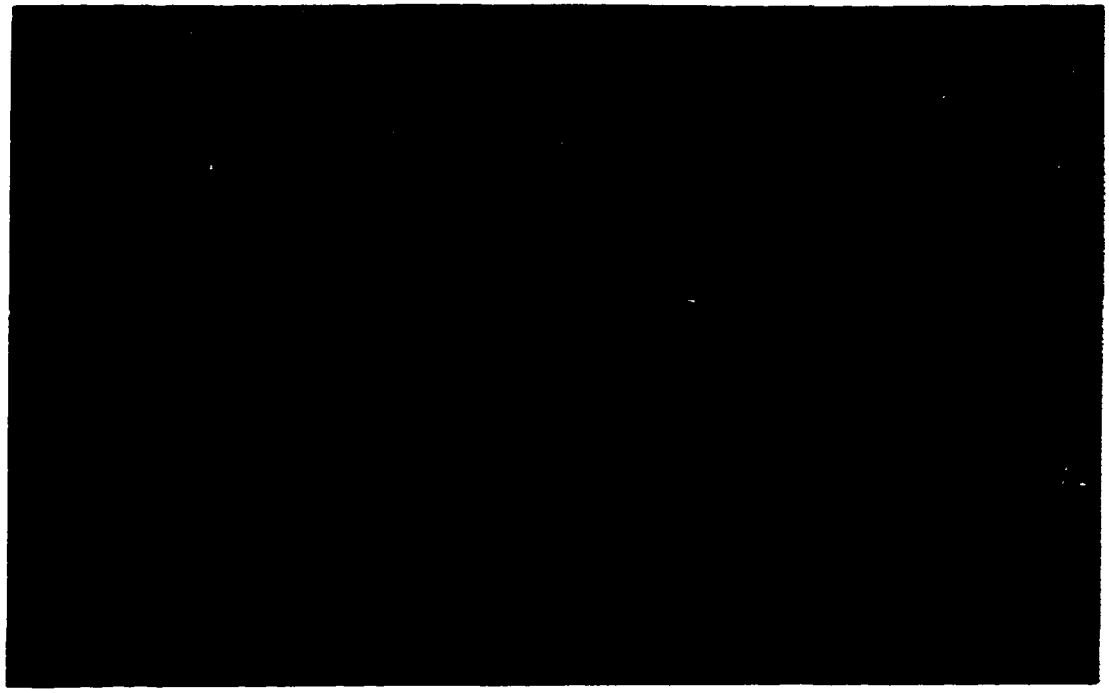

Figure 18. An aerial phototaken in 1989, showing a stretch of river not far upstream from the one in Figure 17. In this case, excessive removal of vegetation along the banks may have precipitated the straightening of the channel that has occurred.

Other studies have documented that changes in bank stability alone have enabled both meandering rivers to become braided (Mackin 1956) and braided rivers to become meandering (Nevins 1969). Mackin (1956) attributed an alternating sequence of meandering to braided to meandering along the Wood River in Idaho to changes in bank resistance as the river passed through a corresponding sequence of forest - prairie - forest environments. The Turandui River in New Zealand has changed over a period of years from a braided to meandering pattern as a result of the planting of willow shrubs along its banks (Nevins 1969). Gough (1993) documented that the meandering channel of Spring Creek in Missouri assumed a braided character, primarily due to clearing of riparian vegetation, overgrazing, and the resulting bank destabilization. Cattle exclusion led to the subsequent restoration of riparian forest cover (and, therefore, bank stability), resulting in the reestablishment of a meandering channel on this river.

Long-term Ecological Implications

If the channel continues to assume a more braided character along the Yampa, there may be serious ramifications for the keystone species of this riparian ecosystem, *Populus* angustifolia. "Safe" sites for *Populus* seedling establishment on the point bars of meander bends will no longer be present, and the sexual recruitment of *Populus* seedlings will only occur on islands and bars along the channel edge where the disturbance regime remains intense, limiting the areal extent of successful *Populus* stands. Research by others (Johnson 1994) suggests that while braided rivers have abundant alluvium, their ability to successfully recruit *Populus* cohorts remains limited under a natural streamflow regime.

This is because *Populus* recruitment along braided channels typically occurs only when the channel narrows as a result of reduced flows that are insufficient to rework the channel bed for several years (Scott *et al.*1997, Johnson 1994). Over the long-term, a reduction in point bar formation and *Populus* seedling recruitment would also result in the reduced abundance of other patch types that follow in the successional trajectory (as defined in Figure 8) associated with lateral migration processes.

The increase in abandoned channel patch types is most likely a transitional phenomenon, associated with the straightening of the channel during this period. For most meandering rivers, channel sinuosity increases due to lateral channel migration and decreases due to meander cut-off. Over appropriate temporal and spatial scales, this results in the maintenance of fairly stable sinuosity values. However, along the Yampa River, the channel has progressively straightened over time, because meander cut-off continues to occur (leading to decreased sinuosity), while reduced lateral channel migration rates no longer compensate for this reduction in sinuosity. There may be multiple interacting factors that are responsible for this trend in channel straightening, but increased bank instability resulting from the removal of streambank vegetation is likely one of these factors.

Every time the channel abandons an old meander loop and "cuts off", the new channel segment becomes straighter in that reach and the probability of future meander cut-offs occurring is reduced or eliminated. Therefore, we might expect the increased abundance of patch types associated with the abandoned channel successional trajectory to

be a transitional phenomenon that will end, or at least be reduced, if overall channel sinuosity stabilizes at a relatively low value.

The progressive reduction in channel sinuosity from 1.72 to 1.39 that occurred during the study period may not appear to be a change of great magnitude, but the geomorphic, and hence ecological, implications may be extremely important because meandering channel patterns typically possess a sinuosity of greater than 1.5 (Knighton 1984). If the channel assumes a truly braided channel pattern, neither lateral channel migration nor meander cut-off processes would continue. Alternately, if channel sinuosity and lateral migration rates could be restored, some equilibrium between rates of lateral channel migration and meander cut-off may also be reestablished.

Therefore, if the channel pattern does assume a completely braided character in the future, a reduction, elimination, or replacement of all patch types, except for perhaps terminal stand types such as *Acer negundo*, and *Cornus sericea* seems inevitable. Both the patch type (beta) diversity and species diversity within the riparian ecosystem would be substantially diminished under this scenario. A steady state would not persist at the larger ecosystem scale until ecosystem simplification had occurred, because the forces of community regeneration would not have counterpoised degenerative disturbance processes (Noss and Harris 1986).

CONCLUSIONS

Construction of an ecological model can elucidate complex and dynamic relationships between fluvial systems and the patch types comprising a riparian mosaic.

Ironically, such models may teach us more about a system when model output is "wrong" (or produces unexpected results) than when they appear to be right. The process of model development in this study highlighted important cause and effect relationships within this ecosystem, and enhanced our understanding of ecosystem trends. Most importantly, this modeling exercise helped to pinpoint some specific questions, or testable hypotheses, whose resolution will substantially advance our ability to wisely manage or restore this significant riparian ecosystem. Hypotheses to be tested include:

1) Reductions in channel sinuosity and lateral channel migration process rates reflect a relatively abrupt episode of stream adjustment that may indicate channel instability and the crossing of a geomorphic threshold from a meandering to a braided channel. Possible causes for these changes include: an intrinsic "vulnerability" of the channel to pattern changes based upon slope / discharge relationships, increased floodpeak variability, and deforestation of streambanks and the related decrease of bank stability.

2) For the Yampa River, the production of bare alluvium is necessary for sexual reproduction by *Populus*; however, this sediment deposition is not sufficient to support the establishment of *Populus* cohorts subject to a relatively unaltered flow regime, unless it is located on actively forming point bar sites, as is characteristic of a meandering channel.

3) If a significant decrease in the recruitment of *Populus* seedling cohorts occurs, the abundance of the other patch types within that successional trajectory (*Populus* pole stands, mature *Populus*, *Acer negundo*, *Cornus sericea*) will also be reduced over the long-term leading to ecosystem simplification.

4) Other patch types that rely upon the deposition of alluvium at point bar sites for sexual recruitment (riverine marsh, *Salix exigua*) will also decline if the channel assumes a more braided character.

5) If sinuosity continues to decrease, patch types associated with abandoned channels (emergent marsh, *Salix lasiandra* sloughs, oxbow lake banks) and meander cut-off processes will initially increase in abundance within the floodplain, and then eventually decline once the channel has straightened.

Even though riparian ecologists have recognized the importance of geomorphic processes for the perpetuation of riparian vegetation for decades, they have not paid as much attention to the feedback that this vegetation exerts on geomorphic processes (Figure 19). Riparian ecologists have instead focused on hydrologic alteration, particularly reservoir construction, as the primary cause for reduced meandering rates leading to the eventual reduction of point bar recruitment sites for riparian species (Johnson and Sharpe 1976, Ohmart *et al.* 1977, Bradley and Smith 1986, Howe and Knopf 1991, Snyder

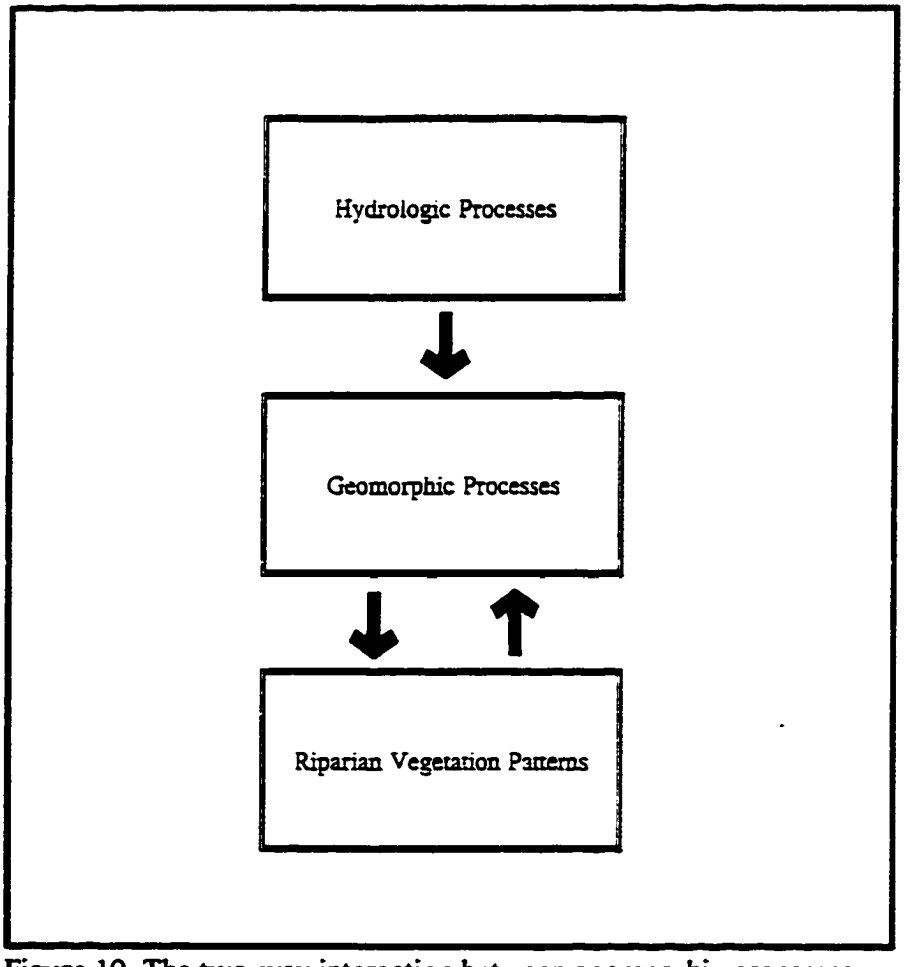

Figure 19. The two-way interaction between geomorphic processes and riparian vegetation patterns was emphasized through development of the Yampa River model.

and Miller 1991). Many interrelated variables are involved in predicting the response of riparian ecosystems to natural and anthropogenic change; in addition, complex feedback and threshold responses further challenge our abilities to understand these systems (Montgomery 1997). However, the Yampa River has provided an interesting case study that suggests that human alteration of riparian vegetation patterns may be at least partially responsible for alteration of geomorphic processes, and ultimately vegetation recruitment mechanisms. Ecological modeling provided an important tool in the discovery of these ecosystem relationships and the formation of these hypotheses.

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Mario Mejia-Navarro provided an essential contribution to this chapter through manipulation of the GIS database and all statistical analyses of GIS data. Brian Richter provided essential hydrologic data and insight into this work. Charles Smythe assisted with programming of the model to accommodate sensitivity analyses. This research was made possible through funding by The Nature Conservancy's Katherine Ordway Stewardship Endowment and the Conservancy's Ecosystem Research Program.

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CHAPTER 4

A STRATEGIC APPROACH TO RIPARIAN RESTORATION BASED UPON GEOMORPHIC AND HYDROLOGIC FACTORS AFFECTING REPRODUCTION OF *POPULUS ANGUSTIFOLIA*

INTRODUCTION

During the past century, the ubiquitous and often intensive human use of riparian habitats in western North America has resulted in severe degradation and loss of these ecosystems. An estimated 70%-90% of all naturally occurring riparian areas in the United States have been extensively altered (Hirsch and Segelquist 1978). Mid-to-low elevation cottonwood riparian forests that provide hospitable climates for human habitation and support high agricultural productivity appear to be especially vulnerable to human development pressures. Human impacts include both the direct clearing of vegetation, and the alteration of ecosystem processes including hydrologic and geomorphic regimes (Briggs 1996, Kauffman *et al.* 1997, Nilsson 1992, Scott *et al.* 1997, Sparks 1995). These habitats are now considered among the most threatened in Colorado, the United States, and the North American continent (Galatowitsch 1985, Terborgh 1989, Noss *et al.* 1995). Therefore, considerable effort and expense is now being directed at riparian restoration projects.

Although the ultimate goal of restoration projects is to ensure that the dynamics of natural ecosystem processes are once again operating efficiently so that both ecosystem structure and function can be recovered (National Research Council 1992), few riparian restoration projects to date in the western states have successfully demonstrated the restoration of ecosystem processes (Briggs 1996). Although the legal and institutional challenges associated with ecosystem restoration can be daunting, restoration programs should target the critical constraints in ecosystem processes that prevent natural regeneration of vegetation from occurring. Unfortunately, when losses in ecosystem structure, composition, or function reach a sufficient magnitude, the simple cessation of perturbations may no longer be sufficient for ecosystem recovery (Kauffman *et al.* 1997).

Restoration Needs on the Yampa River

Historical accounts (Emmons 1876, Fellows 1899) and aerial photography document that clearing and thinning of the riparian forest along the Yampa River in northwestern Colorado was widespread during the period of Anglo settlement from the 1880's to the early 1900's. The result was not only loss of forest cover, resulting in fragmented stands of forest, but fragmentation of the forest canopy within stands as well (Richter 1999). Deforestation of stream banks and the associated loss of bank stability (Figure 20) along the Yampa River was likely one of the primary factors leading to the alteration of geomorphic processes operating there (Richter 1999). In recent decades the channel has straightened significantly and may be in the process of shifting from a meandering channel pattern to a braided channel. In turn, these changes in channel pattern

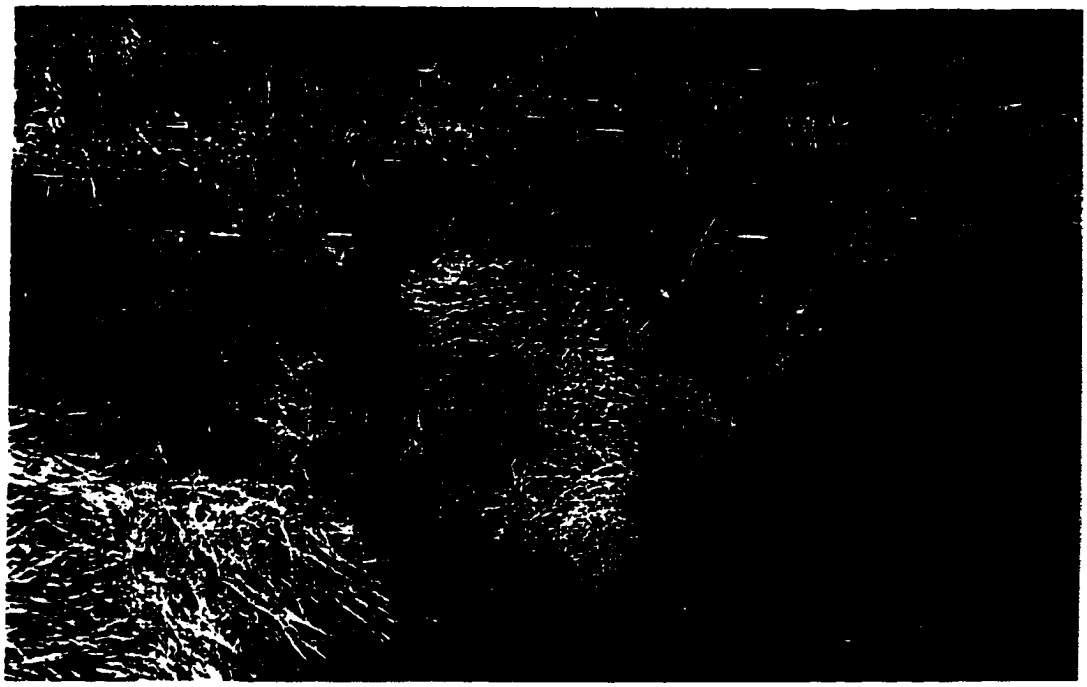

Figure 20. Unstable streambanks along the Yampa River. Native riparian trees and shrubs have been replaced by introduced species of pasture grasses in many agricultural areas.

have altered recruitment mechanisms associated with *Populus angustifolia*, the dominant tree species, by reducing the availability of critical point bar recruitment sites. Fortunately, while vegetation patterns have been significantly altered and, thereby, may have affected geomorphic processes, the hydrology of the Yampa remains relatively unimpaired.

Based upon the working hypothesis that altered geomorphic processes are in part a result of vegetation clearing, initial restoration efforts along the Yampa should be focused on the reestablishment of native vegetation along streambanks. Increased bank stability would help to increase channel sinuosity, reestablish point bar formation, and enhance sexual recruitment of *Populus* over the long term. Analysis by a Geographic Information System (GIS) indicates that approximately 25% of the Yampa's stream banks are

currently devoid of native vegetation within the study area; therefore, the need for streambank restoration will be extensive (Figure 21) Strategic project design and cost-efficient restoration methods will be essential since the costs associated with both land acquisition and the implementation of restoration projects are significant.

Asexual Reproduction of *Populus angustifolia*

Previous research addressing the reproductive ecology of *Populus* species has focused upon the sexual recruitment of seedlings and the interaction of geomorphic and hydrologic processes in perpetuation of the species (Noble 1979; Mahoney and Rood

Figure 21. Riparian forests along the Yampa River have been extensively cleared, primarily for agricultural uses. Along the streambanks only a thin veneer of forest remains, and in some areas none at all, as shown in this picture when overbank flooding was occurring during spring runoff, not far upstream from Hayden, Colorado.

1991; Stromberg *et al.* 1991, 1993; Scott *et al.* 1993; Johnson 1994). However, recent studies have documented that asexual reproduction, particularly through suckering (the emergence of adventitious shoots originating from preexisting parental roots or shoots) occurs relatively frequently for *Populus angustifolia*. Rood *et al.* (1994) documented that 56% of the *P. angustifolia* saplings sampled in southern Alberta were root suckers. However, Rood also found no root suckering of *Populus deltoides* in this same area, although clonal reproduction for this species through shoot suckering was found to occur there.

Ischinger and Shafroth (1995) compared the proportion of sucker-producing *Populus fremontii* in areas that had been partially cleared with a bulldozer for a firebreak in the Bosque del Apache National Wildlife Refuge with nearby uncleared riparian forests. They used a comparison of binomial distribution to analyze data which indicated that a statistically significant difference ($p=.01$) occurred in the proportion of sucker producing trees in cleared and uncleared areas. They concluded that human-induced damage of cottonwood roots promotes root suckering for this species.

Evidently, the mechanisms for clonal reproduction between *Populus* species are highly variable. However, the capability of *Populus* species to reproduce by both sexual and asexual means may suggest novel management and restoration approaches if the environmental conditions that limit or trigger such reproduction can be identified. For example, management that promotes root suckering of *P. angustifolia* may provide more rapid and economical means of restoring forest cover than costly tree planting approaches

since young ramets benefit from the preexisting root systems of parental trees, enabling rapid establishment and growth with little labor input.

Important Successional Relationships of the Yampa Forests

Along meandering river systems of the semi-arid West, sexual regeneration of *Populus* forests typically occurs on fresh alluvial surfaces formed by lateral channel migration. Lateral channel migration rates are higher during moderate or high runoff years, resulting in distinctive bands of parallel, arcuate stands of even-aged cottonwoods (Scott *et al.* 1996). *Populus angustifolia* seedlings are present on point bar sites along the Yampa River, and their average cover on the point bars sampled ranged from approximately 15% to 63% (Richter 1999). One would expect these young cohorts to eventually develop into predominantly even-aged stands of trees.

However, some of the Yampa's mature *P. angustifolia* forests commonly consist of mixed-aged stands of trees, a phenomenon previously considered unlikely for this genus in floodplain environments. While many different sources of error are present in the collection of tree cores and interpretation of tree core data, the age variability found within 15m x 25m sampling plots located within these stands was on the order of 90-110 years (Richter 1999), and cannot, therefore, be solely attributable to sampling error. Within these mixed-aged stands, young *P. angustifolia* root sprouts can be observed arising from the forest floor.

However, *P. angustifolia* ramets are not present in the understory of all mature forest stands along the Yampa. Other stands are instead dominated by *Acer negundo*

seedlings in the understory, and the asexual reproduction of cottonwood does not appear to be as prolific in these areas. Richter (1999) hypothesized that previous management practices, such as forest thinning, has in part produced these mixed-aged stands by increasing light availability to the forest floor. Relatively shallow water tables may also be an important prerequisite for root sprouting to occur, in addition to protection from intensive livestock grazing.

This study assesses the potential for asexual reproduction to provide an alternative mechanism for restoration of *Populus angustifolia* forests. The hydrologic conditions that promote root sprouting by *P. angustifolia* will be explored by comparing existing forest stands where root sprouting is occurring with those where it is not. In addition, successional relationships between *P. angustifolia* and *A. negundo* will be explored to help elucidate how these two species partition floodplain habitats. This information may facilitate the identification of restoration sites with the potential for *P. angustifolia* root sprouting to occur, enabling the design of a restoration program that fully utilizes asexual reproduction mechanisms.

METHODS

To explore successional relationships between *P. angustifolia* and *A. negundo*, and the preferential hydrologic conditions typical of these species, a correlation matrix was constructed that compared the abundance of *P. angustifolia* and *A. negundo* trees of different size classes with each other and with hydrologic variables for twelve macroplots located in mature forest stands. Since *P. angustifolia* is commonly regarded as a riparian

species requiring more saturated soil conditions than *A. negundo*, a one-sided t-test was used to compare hydrologic conditions between sites where *P. angustifolia* root suckers occurred and *A. negundo* seedlings established.

Vegetation Sampling

Seven sampling transects spanned the width of the floodplain and were aligned perpendicular to the river's course. These transects were subjectively located according to land ownership and access limitations. One or two macroplots were subjectively located along each transect (total n=12) to capture the most variability within mature riparian forest types. The macroplot size used was 15 by 25 m, as suggested by The Nature Conservancy's (1988) Community Survey Handbook for deciduous forests, with the long axis of the plot parallel to the river whenever possible. Plots were not located in areas where vegetation had been subject to (known) recent human disturbances, or in locations close to the edge of the vegetation patch. Plots were established in areas with relatively homogeneous physiognomy, floristics, and environmental conditions. An effort was made to include multiple examples of similar stand types along the transects.

Diameter at breast height (dbh) was recorded for all *P. angustifolia* and *A. negundo* trees in each plot, and these data were characterized by size classes. The three size classes used were: 0-10 cm, 10-30 cm, and 30+cm. The individuals that were shorter than breast height were automatically included within the 0-10 cm size class. These data were used to construct the following variables for each plot: number of *P. angustifolia* stems 0-10 cm, number of *P. angustifolia* stems 10-30 cm, and number of *P. angustifolia*

stems more than 30 cm. Similar data were constructed for *A. negundo* individuals in all plots. For trees possessing multiple stems, only the largest diameter stem was measured for each individual. To roughly define the age classes that these size classes represent, the ages of 44 trees were estimated by tree coring and compared with their dbh. From these data, the three size classes were determined to generally represent trees that were less than 20 years old, 20-50 years old and over 50 years old. Data comparing tree ages with size classes can be found in Figure 44 in Appendix F.

Topographic Surveying and Groundwater Well Monitoring

The macroplots were topographically surveyed and a mean elevation (the average of all four plot corners) was assigned to each plot. These plot elevations were calculated as the relative height of the plot above bankfull discharge, not as absolute elevations. This relative measure provides a useful descriptor of the geomorphic and hydrologic settings associated with particular sites within the floodplain. Absolute elevations would not accurately represent these conditions as well, because they would decrease in a down-valley direction. Bankfull discharge for the Yampa River (167 m^3/s) had been previously defined near Hayden, Colorado by Andrews (1980). Rating curves were developed for each transect (Richter and Powell 1996) and the elevation of bankfull discharge was then estimated from those curves. This bankfull elevation was then compared to the elevation of the plot to determine the elevation of the plot above bankfull discharge.

One or two groundwater monitoring wells were installed along each sampling transect (total n=10) and the ground surface elevation at each well was also determined

relative to bankfull discharge. Because some plots were located near others along the transects, some wells provided data for more than one plot. The wells were monitored at approximately two week intervals for two growing seasons. Regression equations were then developed to relate the elevation of the water table with streamflow discharge for each well as described by Richter and Powell (1996). From these equations, daily water table elevations were estimated for the period of 1966-1993 for each plot. After these data were generated, the average number of days each year that the water table was within 1 m of the ground surface, and 2 m of the ground surface, was calculated for each plot for this time period.

Tree Excavation

Without relying on genetic information, the only practical way to determine the origin of individual trees in the field is by excavation of the root system. Tree excavation was used in this study to verify the method of reproduction of young *P. angustifolia* saplings within macroplots. The structure of roots on younger individuals is often quite revealing: asexual ramets obviously originate from a horizontal root, while sexually derived individuals possess one or a few tap roots that descend vertically. In older trees (e.g.> 20 years old), the original parental root of asexual ramets may no longer remain connected with the parent (Oliver and Larson 1996) and determination of reproductive origin is difficult based solely on root excavation. Due to this constraint, only young *P. angustifolia* saplings under approximately 2 m in height that were present within macroplots were excavated to determine method of origin.

RESULTS

Excavation of the root systems of young *P. angustifolia* trees and saplings less than 20 years old that were located within mature stands verified that they had been produced by asexual reproduction. As demonstrated by the correlation matrix shown in Table 5, young and middle-aged *P. angustifolia* ramets typically occur within stands together ($r = .70$, $p \leq .01$), suggesting that asexual reproduction may continue to occur at some sites over fairly long periods of time. However, mature individuals of the two tree species were not typically present with one another in the macroplots sampled, as evidenced by the negative correlation ($r = -.73$, $p = .01$) between the presence of mature *P. angustifolia* versus mature *A. negundo*.

Figures 22 and 23 compare the stand structure (by stem diameter classes) of a plot where root suckering has occurred, resulting in a mixed-aged stand of *P. angustifolia* (plot 31), and a plot in which a stand of mature *P. angustifolia* forest is now dominated by *A. negundo* in the subcanopy and understory (plot 32). The mixed-age stand contains a wide array of *P. angustifolia* stem sizes, with the highest number of stems in the smallest size class. Few *A. negundo* were present in this stand, with the only *A. negundo* stems falling within the smallest size class.

Conversely, in the plot where *A. negundo* dominated in the understory, no *P. angustifolia* were present except for older, large diameter trees. The *A. negundo* ranged from 1-20 cm dbh within the understory and subcanopy of this stand.

These drastic differences in stand structure are at least partially attributable to differences in environmental conditions between stands. The average number of days

Table 5. Correlation matrix of hydrologic variables and density of *Populus* and *Acer* in various age/size classes, Yampa River.

Variables	Plot elevation	# days water table w/in 1 meter	# days water table w/in 2 meters	density young *Populus* / 375m² (0-10 cm)	density middle-aged *Populus* / 375m² (10-30 cm)	density mature *Populus* / 375m² (30+cm)	density young *Acer* / 375m² (0-10 cm)	density middle-aged *Acer* / 375m² (10-30 cm)	density mature *Acer*/ 375m² (30+ cm)
Plot elevation	1.00								
# days water table w/in 1 meter	-0.39	1.00							
# days water table w/in 2 meters	-0.25	0.36	1.00						
density young *Populus* (0-10 cm)	0.17	0.35	0.13	1.00					
density middle-aged *Populus* (10-30 cm)	0.27	0.35	0.19	0.70[1]	1.00				
density mature *Populus* (+30 cm)	-0.05	0.41	0.03	-0.09	-0.09	1.00			
density young *Acer* (0-10 cm)	-0.70[1]	0.37	019	-0.42	-0.13	0.24	1.00		
density middle-aged *Acer* (10-30 cm)	0.19	0.01	0.30	-0.49	-0.13	-0.22	0.16	1.00	
density mature *Acer* (+30 cm)	0.16	-0.63[1]	0.25	-0.21	-0.07	-0.73[1]	-0.12	0.41	1.00

[1]Denotes correlations between variables that are significant at p≤ .05.

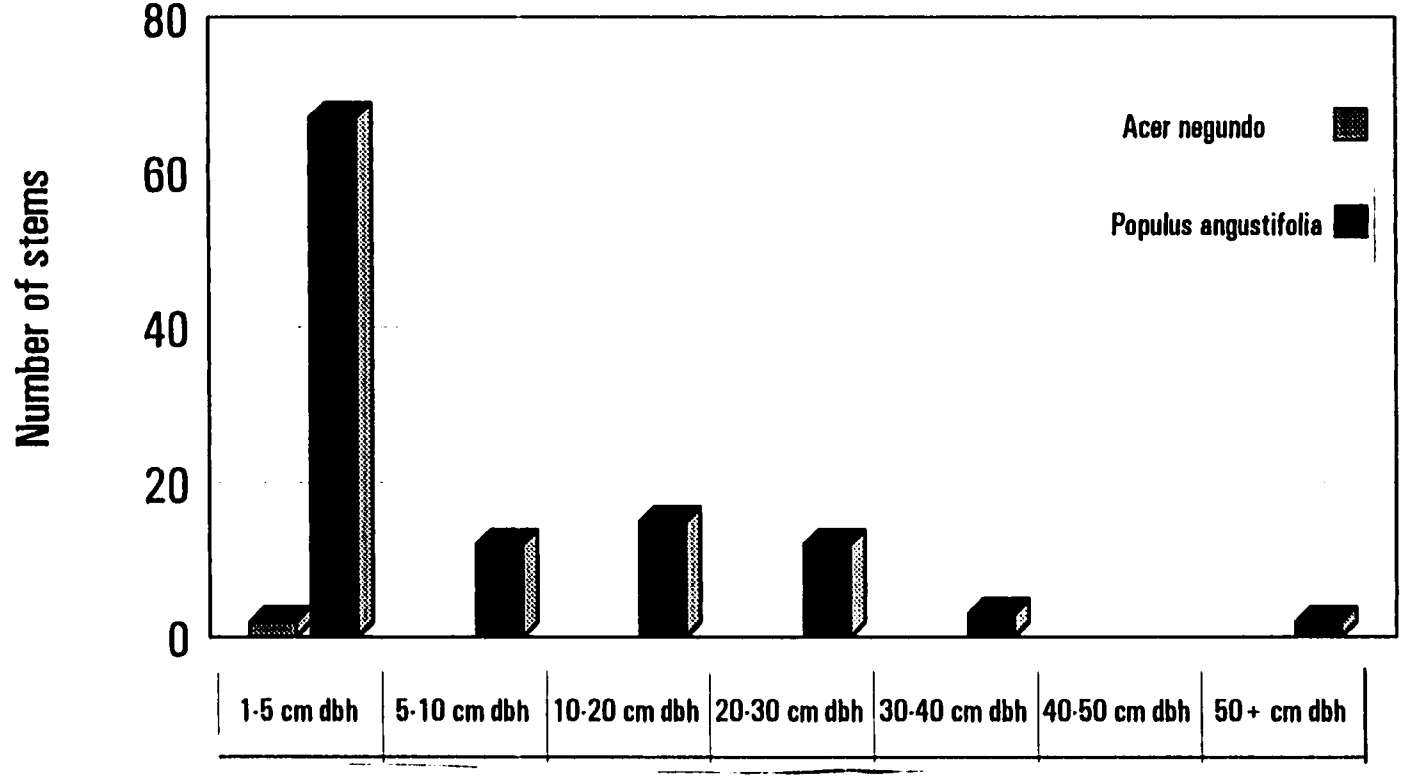

Figure 22. Stand structure (by stem diameter classes) of a mixed-aged *Populus angustifolia* forest on the Yampa River where root suckering is occurring.

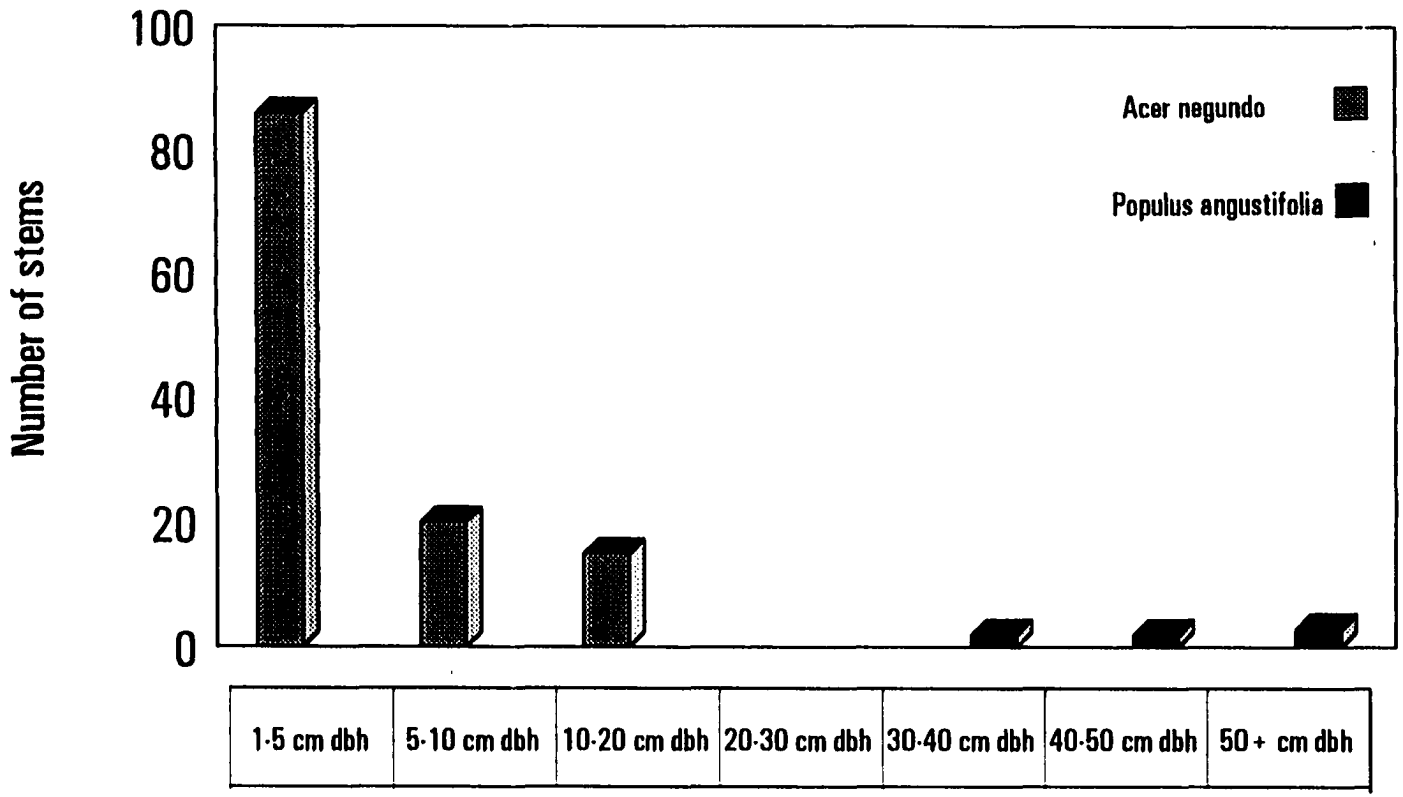

Figure 23. Stand structure (by stem diameter classes) of a *Populus angustifolia* forest along the Yampa River with an *Acer negundo* seedling understory.

per year that the water table is within 1 m of the ground surface was greater for *P. angustifolia* root suckering sites, as compared to *Acer* seedling recruitment (n=12, t=-1.96, p=0.04). Figure 24 compares the hydrographs of groundwater elevations of a plot dominated by mixed-aged *P. angustifolia* with one dominated by *A. negundo* seedlings in the understory, illustrating an obvious difference in the duration of high water table elevations. The water table in the plot with *A. negundo* seedlings remained below a meter in depth, while the water table in the mixed-aged *P. angustifolia* stand remained within a meter of the ground surface throughout much of the growing season.

Groundwater well monitoring within macroplots revealed that stands dominated by *A. negundo* in the canopy, subcanopy, and/or understory occur on sites where the water table is within 1 m of the ground surface for 40 days per year on the average (standard error=12.2), as compared to 73 days per year (standard error=11.1) for those sites where mixed-aged P. angustifolia occur (as a result of root sprouting). Additionally, a negative correlation was found between the presence of young *Acer* and plot elevation (r=-.70, p=.01), as well as between mature *A. negundo* and the average number of days that the water table is within 1 m of the ground surface (r=-.63, p=.03).

DISCUSSION

The depth of the water table relative to the ground surface may be an important variable in predicting how *P. angustifolia* and *A. negundo* partition habitat in floodplain settings, and whether mature *P. angustifolia* can reproduce asexually. Generally,

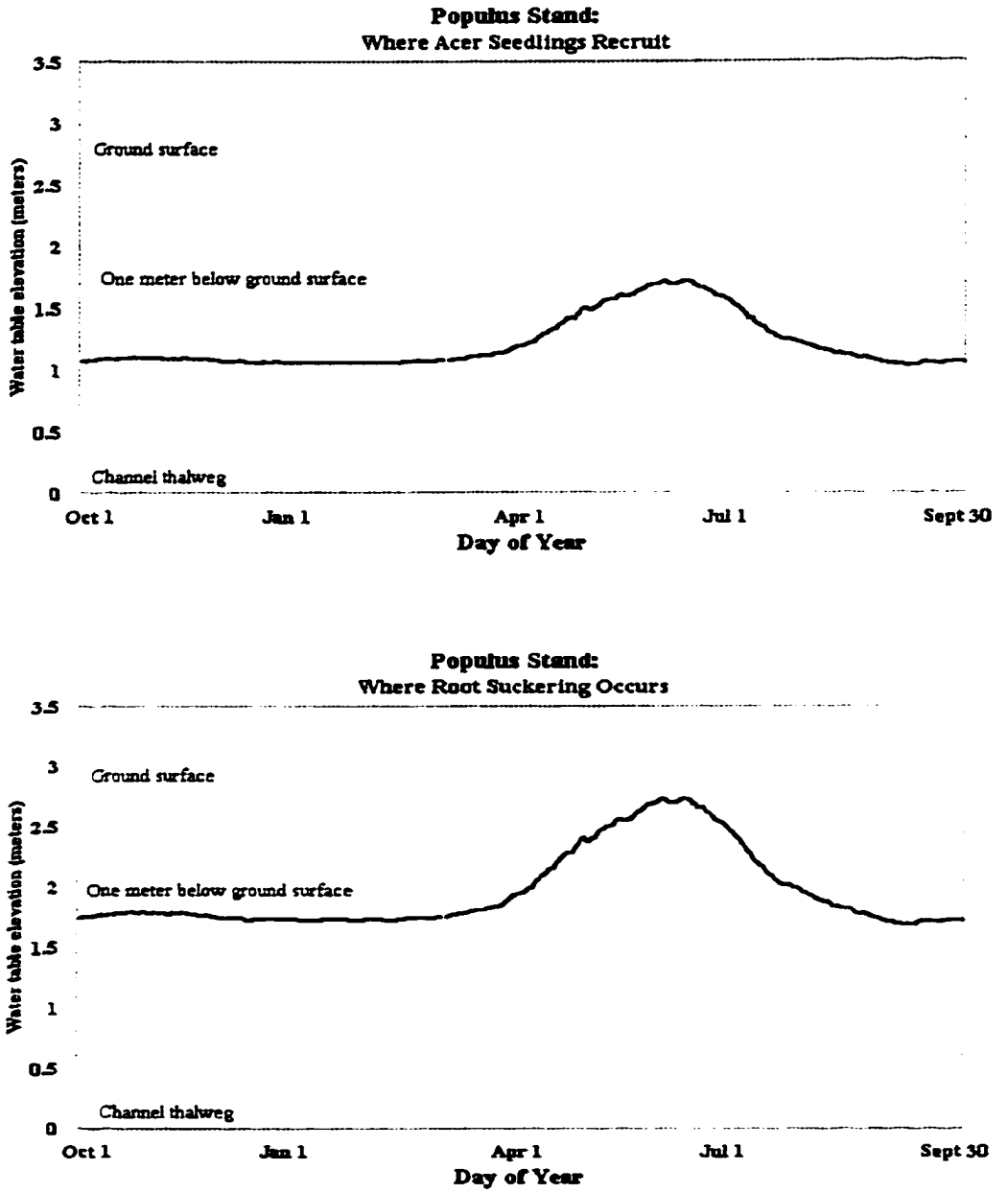

Figure 24. Comparative hydrographs of water table elevations at: (1) a mature *Populus angustifolia* plot (plot 5) where *Acer negundo* seedlings are recruiting in the understory and, (2) a mature *Populus angustifolia* plot (plot 31) where root suckering occurs. Hydrographs represent the daily average water levels for the period 1966-1992.

asexual *P. angustifolia* reproduction appears to occur on sites where the water table is within 1 m of the ground surface for a relatively large proportion of the growing season. However, plots where suckering occurred did exhibit a wide of range of hydrologic variation (i.e., water table within a meter of the ground surface for a mean of 24-117 days each year). This variation may be attributable to the error associated with the development of hydrologic models (see Richter and Powell 1996) or differences in soil texture resulting in perched water tables or variation in soil moisture retention among sites. In addition, the variation of topographic relief within plots (not reflected by the average elevation) may also confound these relationships due to the fact that the water table could be closer or farther from the ground surface in some areas of the macroplot than in other areas of the plot.

The relationship between water table depth and root suckering potential can be used to delineate areas where asexual reproduction could best be utilized to enhance restoration efforts. Such an assessment, however, would need to be based upon fairly accurate estimates of the depth and range of variation in the water table at potential restoration sites. In sites distant from flood irrigated agricultural fields, the ground surface elevation relative to the water elevation in the main river channel ("river stage") is often a good indicator of water table depth. However, river stage cannot reliably be used as an indicator of water table depth in floodplain areas where water management practices such as flood irrigation and irrigation ditches have altered natural water table fluctuations (Richter and Powell 1996). Groundwater monitoring at potential restoration sites may be

the best assessment tool to determine if root suckering will likely occur at any particular location.

Some other confounding factors should be kept in mind when interpreting these results. Stands with a fully closed forest canopy may not offer adequate light penetration to the forest floor to promote suckering. Previous research (Shaw 1991) has determined that root suckering favors unshaded sites. However, light availability will most likely not be a limiting factor at restoration sites that have been cleared, partially cleared, or thinned of vegetation. Proximity to mature *P. angustifolia* trees will of course also determine the potential for suckering to occur. Along the Yampa River isolated trees located within agricultural pastures have been found to be capable of producing root suckers as far as 25 m away from the parental tree (Figure 25).

Although not tested in this study, intense grazing pressure appears to prevent establishment of suckers. In many instances *Populus* suckers may be absent within pastures along the Yampa, but abundant just outside of the pasture fence line, in areas restricted to livestock. Artificial clipping studies may provide useful information for determining the effects of herbivory on *Populus* suckers. Wildlife, particularly mule deer and elk, may also be responsible for significant browsing on suckers, particularly in areas where wildlife concentrates for long periods of time, such as elk winter ranges. Generally, browse by wildlife species has been found to be most intense on small twigs and buds below 1.5 m (Oliver and Larson 1996). Additionally, in hay fields that are harvested every year, young suckers are often repeatedly cut with the hay crop. Promoting the establishment of asexual ramets within and adjacent to existing forest fragments by

Figure 25. Two *Populus angustifolia* clones have established within this abandoned agricultural area. The two large parental trees in this photo (one in the center, one at the left edge) were most likely the only trees left standing in this area of the cleared pasture. The parental tree in the center was approximately 107 years old when this picture was taken. The root systems of the young ramets in the foreground were excavated to verify that asexual reproduction had occurred. Their ages ranged from 4-31 years.

carefully managing livestock grazing, discouraging the concentration of wild herbivores, and reducing hay production in select areas will undoubtedly prove to be a more time and cost effective approach to restoration than offered by traditional tree planting methods.

The current presence or absence of mature *A. negundo* or mixed-aged stands of *P. angustifolia* at specific sites are indicative of the site's historic potential for recruitment of *A. negundo* seedlings or asexual *P. angustifolia* ramets. Thus, the current composition of forest stands immediately adjacent to restoration areas should also be an excellent indicator of the potential for asexual *P. angustifolia* regeneration at that site if similar

hydrologic conditions exist in both areas. Additional research aimed at testing how well this relationship holds is warranted, because this information could provide essential guidance for the design of future restoration projects.

CONCLUSIONS

Conditions that appear to be important for root suckering of *P. angustifolia* to occur along the Yampa River include: water table elevations within a meter of the ground surface for the majority of the growing season, adequate light availability, close proximity to mature *P. angustifolia* trees (within 25 m), and minimal mowing and herbivory during the establishment phase.

Ischinger and Shafroth (1995) also hypothesized that the amount of root suckering and probability of long-term survival for *Populus fremontii* may be influenced by several variables including: the degree of root damage, the age of the parent tree, the size of the damaged root, soil moisture and depth-to-groundwater, browsing by cattle or deer, and the extent to which a sucker is shaded. Rood *et al.* (1994) suggests that although most *Populus* species have the ability to clonally propagate, there are likely to be differences in reproductive strategies between species. Therefore, further investigation is merited to more precisely define the different primary mechanisms that promote root suckering among different *Populus* species.

The most important factors that promote root sprouting for any *Populus* species should be considered in determining the likelihood for sprouting to occur at a potential restoration site. Once restoration sites that have the potential for suckering to occur are

identified, the remaining sites requiring restoration can be targeted with more traditional (but costly) restoration planting efforts. By employing this strategy, costs and more labor intensive restoration plantings can be minimized while maximizing the amount of riparian area restored.

In addition, the restoration sites that offer all of the physical and environmental characteristics that support root suckers (water table, light availability, limited herbivory), but lack existing mature trees can reduce planting costs by anticipating the future potential for asexual reproduction to occur. For example, since suckers were observed up to 25 m away from parental trees, trees planted at 50 m spacing on the Yampa's floodplain may be able to produce suckers that will eventually fill the spaces between planted trees. In contrast, restoration sites that do not appear to have water table elevations that can support sucker development should be planted according to the long-term densities of trees desired (Figure 26).

Additional research and monitoring that more precisely defines the hydrologic requirements for root suckering to occur should be integrated into riparian restoration programs along the Yampa River. Initial data analysis indicates that suckering occurs on sites where water tables remain within 1 m of the ground surface for an average of 40 days during the growing season. These results should be considered a hypothesis that can be further tested with restoration experiments. Over time, the precise hydrologic requirements for root suckering can be more clearly defined. In addition, the percent mortality of root suckers over time should also be monitored over longer periods, to determine what percent of the suckers typically survive to maturity.

For the Yampa River ecosystem, an extensive restoration program that targets deforested streambanks appears to be important for the restoration of geomorphic processes and the long-term viability of the system. To most efficiently restore native vegetation to the Yampa's stream banks over an extensive area, a passive restoration approach that enables root suckering to occur will be most cost efficient. More intensive active restoration efforts should be focused only at sites where root suckering has been determined to be unlikely.

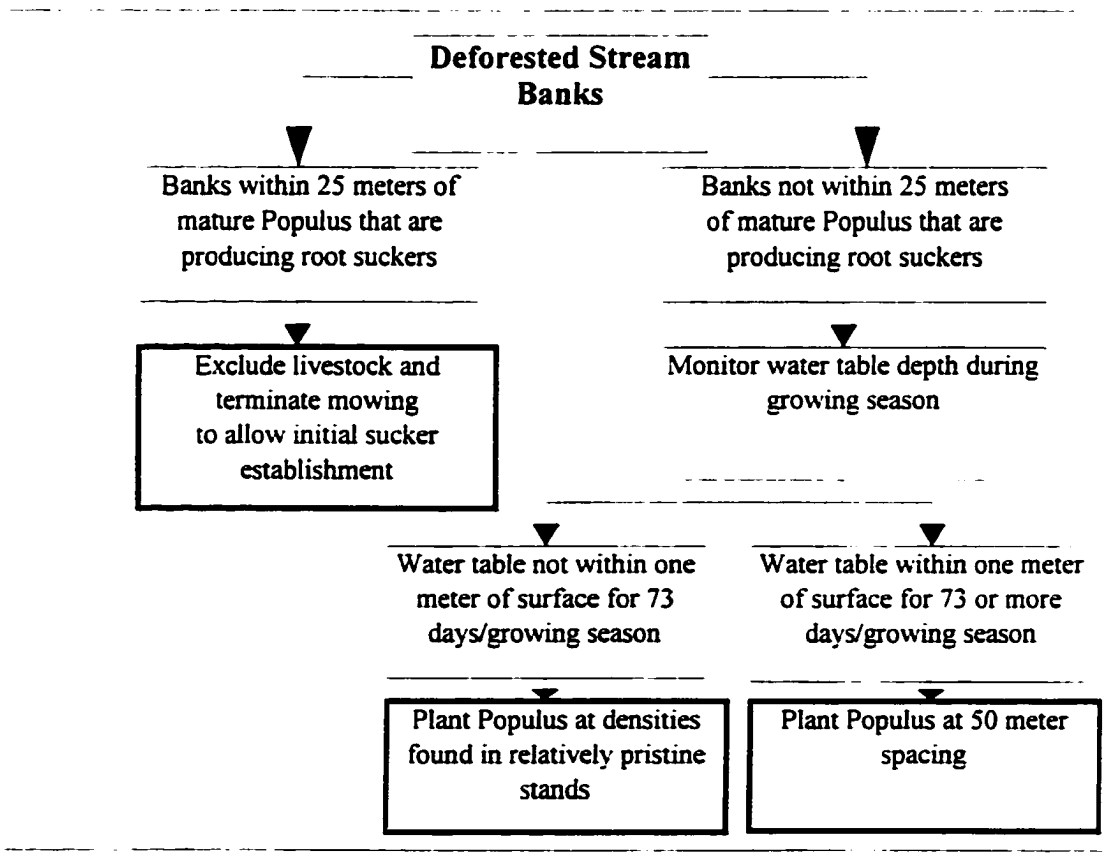

Figure 26. Proposed restoration strategy for the Yampa River ecosystem.

Assessment of the potential for root suckering to occur at specific sites will be critical to this restoration strategy. While this study has provided preliminary guidelines to determine the potential for suckering to occur at restoration sites, further research and monitoring are needed to refine a detailed planting model. This may best be accomplished through the use of an adaptive management approach; i.e., learning through the careful evaluation of restoration plantings that have been installed, based upon these hypotheses.

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CHAPTER 5

SUMMARY AND REMARKS

OVERVIEW

Before Anglo settlement, the fluvial landscape along the Yampa River probably consisted of a dominant matrix of *Populus angustifolia* forest occupying the majority of the active floodplain, as suggested by S.F. Emmons in 1876. This riparian forest was likely maintained largely by the geomorphic process of lateral channel migration, and the associated sexual regeneration of *P. angustifolia* on point bars. Within this matrix, wetland plant associations characteristic of abandoned channels and oxbows were likely present in long "stringers," reflecting the shape of the abandoned channels in which they were located. However, today the riparian corridor along the Yampa is characterized by remnants of riparian forest stands and abandoned channel wetlands within an agricultural matrix.

When a natural landscape is fragmented, the overall community diversity may stay the same or even increase, yet the integrity of the community can be compromised by the invasion of weedy species and the loss of species unable to persist in small, isolated patches of habitat (Noss 1983). Edge-adapted and/or habitat generalist species usually benefit at the expense of forest interior species intolerant of fragmentation (Noss and

Harris 1986). More importantly, significant alteration of vegetation patterns may affect the proper functioning of large-scale ecosystem processes.

The reduction of total forest cover, along with the reduction in width of the riparian corridor, may have important ramifications for riparian ecosystem processes along the Yampa River. As discussed previously, deforestation of streambanks and the associated loss of bank stability was likely one of the primary factors leading to alteration of geomorphic processes there, including point bar formation. However, the majority of the remaining stands of *Populus* forest are located in close proximity to the active stream channel, since risks associated with flooding have limited human uses in these areas. This preferential clearing of forest has eliminated those forest stands and wetlands that would be typically most secure from catastrophic flood events on the outer edges of the broad floodplain, likely reducing the resiliency of the ecosystem to catastrophic flood events. Not only is riparian vegetation now vulnerable to more comprehensive stand destruction by flood flows, but future sources of propagules for post-disturbance recovery may also be severely reduced as a result of narrowed corridor width.

Due to the overall reduction and fragmentation of riparian vegetation cover in many areas, it is difficult to determine the natural extent (particularly in regards to width) of the riparian corridor prior to Anglo settlement, based solely on the current distribution of vegetation. However, geologic maps that depict the extent of the Yampa's alluvial deposits (as opposed to colluvium derived from the valley sides and alluvium from small tributaries) can be used to delineate the active "meander belt" of the river channel since the

Pleistocene. These alluvial deposits can be considered equivalent to the maximum potential extent of the riparian mosaic over the long-term.

The concept of "minimum dynamic area" (Pickett and Thompson 1978) states that the design of nature reserves should be based on the smallest area with a natural disturbance regime, which maintains internal recolonization sources for each habitat type and hence minimizes extinction. It is assumed that even the largest possible natural flood disturbance would not eliminate vegetation across the entire width of the meander belt during a single disturbance event, allowing some flood refugia and, therefore, some source of propagules for post-disturbance recolonization. However, if conservation efforts focus only on that portion of the forest corridor that remains directly adjacent to the current stream channel, sources of propagules for post-disturbance recolonization may be drastically reduced after a severe flood. Restoration of previously cleared areas located at the outer fringes of the floodplain should also be considered a high priority to ensure that adequate flood refugia persist for future catastrophic events.

In addition, protection actions should not only focus on existing vegetation patterns, but should also include sites with the potential for either natural regeneration to occur (based on the probability of the stream channel gaining access to a particular site and forming point bars or abandoned channels), or for restoration efforts through asexual mechanisms (*Populus* root sprouting, etc.).

The segments of stream channel in the wide valley settings that currently possess the most sinuosity and native woody vegetation along the banks are the segments that will most likely retain active point bar development, and continue to successfully recruit

sexually-derived *P. angustifolia* seedlings. These sites should be the highest priorities for protection activities in the short-term. It is uncertain, however, whether the seedling cohorts that have established on lateral islands and mid-channel bars in the reaches where channel straightening has occurred, will be able to achieve long-term survival within the context of the more intense disturbance regime characteristic of those sites. It is also important to keep in mind that while asexual reproduction may serve as an important tool for restoration, genetic diversity within the floodplain can only be maintained over the long-term through sexual recruitment.

The need for restoration along the Yampa is clear. To effectively restore the function of this riparian ecosystem, reestablishment of riparian forest must occur not at a few selected sites, but throughout significant portions of the river system. Because of the logistical and financial ramifications of such an endeavor, the most cost-effective approaches to restoration must be employed.

However, the potential for reestablishment of native vegetation appears to be great, primarily due to the clonal reproduction mechanisms associated with *Populus angustifolia*, the keystone species of this ecosystem. For example, a reversal of forest thinning practices appears to have already begun, without intentional management efforts, throughout much of the riparian corridor since 1925 (Richter 1999).

The more "work" that can be accomplished by *facilitating restoration of ecological processes*, as opposed to manually replanting vegetation, the better. In addition, restoration goals focused at "within-patch" species composition and structure of the riparian plant communities should be accompanied by considerations of the "among-

patch" structure of the vegetation over the riparian landscape. Therefore, true "restoration" involves consideration of the interaction of ecosystem structure and function. The list of potential restoration goals that follows is aimed at addressing these considerations.

In addition, protection of both the narrow and broad valley settings may also be important for ensuring the long-term viability of the riparian forest along the stream corridor. Because regeneration of *Populus angustifolia* may be triggered by different flood magnitudes in broad valleys, as compared to confined valley settings, protection of both types of areas may be important to the long-term viability of the species along the river. This would be particularly important if the variability of streamflows in the Yampa is artificially reduced in the future. Regeneration in narrow canyon settings may be curtailed before recruitment in broad valley settings if the largest flood flows are eliminated through impoundment or other water management practices.

On a larger scale, longitudinal connectivity between protected areas may also be important along the riparian corridor to enhance the flows of energy, matter and species. For example, sources of propagules for some narrow canyon settings may actually be wide valley reaches just upstream (or up wind) and vice versa. In addition, a great deal of species and community diversity along the Yampa is attributable to the relatively steep elevational gradients along the Yampa's riparian corridor. The ability of species to shift their elevational range in response to global climate change may also be critical to their long-term persistence.

For the Yampa, the geomorphic changes that have occurred may partially be attributable to extensive forest clearing that has occurred within the riparian landscape (especially that which has occurred adjacent to the channel). This clearing of forest has likely decreased bank stability and in turn reduced the ability of the system to create and destroy the diverse geomorphic landforms that are necessary to perpetuate the mosaic of riparian plant communities. Ecological simplification of the riparian ecosystem will likely be the end result of such a "positive feedback loop". Specifically, younger seral patch types would decrease in abundance first, followed by older seral stages over time.

Hopefully, the design and application of management strategies to reverse these trends can be implemented effectively within the Yampa Valley. Conservation of this dynamic ecosystem will need to address essential fluvial processes, as well as the landscape patterns with which they interact. An overall goal for site conservation planning might include:

> *To protect and restore the natural function and structure of the riparian ecosystem along the Yampa River. This includes representation of the full array of vegetation patch types that comprise the riparian mosaic, and the physical processes that sustain them.*

Several specific objectives would be required to accomplish this broad goal:

1) Ecosystem function:

A) *Maintain or restore the natural variation of hydrologic processes within the watershed that results in a natural disturbance regime for riparian plant associations.*

B) *Promote natural rates of fluvial landform creation and destruction within the floodplain that are necessary to initiate biotic succession (point bars, abandoned channels) by reversing the current geomorphic trend toward*

channel instability (reduced sinuosity and fluctuating channel width). Accomplish this by focusing restoration efforts on stabilizing streambanks in channel segments where woody vegetation has been cleared and streambanks destabilized.

C) *Protect stream channel segments where woody riparian vegetation remains to stabilize the stream banks, especially in areas where point bar development and sexual* Populus *recruitment are occurring.*

D) Provide protection of possible Populus *recruitment sites in both wide valley and narrow canyon settings to enhance the ability of the species to regenerate in the face of hydrologic variability.*

2) Riparian Landscape Structure:

A) *Restore riparian vegetation on deforested stream banks to the extent possible so that it can provide bank stability for the channel, similar to that provided by the continuous forest cover which likely existed prior to Anglo settlement.*

B) *Protect or restore the full array of riparian patch types that comprise the "shifting-mosaic" within the floodplain, such that there is adequate abundance, connectivity, shapes and sizes of each indigenous patch type to ensure their long-term viability, as well as the viability of wildlife species that depend upon them.*

C) *Protect and/or restore riparian vegetation in areas that are not directly adjacent to the current location of the stream channel, in hopes of including flood refugia during catastrophic floods within protected areas.*

While the successful accomplishment of these goals will require substantial planning, resources, and cooperation from Yampa Valley landowners and land managers, the Yampa River still represents one of the last large-river ecosystems in the western United States that continues to hold the promise of long-term viability for native species and communities.

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APPENDIX A: GIS DATA AND ANALYSES

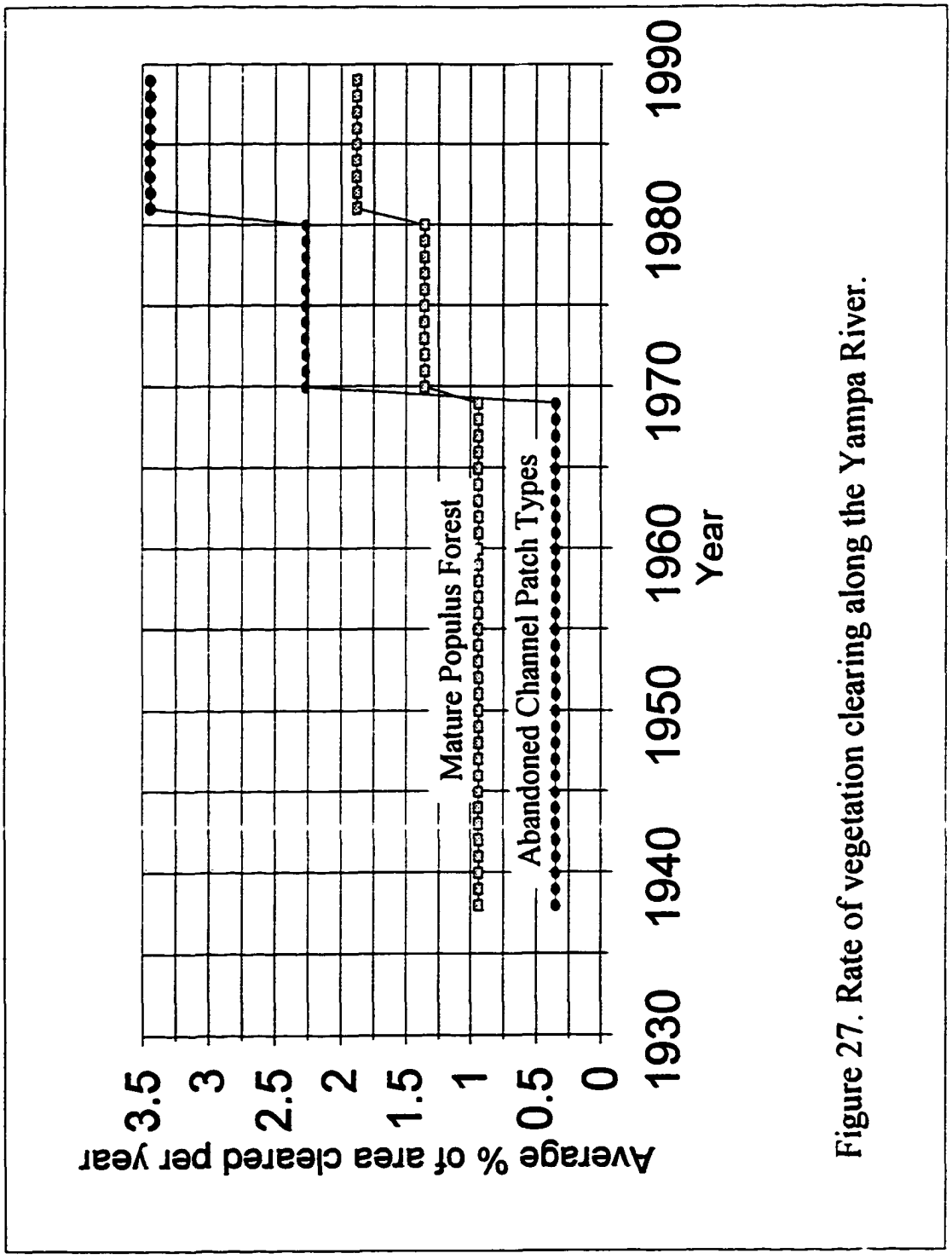

Figure 27. Rate of vegetation clearing along the Yampa River.

Table 6. Yampa River GIS statistics: 1938.

RASTER MAP CATEGORY REPORT

LOCATION: mario Sun Jan 28 12:11:22 1996

REGION				
	north:	4487979	east:	318819
	south:	4482308	west:	307516
	res:	2.49933892	res:	2.49955772

MASK:none

MAP: VEG38 LIFE ZONES (VEG38 in yampa)

#	Category Information description	acres	hectares	% cover
0	No data.	10,832.071	4383.67900	68.39
1	1: PRIMARY STREAM CHANNEL.	201.458	81.52901	1.27
2	2: SECONDARY CHANNELS.	13.640	5.52006	0.09
3	3: OLD CHANNEL VEGETATION.	172.225	69.69860	1.09
4	4: FOREST TYPES.	702.759	284.40256	4.44
5	5: YOUNGER DEPOSITIONAL SURFACES	66.366	26.85814	0.42
6	6: BARE ALLUVIUM	73.258	29.64691	0.46
7	7: DISTURBED AREAS	3777.163	1528.59701	23.85
TOTAL		15,838.940	6409.93130	100.00

Table 7. Yampa River GIS statistics: 1989.

RASTER MAP CATEGORY REPORT

LOCATION: mario — Sun Jan 28 12:12:43 1996

REGION				
	north:	4487979	east:	318819
	south:	4482308	west:	307516
	res:	2.49933892	res:	2.49955772

MASK:none

MAP: VEG89 LIFE ZONES (VEG89 in yampa)

Category Information				%
#	description	acres	hectares	cover
0	No data.	10,764.306	4356.25486	67.96
1	1: PRIMARY STREAM CHANNEL.	183.965	74.44963	1.16
2	2: SECONDARY CHANNELS.	63.781	25.81173	0.40
3	3: OLD CHANNEL VEGETATION.	191.995	77.69945	1.21
4	4: FOREST TYPES.	620.091	250.94733	3.91
5	5: YOUNGER DEPOSITIONAL SURFACES	51.064	20.66525	0.32
6	6: BARE ALLUVIUM	111.641	45.18068	0.70
7	7: DISTURBED AREAS	3852.097	1558.92237	24.32
TOTAL		15,838.940	6409.93130	100.00

Table 8. Yampa River GIS statistics: differences between 1938 and 1989.

RASTER MAP CATEGORY REPORT

LOCATION: mario — Tue Jan 30 09:51:01 1996

REGION — north: 4487979 east: 318819; south: 4482308 west: 307516; res: 2.49933892 res: 2.49955772

MASK: none

MAPS: VEG38 LIFE ZONES (VEG38 in yampa)
VEG89 LIFE ZONES (VEG89 in yampa)

#	Category Information description	acres	hectares	% cover
0	No data	107.53369	43.51829	2.10
1	1: PRIMARY STREAM CHANNEL.	8.06425	3.26356	7.50
2	2: SECONDARY CHANNELS.	0.93239	0.37733	0.87
3	3: OLD CHANNEL VEGETATION.	10.16059	4.11193	9.45
4	4: FOREST TYPES.	25.41846	10.28671	23.64
6	6: BARE ALLUVIUM	0.54029	0.21865	0.50
7	7: DISTURBED AREAS	62.41770	25.26010	58.04
1	1: PRIMARY STREAM CHANNEL	201.45817	81.52901	3.94
0	No data.	3.94722	1.59742	1.96
1	1: PRIMARY STREAM CHANNEL.	68.56623	27.74837	34.03
2	2: SECONDARY CHANNELS.	12.63204	5.11212	6.27
3	3: OLD CHANNEL VEGETATION.	34.51699	13.96883	17.13
4	4: FOREST TYPES.	24.66359	9.98122	12.24
5	5: YOUNGER DEPOSITIONAL SURFACES	15.02477	6.08044	7.46
6	6: BARE ALLUVIUM	34.43517	13.93572	17.09
7	7: DISTURBED AREAS	7.67216	3.10488	3.81
2	2: SECONDARY CHANNELS	13.64008	5.52006	0.27
0	No data.	0.41525	0.16805	3.04
1	1: PRIMARY STREAM CHANNEL.	1.39550	0.56475	10.23
2	2: SECONDARY CHANNELS.	1.04817	0.42419	7.68
3	3: OLD CHANNEL VEGETATION.	1.65638	0.67033	12.14
4	4: FOREST TYPES.	4.16334	1.68488	30.52
5	5: YOUNGER DEPOSITIONAL SURFACES	0.77030	0.31174	5.65
6	6: BARE ALLUVIUM	1.41711	0.57350	10.39
7	7: DISTURBED AREAS	2.77402	1.12263	20.34
3	3: OLD CHANNEL VEGETATION	172.22525	69.69860	3.37
0	No data.	2.16117	0.87461	1.25
1	1: PRIMARY STREAM CHANNEL.	7.30167	2.95495	4.24
2	2: SECONDARY CHANNELS.	7.65981	3.09988	4.45
3	3: OLD CHANNEL VEGETATION.	40.63156	16.44337	23.59
4	4: FOREST TYPES.	53.23118	21.54236	30.91
5	5: YOUNGER DEPOSITIONAL SURFACES	4.31154	1.74485	2.50
6	6: BARE ALLUVIUM	9.95837	4.03010	5.78
7	7: DISTURBED AREAS	46.96996	19.00848	27.27

4	4: FOREST TYPES		702.75873	284.40256	13.74
	0	No data.	6.44492	2.60822	0.92
	1	1: PRIMARY STREAM CHANNEL.	39.40432	15.94671	5.61
	2	2: SECONDARY CHANNELS.	12.50083	5.05902	1.78
	3	3: OLD CHANNEL VEGETATION.	37.46235	15.16081	5.33
	4	4: FOREST TYPES.	351.93432	142.42587	50.08
	5	5: YOUNGER DEPOSITIONAL SURFACES	9.37022	3.79208	1.33
	6	6: BARE ALLUVIUM	23.00875	9.31151	3.27
	7	7: DISTURBED AREAS	222.63302	90.09835	31.68
5	5: YOUNGER DEPOSITIONAL SURFACES		66.36647	26.85814	1.30
	0	No data.	0.53721	0.21740	0.81
	1	1: PRIMARY STREAM CHANNEL.	7.00219	2.83375	10.55
	2	2: SECONDARY CHANNELS.	0.39673	0.16055	0.60
	3	3: OLD CHANNEL VEGETATION.	7.57182	3.06427	11.41
	4	4: FOREST TYPES.	34.80411	14.08503	52.44
	5	5: YOUNGER DEPOSITIONAL SURFACES	3.79594	1.53620	5.72
	6	6: BARE ALLUVIUM	7.34489	2.97244	11.07
	7	7: DISTURBED AREAS	4.91358	1.98850	7.40
6	6: BARE ALLUVIUM		73.25752	29.64691	1.43
	0	No data.	0.18987	0.07684	0.26
	1	1: PRIMARY STREAM CHANNEL.	13.07354	5.29079	17.85
	2	2: SECONDARY CHANNELS.	2.46065	0.99581	3.36
	3	3: OLD CHANNEL VEGETATION.	13.79599	5.58316	18.83
	4	4: FOREST TYPES.	22.67840	9.17782	30.96
	5	5: YOUNGER DEPOSITIONAL SURFACES	7.72927	3.12799	10.55
	6	6: BARE ALLUVIUM	11.99295	4.85348	16.37
	7	7: DISTURBED AREAS	1.33684	0.54101	1.82
7	7: DISTURBED AREAS		3777.16321	1528.59701	73.85
	0	No data.	26.07298	10.55159	0.69
	1	1: PRIMARY STREAM CHANNEL.	39.15733	15.84675	1.04
	2	2: SECONDARY CHANNELS.	26.15017	10.58283	0.69
	3	3: OLD CHANNEL VEGETATION.	46.19966	18.69675	1.22
	4	4: FOREST TYPES.	103.19745	41.76344	2.73
	5	5: YOUNGER DEPOSITIONAL SURFACES	10.06179	4.07195	0.27
	6	6: BARE ALLUVIUM	22.94392	9.28528	0.61
	7	7: DISTURBED AREAS	3503.37991	1417.79842	92.75
TOTAL			5114.40311	2069.77058	100.00

APPENDIX B: HYDROLOGIC ANALYSES

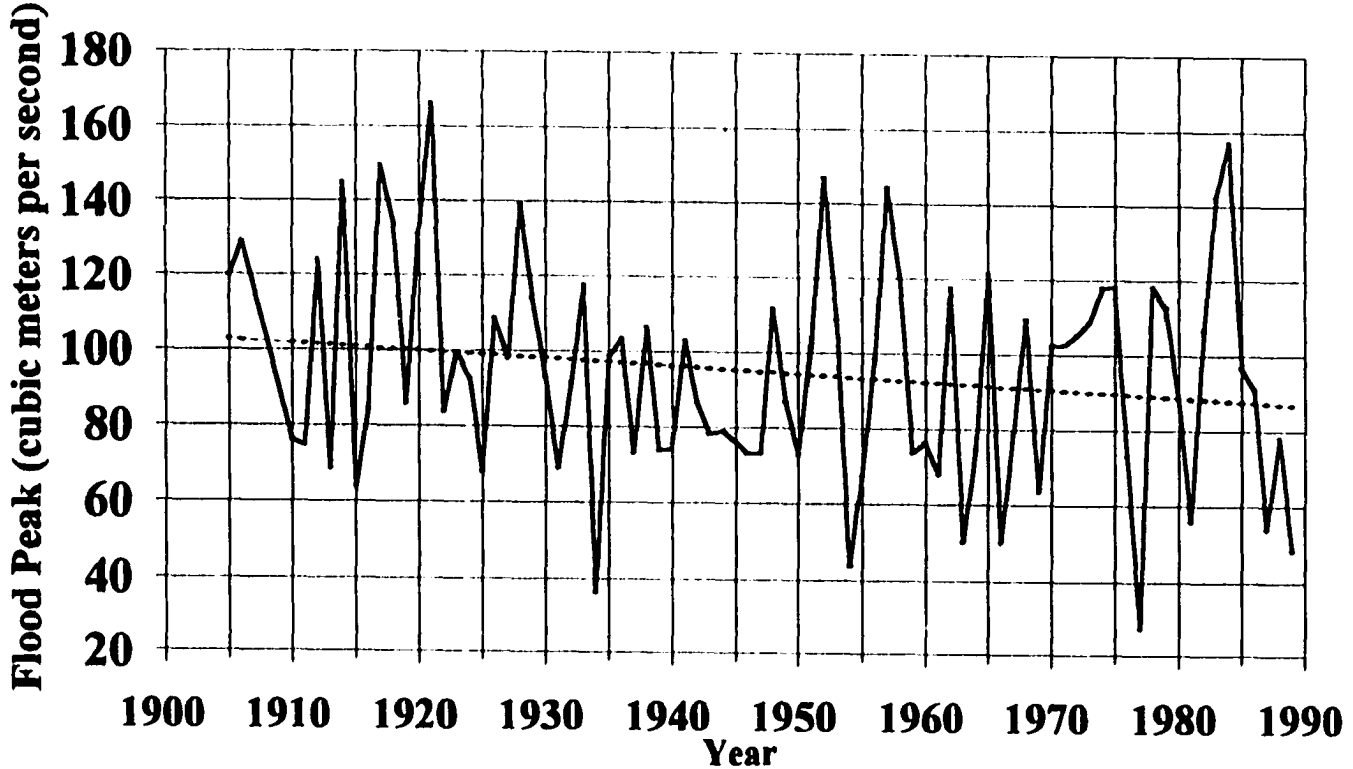

Figure 28. Hydrologic trend analysis: one day flood peaks, Yampa River, Steamboat Springs, 1905-1989

Table 9. Hydrologic trend analysis: Yampa River at Steamboat Springs, 1938-1989.

	Trend Slope	P Value
Month		
January	-0.48	0.25
February	-0.83	0.0025
March	-0.58	0.0025
April	-0.03	0.50
May	-0.10	0.25
June	-0.06	0.50
July	0.12	0.50
August	0.02	0.50
September	-0.48	0.50
October	-0.24	0.50
November	-0.30	0.50
December	-0.14	0.50
High Flows		
1-day	-0.19	0.25
3-day	-0.22	0.10
7-day	-0.22	0.10
30-day	-0.12	0.25
90-day	-0.05	0.50
Low Flows		
1-day	-0.02	0.50
3-day	-0.01	0.50
7-day	-0.01	0.50
30-day	-0.04	0.50
90-day	-0.03	0.50

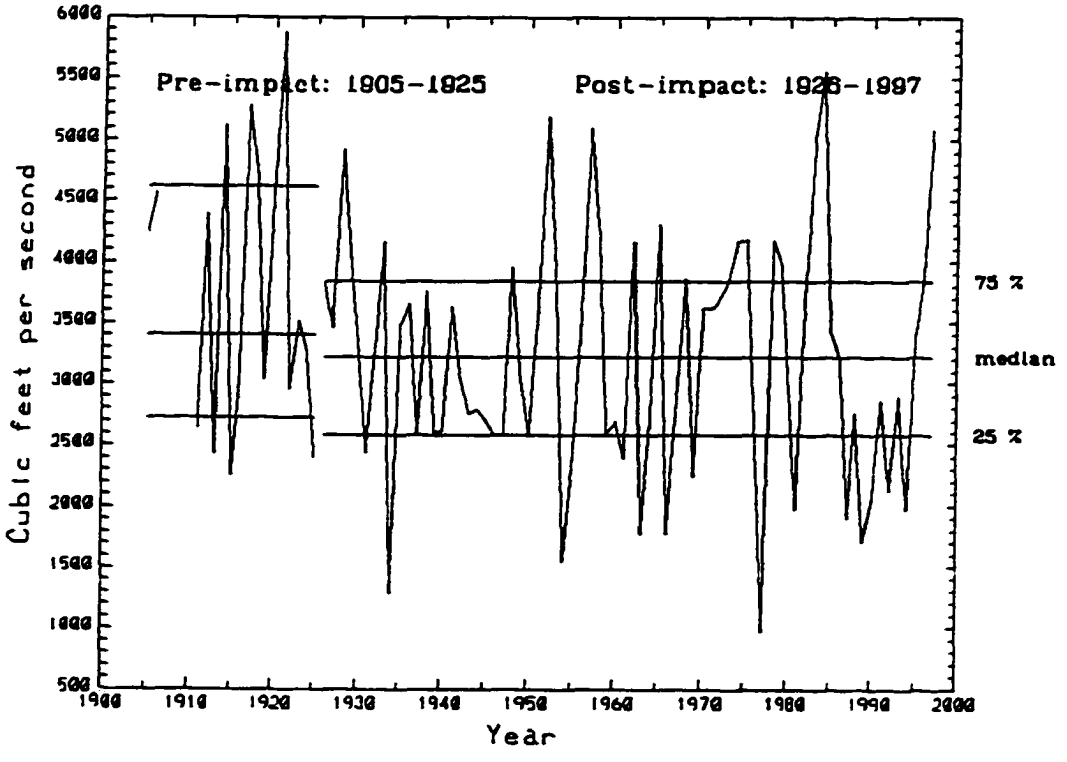

Figure 29. Yampa River one day maximum streamflows 1905-1925 versus 1926-1997.

APPENDIX C: GEOMORPHIC ANALYSES

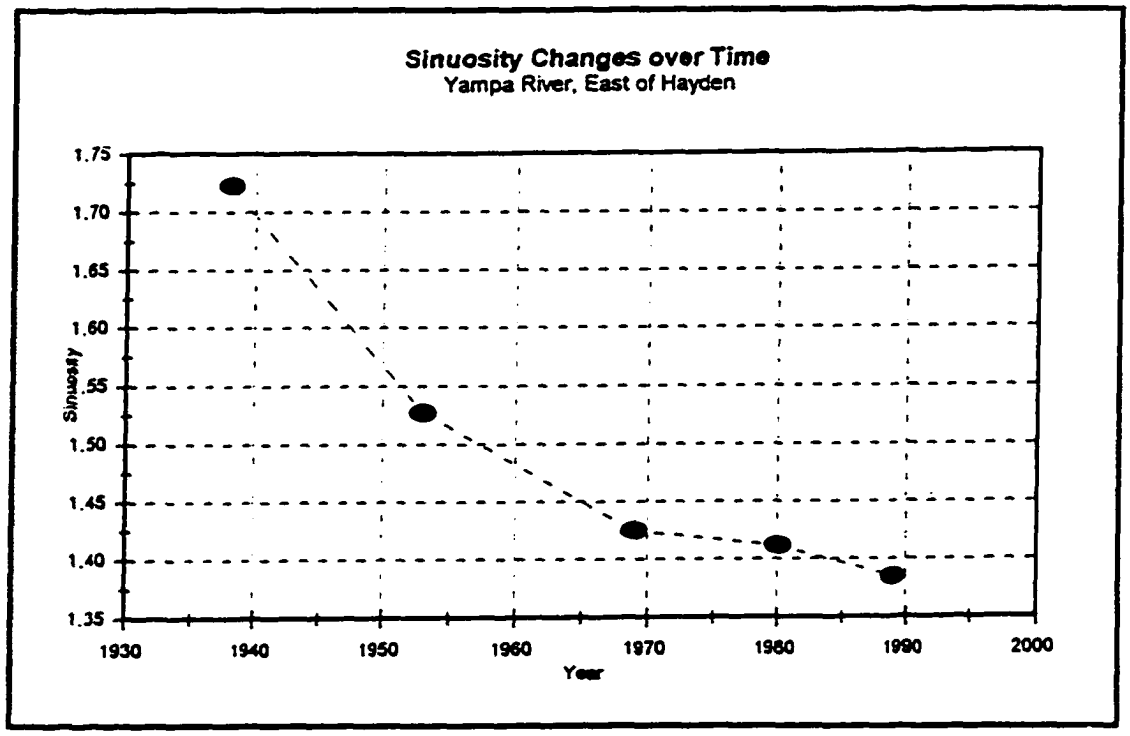

Figure 30. Sinuosity changes (1938-1989), Yampa River, east of Hayden (Ostendorf 1995)

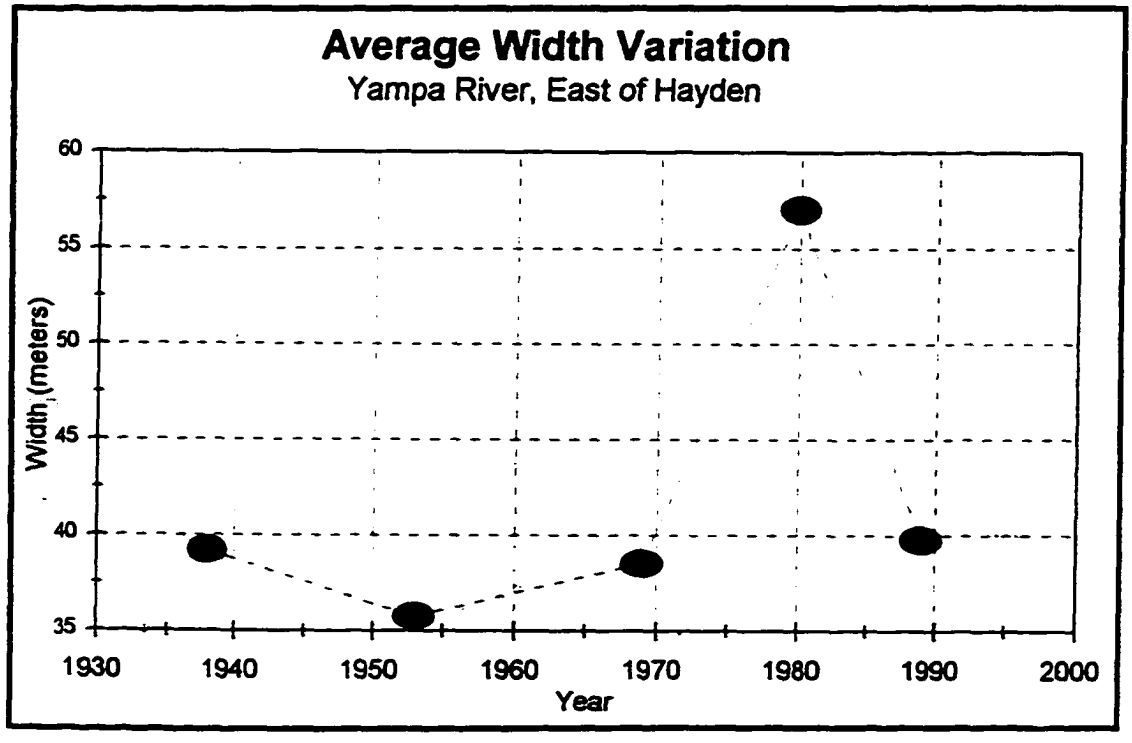

Figure 31. Average stream channel width variation (1938-1989), Yampa River, east of Hayden (Ostendorf 1995).

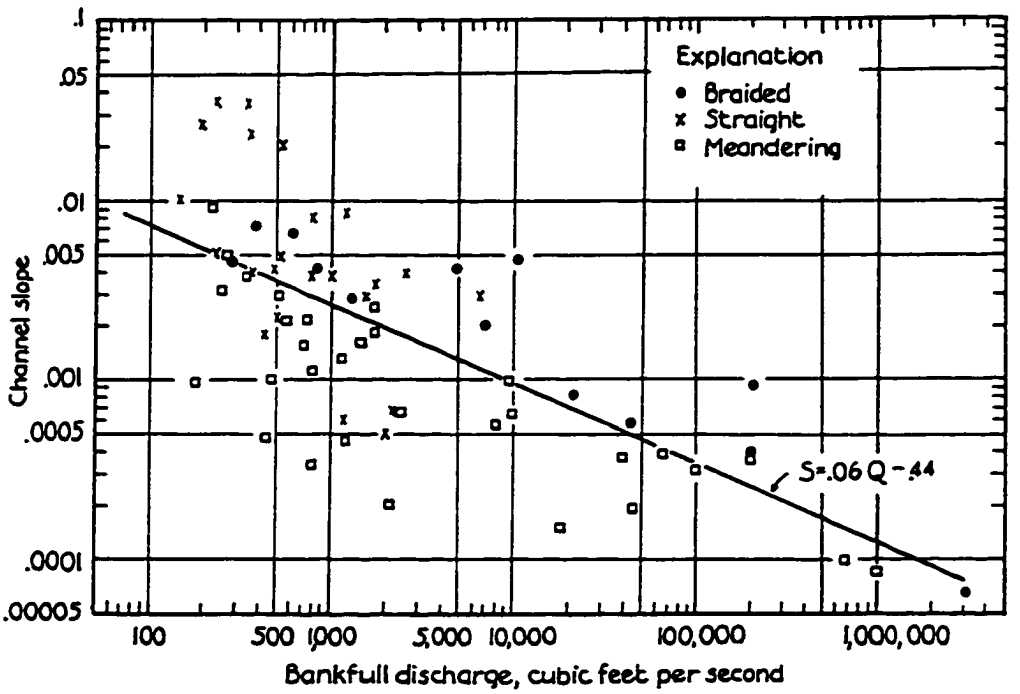

Figure 32. The adjustment of channel form, based on the relationship between slope and bankfull discharge, from Leopold *et al.* 1992. For the Yampa River bankfull discharge is 167 m^3s^{-1}, and channel slope is .0013. These values place the river very near the threshold between a braided and meandering channel form.

APPENDIX D: MACROPLOT VEGETATION DATA

1) The authority for plant names is Weber[1] except for members of the Poaceae which follow Hitchcock[2], Juncaceae which follow Hermann[3], and Carex species which follow Hermann[4]. Species names in parentheses ( ) are species that were not rooted inside the macroplot, but whose canopy covered part of the plot

2) The cover of each species within each plot was initially estimated using seven cover classes (0-1%, 1-5%, 5-25%, 25-50%, 50-75%, 75-95%, 95-100%). For species that occupied mutiple strata within a plot, cover was estimated separately for each strata that the species occupied. Values provided in this appendix are the mid-point of the range of percent cover within each cover class (e.g., 0-1% cover = .5).

3) Macroplots have been subjectively grouped into patch types to provide a general description of the species composition of patch types used within the ecological model. These patch types do not represent a formal classification scheme based upon statistical information.

1. Weber, W.A. 1976. Rocky Mountain flora. Colorado Associated University Press, Boulder. 479 p.

2. Hitchcock, A.S. 1971. Manual of the grasses of the United States, volumes one and two. Second edition revised by Agnes Chase, Dover Publications, New York. 1051 p.

3. Hermann, F.J. 1975. Manual of the rushes (Juncus spp.) of the Rocky Mountains and Colorado Basin. USDA Forest Service General Technical Report RM-18. 107 p.

4. Hermann, F.J. 1970. Manual of the Carices of the Rocky Mountains and Colorado Basin. USDA Forest Service, Agricultural Handbook No. 374. 397 p.

Table 10. Yampa River *Populus angustifolia* seedling patch type, 1992. Values shown represent the mid-point of the range of percent canopy cover within each cover class.

	Mid-point of cover class							
Species	**Plot 11**	**Plot 17**	**Plot 28**	**Plot 34**	**Plot 35**	**Plot 37**	**Plot 42**	**Plot 45**
Tall shrubs								
Populus angustifolia	0.0	0.0	0.0	37.5	0.0	0.0	0.0	0.0
Low shrubs								
Acer negundo	0.0	0.0	0.0	0.5	0.5	0.0	0.0	0.0
Amelanchier utahensis	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Populus angustifolia	15.0	15.0	37.5	0.0	37.5	62.5	37.5	37.5
Salix exigua	0.0	0.5	0.5	0.0	15.0	0.0	3.0	3.0
Graminoids								
Agropyron repens	0.0	0.0	0.0	0.0	0.5	0.0	0.0	0.0
Agrostis gigantea	0.0	0.0	0.0	0.5	0.0	0.0	0.0	0.0
Agrostis stolonifera	0.5	0.0	0.0	0.0	0.0	0.5	0.0	0.0
Agrostis spp.	0.0	0.0	0.0	0.0	3.0	0.0	0.0	0.0
Bromus squarrosus	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Carex athrostachya	0.0	0.0	0.5	0.5	0.5	0.0	0.0	0.5
Carex retrorsa	0.0	0.0	0.0	0.5	0.0	0.0	0.0	0.0
Eleocharis macrostachya	0.0	0.0	0.0	0.0	0.5	0.0	0.0	0.0
Hordeum jubatum	0.0	0.0	0.0	0.5	0.0	0.0	0.0	0.0
Phalaris arundinacea	0.5	0.0	0.5	0.5	0.5	0.5	0.0	0.5
Phleum pratense	0.0	0.5	0.0	0.5	3.0	0.0	0.0	0.0
Poa interior	0.0	0.0	0.0	0.5	0.0	0.0	0.0	0.0
Poa palustris	0.5	0.5	0.5	0.5	0.5	0.5	0.0	0.5
Poa pratensis	0.5	0.0	0.0	0.0	0.0	0.5	0.0	0.0
Forbs								
Amaranthus blitoides	0.0	0.0	0.5	0.0	0.0	0.0	0.0	0.0
Aster ascendens	0.0	0.0	0.0	0.0	0.0	0.5	0.0	0.0

Aster hesperius	0.0	0.0	0.0	0.0	0.5	0.0	0.0	0.0
Barbarea vulgaris	0.0	0.5	0.0	0.5	0.0	0.0	0.0	0.0
Chamaesyce serpyllifolia	0.0	0.0	0.0	0.5	0.0	0.0	0.0	0.0
Chenopodium berlandieri	0.0	0.0	0.5	0.0	0.0	0.0	0.0	0.0
Cirsium arvense	0.0	0.0	0.0	0.5	0.5	0.5	0.0	0.0
Cynoglossum officinale	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Epilobium paniculatum	0.5	0.0	0.0	0.5	0.0	0.0	0.0	0.0
Erigeron divergens ssp. divergens	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Euphorbia serpyllifolia	0.0	0.0	0.0	0.0	0.0	0.5	0.0	0.0
Lepidium virginicum	0.5	0.5	0.0	0.0	0.0	0.0	0.0	0.0
Medicago lupulina	0.5	0.0	0.5	0.5	0.5	0.5	0.0	0.0
Medicago sativa	0.0	0.0	0.5	0.5	0.0	0.0	0.0	0.0
Melilotus officinalis	0.0	0.0	0.0	0.5	0.5	0.0	0.0	0.0
Mentha arvensis	0.0	0.0	0.5	0.5	0.5	0.5	0.0	0.5
Oenothera strigosa	0.0	0.0	0.0	0.5	0.0	0.0	0.0	0.0
Persicaria lapathifolium	0.0	0.0	0.5	0.0	0.0	0.0	0.0	0.0
Persicaria pensylvanica	0.0	0.0	0.0	0.5	0.0	0.0	0.0	0.0
Plantago lanceolata	0.0	0.0	0.0	0.5	0.0	0.0	0.0	0.0
Plantago major	0.0	0.0	0.0	0.5	0.5	0.5	0.5	0.5
Polygonum amphibium	0.5	0.0	0.0	0.5	0.5	0.0	0.0	0.0
Polygonum aviculare	0.0	0.0	0.5	0.0	0.0	0.0	0.0	0.0
Potentilla gracilis	0.0	0.0	0.0	0.0	0.0	0.5	0.0	0.0
Potentilla rivalis	0.0	0.0	0.5	0.0	0.0	0.0	0.0	0.0
Prunella vulgaris	0.0	0.0	0.0	0.0	0.5	0.0	0.0	0.0
Ranunculus cymbalaria	0.0	0.0	0.0	0.0	0.5	0.0	0.0	0.0
Rorippa curvipes	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Rudbeckia lacinata	0.0	0.0	0.0	0.5	0.0	0.0	0.0	0.0
Rumex acetosella	0.5	0.0	0.0	0.5	0.0	0.0	0.0	0.0
Rumex crispus	0.5	0.0	0.5	0.5	0.5	0.0	0.0	0.0
Solidago gigantea	0.0	0.0	0.0	0.5	0.5	0.0	0.0	0.0
Taraxacum officinale	0.5	0.5	0.0	0.5	0.5	0.5	0.5	0.0
Tragopogon dubius	0.0	0.0	0.0	0.5	0.0	0.0	0.0	0.0
Trifolium hybridum	0.0	0.0	0.0	0.5	0.5	0.5	0.5	0.0

Verbascum thapsus	0.5	0.0	0.0	0.5	0.0	0.0	0.0	0.0
Xanthium strumarium	0.0	0.0	0.0	0.0	0.5	0.0	0.0	0.0
Ferns and allies								
Equisetum arvense	0.0	0.0	0.5	0.5	0.5	0.0	0.5	0.0
Equisetum hyemale	0.0	0.0	0.0	0.0	0.5	0.0	0.0	0.0

Comments: Other species found in these sites include: Chenopodium capitatum, Matricaria perforata, Urtica dioica, and Verbena bractea.

Table 11. Yampa River *Populus angustifolia* pole stand patch type, 1992. Values shown represent the mid-point of the range of percent canopy cover within each cover class.

Species	Mid-point of cover class				
	Plot 24	Plot 25	Plot 30	Plot 43	Plot 44
Trees (Canopy)					
Populus angustifolia	15.0	15.0	62.5	15.0	62.5
Tall shrubs					
Populus angustifolia	0.0	0.0	3.0	0.0	0.0
Salix exigua	0.0	0.0	37.5	0.0	0.0
Low shrubs					
Acer negundo	0.0	0.0	0.5	0.5	0.0
Cornus sericea	0.5	0.0	0.5	0.5	0.0
Crataegus rivularis	0.0	0.0	0.0	0.0	0.5
Populus angustifolia	15.0	0.0	0.5	0.5	0.5
Rosa woodsii	0.0	0.0	0.0	0.0	0.5
Salix exigua	0.0	0.0	0.0	0.5	3.0
Graminoids					
Agropyron repens	0.5	0.0	0.5	3.0	0.0
Agropyron trachycaulum	0.0	0.5	0.0	0.0	0.0
Agrostis gigantea	15.0	0.5	0.5	0.0	0.0
Agrostis stolonifera	0.0	0.0	0.0	0.5	0.5
Bromus inermis	0.5	0.5	0.0	3.0	0.0
Dactylis glomerata	0.0	0.5	0.5	0.0	0.0
Festuca elatior	0.5	0.0	0.5	0.0	3.0
Juncus interior	0.0	0.5	0.0	0.0	0.0
Phalaris arundinacea	0.0	0.0	0.0	0.5	0.0
Phleum pratense	0.5	0.5	15.0	3.0	15.0
Poa compressa	0.0	0.0	0.0	15.0	3.0
Poa palustris	0.5	0.0	0.5	0.5	0.0
Poa pratensis	3.0	3.0	0.5	0.0	0.0

Forbs					
Achillea lanulosa	0.5	0.5	0.0	0.5	0.0
Arctium minus	0.0	0.0	0.5	0.0	0.0
Arnica chamissonis ssp. foliosa	0.0	0.0	0.0	0.0	0.5
Artemisia ludoviciana	0.0	0.5	0.0	0.5	0.0
Cicuta douglasii	0.0	0.0	0.5	0.0	0.0
Cirsium arvense	0.5	0.5	0.5	0.5	15.0
Cirsium vulgare	0.0	0.0	0.5	0.0	0.0
Cynoglossum officinale	0.5	0.5	0.0	0.5	0.5
Epilobium ciliatum	0.0	0.0	0.5	0.0	0.0
Erigeron sp.	0.0	0.5	0.0	0.0	0.0
Fragaria ovalis	0.0	0.0	0.0	0.0	0.5
Geum macrophyllum	0.0	0.0	0.0	0.0	0.5
Heracleum lanatum	0.0	0.5	0.5	0.0	0.5
Lactuca serriola	0.0	0.5	0.0	0.0	0.0
Lepidium virginicum	0.0	0.0	0.5	0.0	0.0
Ligusticum filicinum	0.0	0.0	0.5	0.0	0.0
Lysimachia ciliata	0.0	0.0	0.0	0.0	0.5
Medicago lupulina	0.5	15.0	0.5	3.0	3.0
Medicago sativa	0.0	0.0	0.5	0.0	0.0
Melilotus officinalis	0.0	0.5	0.5	0.5	0.0
Plantago major	0.0	0.0	0.5	0.0	0.0
Polygonum amphibium	0.0	0.0	0.5	0.0	0.0
Potentilla rivalis	0.0	0.0	0.0	0.5	0.5
Rudbeckia laciniata	0.0	0.0	0.5	0.0	0.5
Rumex crispus	0.0	0.0	0.5	0.0	0.0
Smilicina stellata	0.0	0.5	0.0	0.0	0.0
Solidago giganteum	3.0	0.5	0.5	3.0	0.5
Taraxacum officinale	3.0	0.5	3.0	0.5	0.5
Tragopogon dubius	0.0	0.5	0.5	0.5	0.0
Trifolium hybridum	0.5	0.5	15.0	0.0	15.0
Verbascum thapsus	0.0	0.0	0.5	0.0	0.0
Vicia americana	0.0	0.5	0.0	0.5	0.5

Ferns and allies					
Equisetum arvense	0.0	0.0	0.0	0.0	0.5

Comments: Other species found in these sites include: Aster ascendens, Chrysanthemum leucanthemum, and Sidalcea nemexicana.

Table 12. Yampa River mature *Populus angustifolia* patch type, 1992. Values shown represent the mid-point of the range of percent canopy cover within each cover class.

Species	Mid-point of cover class							
	Plot 3	Plot 5	Plot 10	Plot 15	Plot 18	Plot 27	Plot 31	Plot 32
Trees								
(Canopy)								
Populus angustifolia	62.5	15.0	37.5	15.0	37.5	15.0	37.5	15.0
(Subcanopy)								
Acer negundo	62.5	15.0	15.0	15.0	15.0	3.0	0.0	37.5
Amelanchier utahensis	0.0	0.0	0.0	0.0	0.0	0.0	3.0	0.0
Crataegus rivularis	3.0	0.0	0.0	0.0	3.0	0.0	15.0	15.0
Populus angustifolia	0.0	0.0	0.0	0.0	0.0	0.0	15.0	0.0
Prunus virginiana	0.0	0.0	0.0	0.0	3.0	0.0	15.0	0.0
Tall shrubs								
Acer negundo	0.0	3.0	0.0	3.0	3.0	0.5	0.5	0.0
Amelanchier utahensis	0.5	0.0	0.0	0.5	0.0	0.0	0.0	3.0
Cornus sericea	0.0	15.0	62.5	15.0	37.5	3.0	0.0	0.0
Crataegus rivularis	0.0	5.0	0.0	0.0	0.0	0.0	0.0	0.0
Prunus virginiana	0.0	0.0	0.0	0.5	0.0	0.0	0.0	3.0
Rosa woodsii	0.0	0.0	0.0	0.5	0.5	0.5	0.0	0.0
Salix bebbiana	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5
Salix exigua	0.0	0.0	0.0	0.5	0.0	0.0	0.0	0.0
Salix lasiandra	0.0	0.0	0.0	0.0	0.0	3.0	0.0	0.0
Low shrubs								
Acer negundo	15.0	37.5	0.0	3.0	3.0	0.0	0.5	0.0
Amelanchier utahensis	0.0	0.5	0.5	0.5	3.0	0.0	0.5	0.5
Cornus sericea	15.0	37.5	0.0	15.0	15.0	3.0	0.5	0.5
Crataegus rivularis	0.0	0.0	0.5	0.5	0.5	0.0	0.0	0.0
Populus angustifolia	0.5	0.0	0.0	0.0	0.5	0.0	0.5	0.0

Populus tremuloides	0.5	0 0	0 0	0 0	0 0	0 0	0 0	0 0
Prunus virginiana	0.0	0 0	0 5	0 5	0 5	0 0	0.0	0.5
Ribes aureum	0.0	3 0	0 5	0 0	0 0	0.0	0.0	0 0
Ribes inerme	0.5	0 0	0 5	0 5	0 5	0 0	0.5	0 0
Rosa woodsii	0.5	0 5	0 5	0 5	0 5	0.5	0 5	0 5
Rubus idaeus	0.0	0 0	0 0	0 0	0 0	0 0	0.5	0 0
Salix bebbiana	0.0	0 0	0 0	0 0	0 0	0 5	0 0	0 0
Salix exigua	0 0	0 0	0 0	0.0	0 0	0 5	0 0	0.0
Symphoricarpus oreophilus	0.5	0 5	0 0	3 0	0 0	0 0	0 0	0 0
Graminoids								
Agrostis gigantea	0 0	0 0	0 0	0 0	0 0	0 0	0 5	0 5
Agropyron repens	0.0	0 0	0 0	0 0	0 0	0 5	0 0	0 0
Bromus inermis	0.5	0 0	0 5	3 0	0 5	3 0	0 5	0 0
Bromus sp.	0.0	0 0	0 0	0 0	0 5	0 0	0 0	0 0
Carex athrostachya	0.5	0 0	0 0	0 0	0 0	0 0	0 0	0 5
Carex lanuginosa	0.5	0 0	0 0	0 0	0 0	0 0	0 0	0 0
Carex praticola	0.0	0 0	0 0	0 0	0 5	0 0	0 0	0 5
Carex microptera	0.0	0 0	0 0	0 0	0 5	0 0	0 0	0 5
Dactylis glomerata	0 5	0 0	0 5	0 0	0 0	0 5	0 5	0 0
Elymus canadensis	0 0	0 5	0 0	0.0	0 5	0 0	0 5	0 0
Elymus virginicus	0 0	0 0	0 0	0 0	0 0	0 0	0 5	0 5
Festuca elatior	0 0	0 0	0 0	0 0	0 0	0 0	0 0	0 5
Phalaris arundinacea	0 5	0 0	0 0	0 5	0 0	0 5	0 0	0 5
Phleum pratense	0 0	0 0	0 0	0 0	0 0	3 0	0 5	0 5
Poa compressa	0 5	0 5	0 0	0 0	0 0	0 0	0 0	0 0
Poa interior	0 0	0 0	0 0	0 0	0 0	0 0	0 5	0 5
Poa palustris	0 5	0 0	0 0	0 0	0 5	0 5	0 0	0 5
Poa pratensis	0 0	0 0	0 0	0 5	0 0	0 5	0 5	0 5
Poa sp.	15.0	3 0	0 0	0 0	0 0	0 0	0 5	0 0

Forbs								
Achillea lanulosa	0.0	0.0	0.0	0.0	0.0	0.5	0.0	0.0
Arctium minus	0.0	0.0	0.0	0.5	0.0	0.0	3.0	0.5
Artemisia ludoviciana	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5
Aster hesperius	0.0	0.0	0.0	0.0	0.0	0.5	0.0	0.5
Barbarea vulgaris	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.5
Chrysanthemum leucanthemum	0.0	0.5	0.0	0.0	0.0	0.5	0.0	0.0
Cirsium arvense	0.5	0.5	0.5	0.0	0.5	3.0	0.5	15.0
Cirsium vulgare	0.0	0.0	0.0	3.0	0.0	0.0	0.0	0.0
Clematis ligusticifolia	0.0	0.0	0.0	0.5	0.0	0.0	0.0	0.0
Corallorhiza maculata	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.5
Cynoglossum officinale	0.0	0.0	0.5	3.0	0.0	0.0	0.5	0.5
Epilobium ciliatum	0.0	0.0	0.0	0.0	0.5	0.0	0.5	0.5
Fragaria ovalis	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Galium boreale	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.5
Geum macrophyllum	0.5	0.0	0.0	0.0	0.5	0.0	0.0	0.5
Hackelia floribunda	0.0	0.0	0.5	0.0	0.0	0.0	0.0	0.0
Heracleum lanatum	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.5
Humulus lupulus	0.0	0.0	0.0	0.0	0.5	0.0	0.0	0.0
Lysimachia ciliata	0.5	0.0	0.0	0.5	0.5	0.5	0.5	0.5
Medicago lupulina	0.0	0.0	0.0	0.0	0.0	0.5	0.0	0.0
Melilotus officinalis	0.0	0.0	0.0	0.0	0.0	0.5	0.0	0.0
Mentha arvensis	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5
Oenothera strigosa	0.0	0.0	0.0	0.0	0.0	0.5	0.0	0.0
Osmorhiza chilensis	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.5
Polygonum amphibium	0.0	0.0	0.0	0.5	0.0	0.0	0.0	0.0
Potentilla gracilis	0.0	0.0	0.0	0.0	0.0	0.5	0.0	0.0
Prunella vulgaris	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Ranunculus macounii	0.5	3.0	0.5	0.0	0.5	0.0	0.0	0.0
Rudbeckia laciniata	0.0	0.0	0.0	0.5	0.0	0.5	3.0	0.5
Rumex crispus	0.5	0.5	0.0	0.5	0.0	0.0	0.0	0.5
Rumex salicifolius	0.0	0.0	0.0	0.0	0.5	0.0	0.0	0.0
Scrophularia lanceolata	0.0	0.0	0.0	0.5	0.0	0.0	0.0	0.0

Senecio eremophilus	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5
Sidalcea candida	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Silene latifolia ssp. alba	0.0	0.0	0.0	0.0	0.0	0.5	0.0	0.0
Smilicina stellata	15.0	3.0	3.0	3.0	3.0	0.5	0.5	0.5
Solidago gigantea	0.0	0.5	0.0	0.0	0.0	3.0	3.0	15.0
Taraxacum officinale	0.0	0.5	0.5	0.5	0.0	0.5	0.0	0.5
Thalictrum fendleri	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.0
Tragopogon dubius	0.0	0.0	0.0	0.0	0.5	0.5	0.0	0.0
Trifolium hybridum	0.0	0.0	0.0	0.0	0.0	0.5	0.0	0.5
Urtica dioica	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.0
Verbascum thapsus	0.0	0.0	0.0	0.0	0.0	0.5	0.0	0.5
Veronica americana	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Vicia americana	0.0	0.0	0.0	0.5	0.0	0.5	0.0	0.0
Ferns and allies								
Equisetum hyemale	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Comments: Other species found in these sites include: Solanum dulcamara, Stachys palustris, Poa palustris, Veronica wormskjoldii, and Carex sprengelii.

Table 13. Yampa River transitional stands between mature *Populus angustifolia* and *Acer negundo* patch types, 1992. Values shown represent the mid-point of the range of percent canopy cover within each cover class

Species	Mid-point of cover class Plot 6	Plot 7
Trees		
(Canopy)		
Populus angustifolia	15.0	37.5
(Subcanopy)		
Acer negundo	37.5	15.0
Populus tremuloides	3.0	0.0
Tall shrubs		
Acer negundo	0.0	3.0
Cornus sericea	37.5	3.0
Low shrubs		
Amelanchier utahensis	0.5	0.0
Cornus sericea	15.0	0.5
Crataegus rivularis	0.5	0.0
Populus tremuloides	0.5	0.0
Prunus virginiana	0.0	0.5
Ribes inerme	0.5	0.5
Rosa woodsii	0.5	0.5
Graminoids		
Bromus inermis	0.5	0.5
Carex microptera	0.5	0.0
Carex praticola	0.5	0.0
Carex lanuginosa	0.5	0.0
Dactylis glomerata	3.0	15.0
Elymus canadensis	0.0	0.5

Phalaris arundinacea	0.5	0.0
Poa compressa	0.0	0.5
Poa sp.	62.5	0.0
Forbs		
Chrysanthemum leucanthemum	0.5	0.0
Cirsium arvense	0.5	3.0
Corallorhiza maculata	0.0	0.5
Cynoglossum officinale	0.0	3.0
Hackelia floribunda	0.0	0.5
Lysimachia ciliata	3.0	0.0
Melilotus officinalis	0.5	0.0
Osmorhiza chilensis	0.0	15.0
Plantago major	0.5	0.0
Prunella vulgaris	0.5	0.0
Ranunculus macounii	0.5	0.5
Rudbeckia laciniata	0.0	37.5
Rumex acetosella	0.5	0.0
Rumex crispus	0.5	0.0
Scrophularia lanceolata	0.5	0.0
Smilicina stellata	15.0	3.0
Solidago gigantea	3.0	3.0
Taraxacum officinale	0.5	0.0
Thermopsis divaricarpa	0.5	0.0
Thalictrum fendleri	0.5	0.5
Tragopogon dubius	0.5	0.0
Urtica dioica	0.0	3.0
Veronica serpyllifolia	0.5	0.0

Ferns and allies		
Equisetum hyemale	0.5	0.0

Comments: Another species found in these sites is Fragaria ovalis

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Table 14. Yampa River *Acer negundo* patch type, 1992. Values shown represent the mid-point of the range of percent canopy cover within each cover class.

Species	Mid-point of cover class: Plot 4	Plot 19
Trees		
(Canopy)		
Acer negundo	0.0	2.5
Populus angustifolia	15.0	3.0
(Subcanopy)		
Acer negundo	85.0	0.0
Tall shrubs		
Acer negundo	3.0	3.0
Cornus sericea	0.5	15.0
Crataegus rivularis	0.0	0.0
Lonicera involucrata	0.0	0.5
Low shrubs		
Acer negundo	3.0	3.0
Amelanchier utahensis	0.5	0.5
Cornus sericea	15.0	3.0
Crataegus rivularis	0.0	0.5
Lonicera involucrata	0.0	0.5
Populus angustifolia	3.0	0.0
Prunus virginiana	0.0	0.5
Ribes aureum	0.0	0.0
Rosa woodsii	0.5	0.5
Salix lasiandra	0.0	0.5
Symphoricarpus oreophilus	0.0	0.0
Graminoids		
Carex microptera	0.5	0.0

Carex praticola	0.5	0.0
Carex sprengelii	0.5	0.0
Carex athrostachya	0.5	0.0
Phalaris arundinacea	0.5	3.0
Poa pratensis	0.5	0.0
Poa palustris	0.5	0.0
Forbs		
Chrysanthemum leucanthemum	0.5	0.0
Cirsium arvense	0.5	0.5
Geum macrophyllum	0.0	0.5
Lysimachia ciliata	3.0	0.5
Ranunculus macounii	0.5	0.0
Rumex crispus	0.5	0.0
Sidalcea candida	0.0	0.5
Smilicina stellata	3.0	0.5
Solidago gigantea	0.5	0.5
Stachys palustris	0.5	0.0
Taraxacum officinale	0.5	0.0
Thalictrum fendleri	0.0	0.5
Veronica serpyllifolia	0.5	0.0

Comments: Other species found in these sites include: Populus tremuloides, Salix bebbiana, Verbascum thapsus, and Articum minus.

Table 15. Yampa River *Cornus sericea* patch type, 1992. Values shown represent the mid-point of the range of percent canopy cover within each cover class.

Species	Mid-point of cover class Plot 1	Plot 14	Plot 21
Trees			
Canopy			
(Acer negundo)	3.0	0.0	0.0
Tall shrubs			
Cornus sericea	85.0	85.0	62.5
Low shrubs			
Acer negundo	0.5	0.0	0.0
Amelanchier utahensis	0.0	0.0	0.5
Cornus sericea	0.5	0.0	0.0
Crataegus rivularis	0.5	0.0	0.0
Populus angustifolia	0.0	0.0	0.5
Prunus virginiana	0.5	0.0	0.5
Ribes inerme	0.5	0.0	0.5
Rosa woodsii	0.5	0.0	0.5
Rubus idaeus	0.0	0.0	0.5
Salix exigua	0.0	0.5	0.5
Graminoids			
Agrostis gigantea	0.0	0.0	0.5
Carex praticola	0.5	0.0	0.0
Carex sprengelii	0.0	0.0	0.5
Dactylis glomerata	0.5	0.0	0.0
Glyceria striata	0.0	0.0	0.5
Phalaris arundinacea	0.0	0.5	0.5
Poa palustris	0.0	0.5	3.0
Poa pratensis	0.0	0.0	0.5

Forbs			
Cirsium arvense	0.0	0.5	0.5
Cynoglossum officinale	0.0	0.0	0.5
Epilobium ciliatum	0.0	0.0	0.5
Geum macrophyllum	0.5	0.0	0.0
Lysimachia ciliatum	0.0	0.0	0.5
Oenothera strigosa	0.0	0.0	0.5
Ranunculus macounii	0.0	0.0	0.5
Scrophularia lanceolata	0.0	0.0	0.5
Smilicina stellata	0.5	0.0	0.0
Taraxacum officinale	0.0	0.0	0.5
Tragopogon dubius	0.0	0.0	0.5
Urtica dioica	0.0	0.5	0.0
Verbascum thapsus	0.0	0.0	0.5
Ferns and allies			
Equisetum arvense	0.0	0.0	0.5

Comments: Another species found at these sites is Carex retrorsa

Table 16. Yampa River overflow channel patch type, 1992 Values shown represent the mid-point of the range of percent canopy cover within each cover class.

Species	Mid-point of cover class Plot 8	Plot 36
Trees		
Canopy		
(Acer negundo)	0.0	15.0
(Populus angustifolia)	0.0	37.5
Tall Shrubs		
Cornus sericea	0.0	0.5
Ribes aureum	0.0	3.0
Salix exigua	3.0	0.0
Low shrubs		
Cornus sericea	0.0	0.5
Crataegus rivularis	0.0	0.5
Rosa woodsii	0.0	0.5
Graminoids		
Agropyron repens	0.5	0.0
Carex athrostachya	0.5	0.5
Carex retrorsa	3.0	15.0
Carex lanuginosa	0.0	0.5
Carex praticola	0.0	0.5
Cyperus microcarpus	0.5	0.0
Eleocharis macrostachya	3.0	0.0
Elymus virginicus	0.0	0.5
Festuca elatior	0.0	0.5
Glyceria borealis	3.0	0.0
Glyceria grandis	0.5	0.0
Phalaris arundinacea	0.5	0.0
Phleum pratense	0.0	0.5

Poa palustris	0.5	0.5
Poa pratensis	0.0	0.5
Forbs		
Cicuta douglasii	0.0	0.5
Cirsium arvense	0.0	0.5
Epilobium ciliatum	0.0	0.5
Fragaria ovalis	0.0	0.5
Geum macrophyllum	0.0	0.5
Lysimachia ciliatum	0.0	0.5
Mentha arvensis	0.0	0.5
Polygonum amphibium	0.5	0.5
Ranunculus gmelinii var. hookeri	0.5	0.0
Rumex crispus	0.5	0.5
Sagittaria sp.	0.5	0.0
Smilcina stellata	0.0	0.5
Solidago gigantea	0.0	0.5
Ferns and allies		
Equisetum hyemale	0.0	0.5
Isoetes sp.	0.5	0.0

Table 17. Yampa River herbaceous marsh patch type, 1992 Values shown represent the mid-point of the range of percent canopy cover within each cover class.

Species	Mid-point of cover class			
	Plot 2	Plot 13	Plot 20	Plot 38
Low shrubs				
Salix exigua	0.5	3 0	37 5	0 5
Salix lasiandra	0.5	0 5	0 0	0 5
Graminoids				
Agrostis gigantea	0.0	0 0	0 0	0 5
Alopecurus aequalis	0.0	0 5	0 5	0 5
Beckmannia syzigachne	0.5	0 0	0 0	0 5
Carex aquatilis	0.0	0 5	0 0	0 0
Carex athrostachya	0.5	0 0	0 0	3 0
Carex retrorsa	3.0	0 0	0 0	3 0
Cyperus microcarpus	0.0	3 0	0 5	0 0
Eleocharis macrostachya	62.5	3 0	3 0	3 0
Glyceria borealis	0.0	0 0	0 0	0 5
Glyceria grandis	3.0	3 0	0 5	0 5
Hordeum jubatum	0.0	0 0	0 0	0 5
Juncus articulatus	0.0	0 0	0 5	0 0
Juncus bufonius	0.0	0 0	0 0	0 5
Juncus saximontanus	0.0	0 0	0 0	0 5
Juncus interior	0.0	0 0	0 0	0 5
Phalaris arundinacea	3.0	85 0	62 5	3 0
Poa pratensis	0.0	0 0	0 5	0 0
Forbs				
Alisma triviale	0.0	0 0	0 0	0 5
Barbarea vulgaris	0.0	0 0	0 0	0 5
Bidens cernua	0.0	0 0	0 0	0 5

Chrysanthemum leucanthemum	0.0	0.0	0.0	0.5
Cirsium spp.	0.0	0.0	0.0	0.5
Epilobium ciliatum	0.0	0.0	0.0	0.5
Gnaphalium palustris	0.0	0.0	0.0	0.5
Mentha arvensis	0.5	3.0	3.0	62.5
Persicaria pensylvanica	0.0	0.0	0.0	0.5
Plantago major	0.0	0.0	3.0	0.5
Polygonum amphibium	0.5	0.0	0.5	0.5
Potentilla rivalis	0.0	0.0	0.0	0.5
Ranunculus cymbalaria	0.0	0.0	0.0	0.5
Ranunculus macounii	0.0	0.0	0.5	0.5
Rorippa curvipes	0.0	0.0	0.5	0.5
Rumex crispus	0.0	0.0	0.0	0.5
Rumex maritimus ssp. fueginus	0.0	0.0	0.0	0.5
Rumex salicifolius	0.0	0.0	0.5	0.0
Sagittaria	0.5	0.5	0.5	0.0
Sium suave	0.0	0.0	0.0	0.5
Trifolium hybridum	0.0	0.0	0.5	0.0
Typha latifolia	0.0	0.0	0.5	0.5
Veronica americana	0.0	0.0	0.5	0.5
Veronica catenata	0.0	0.0	0.0	0.5
Ferns and allies				
Equisetum arvense	0.5	0.5	37.5	3.0
True aquatic plants				
Elodea canadensis	3.0	0.0	0.5	0.0

Comments: The submerged aquatic species, Elodea canadensis, is commonly associated with shallow still water habitats adjacent to or within these areas

Table 18. Yampa River *Salix exigua* patch type, 1992. Values shown represent the mid-point of the range of percent canopy cover within each cover class.

Species	Mid-point of cover class			
	Plot 9	Plot 12	Plot 16	Plot 29
Tall shrubs				
Salix exigua	85.0	37.5	62.5	37.5
Salix lasiandra	0.0	3.0	0.0	0.0
Rosa woodsii	0.0	0.0	0.0	0.5
Low shrubs				
Cornus sericea	0.0	0.5	0.5	0.0
Crataegus rivularis	0.0	0.0	0.0	0.5
Rosa woodsii	0.0	0.0	0.0	0.5
Graminoids				
Agropyron repens	0.0	0.5	0.0	0.5
Agrostis stolonifera	0.0	0.0	0.0	0.5
Bromus inermis	0.5	0.5	0.0	0.0
Carex microptera	0.0	0.5	0.0	0.0
Carex praticola	0.0	0.0	0.0	0.5
Dactylis glomerata	0.0	0.0	0.0	0.5
Phalaris arundinacea	15.0	15.0	15.0	3.0
Phleum pratense	0.0	0.5	0.0	0.5
Poa pratensis	0.0	0.5	0.0	0.0
Poa palustris	0.0	3.0	3.0	0.5
Poa sp.	0.5	0.0	0.0	0.0
Forbs				
Artemisia ludoviciana	0.0	0.0	0.0	0.5
Aster hesperius	0.0	0.0	0.0	0.5

Barbarea vulgaris	0.0	0.5	0.5	0.5
Chrysanthemum leucanthemum	0.0	0.5	0.0	0.5
Cirsium arvense	0.5	0.5	15.0	15.0
Cynoglossum officinale	0.0	0.0	3.0	0.5
Humulus lupulus	0.5	0.0	0.0	0.0
Lactuca serriola	0.0	0.0	0.0	0.5
Lepidium virginicum	0.0	0.5	0.0	0.0
Lysimachia ciliata	0.5	0.0	0.0	0.0
Mentha arvensis	0.0	0.5	0.0	0.0
Plantago lanceolata	0.0	0.0	0.0	0.5
Plantago major	0.0	0.5	0.0	0.0
Polygonum amphibium	0.0	0.0	0.0	0.5
Ranunculus macounii	0.0	0.5	0.0	0.5
Rudbeckia laciniata	0.0	0.5		
Rumex crispus	0.0	0.0	0.0	0.5
Scutellaria galericulata	0.0	0.0	0.0	0.5
Solidago gigantea	15.0	0.5	0.5	0.5
Stachys palustris	0.0	0.5	0.0	0.0
Taraxacum officinale	0.0	0.0	0.0	3.0
Tragopogon dubius	0.0	0.0	0.0	0.5
Verbascum thapsus	0.0	0.0	0.0	0.5
Ferns and allies				
Equisetum arvense	0.0	0.5	0.0	0.0

Comments: Other species that occur in these sites are Senecio eremophilus, Aster falcatus ssp. commutatus, Arctium minus, Silene latifolia ssp alba, Potentilla gracilis, Glycyrrhiza lepidota, Erigeron divergens ssp. divergens, Oenothera strigosa, Medicago lupulina, and Heracleum sphondylium.

Table 19. Yampa River emergent marsh patch type, 1992. Values shown represent the mid-point of the range of percent canopy cover within each cover class.

Species	Mid-point of cover class: Plot 23	Plot 41
Low shrubs		
Salix exigua	0.0	0.5
Graminoids		
Carex retrorsa	0.5	0.0
Eleocharis macrostachya	0.0	0.5
Glyceria grandis	0.0	0.5
Phalaris arundinacea	3.0	3.0
Forbs		
Polygonum amphibium	0.5	0.0
Typha latifolia	37.5	85.0

Table 20. Yampa River *Salix lasiandra* patch type, 1992. Values shown represent the mid-point of the range of percent canopy cover within each cover class.

Species	Mid-point of cover class Plot 22	Plot 26
Tall Shrubs		
Salix lasiandra	62.5	85.0
Low shrubs		
Acer negundo	0.5	0.0
Cornus sericea	0.5	0.0
Graminoids		
Carex athrostachya	0.5	0.0
Carex retrorsa	3.0	37.5
Carex praticola	0.5	0.0
Phalaris arundinacea	37.5	0.5
Poa compressa	0.5	0.0
Poa palustris	0.0	0.5
Poa pratensis	0.0	0.5
Forbs		
Epilobium ciliatum	0.5	0.0
Geum macrophyllum	0.5	0.5
Lysimachia ciliatum	0.5	0.0
Mentha arvensis	3.0	0.5
Polygonum amphibium	0.5	3.0
Rumex crispus	0.5	0.0

Table 21. Yampa River oxbow lake banks patch type, 1992. Values shown represent the mid-point of the range of percent canopy cover within each cover class.

Species	Mid-point of cover class Plot 39	Plot 40
Tall shrubs		
Alnus tenuifolia	0.5	0.0
Populus angustifolia	0.0	15.0
Salix exigua	15.0	3.0
Salix lasiandra	3.0	0.0
Low shrubs		
Cornus sericea	0.5	0.0
Populus angustifolia	0.5	0.0
Rosa woodsii	0.5	0.0
Salix bebbiana	0.5	0.0
Salix exigua	37.5	15.0
Salix lasiandra	3.0	0.0
Graminoids		
Agrostis gigantea	0.5	0.5
Bromus inermis	0.0	0.5
Carex athrostachya	0.5	0.0
Carex lanuginosa	0.0	3.0
Carex microptera	0.5	0.0
Carex nebraskensis	3.0	0.0
Cyperus microcarpus	3.0	0.0
Eleocharis macrostachya	3.0	0.0
Hordeum jubatum	0.5	0.0
Juncus longistylis	0.5	0.0
Phalaris arundinacea	3.0	0.0
Phleum pratense	0.5	0.5
Poa palustris	15.0	0.5
Poa pratensis	0.0	15.0

	Scirpus validus	0.5	0.0
Forbs			
	Cirsium arvense	0.5	0.5
	Geum macrophyllum	0.5	0.0
	Lysimachia ciliata	0.0	0.5
	Melilotus officinalis	0.5	0.0
	Mentha arvensis	0.5	0.0
	Plantago major	0.5	0.0
	Polygonum amphibium	0.5	0.5
	Rumex crispus	0.5	0.5
	Smilicina stellata	0.0	0.5
	Solidago giganteum	3.0	3.0
	Taraxacum officinale	0.5	0.0
	Trifolium hybridum	0.5	0.5
	Vicia americana	0.5	0.5
Ferns and allies			
	Equisetum arvense	0.0	0.5
	Equisetum hyemale	0.5	0.0

Comments: Other species commonly found in these sites include: Glyceria grandis and Typha latifolia

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APPENDIX E: PATCH TYPE DESCRIPTIONS

Note: Patch types were defined for this project as repetitious assemblages of plant species within the riparian landscape that exhibit similar species composition, and physiognomic and age structure, and occur within similar geomorphic settings of the fluvial environment. Patch types were used as the state variables within the ecological model for this riparian ecosystem. This appendix is intended to provide a relative description of the structure and function of the patch types that compose the overall riparian mosaic. These patch types do not represent a formal classification scheme based upon statistical information.

Figure 33. *Populus angustifolia* seedlings (Plots 11, 17, 28, 34, 35, 37, 42, 45)

Geomorphic Setting Large cohorts of sexually-derived *Populus angustifolia* seedlings establish on actively forming point bars on the inside of meander bends. Sediment continues to be deposited around the seedlings after they have successfully germinated. Sediment textures at these sites typically include very coarse sand, gravel and cobble. Plots ranged from 1.4 to 2.1 m above the thalweg.

Successional Relationships Competition from other species is very low on these sites due to the water stress that results from these well-drained, coarse sediments that are exposed to full sun. Seedlings successfully establish on sites whose elevation is low enough relative to the thalweg for their roots to maintain contact with the water table as it declines in the spring, but high enough to evade scouring flood flows.

Figure 34. *Populus angustifolia* pole stands (Plots 24, 25, 30, 43, 44)

Geomorphic Setting These sites are typically located on the inside of meander bends, adjacent to developing point bars. High streamflows can result in the deposition of coarse sands and gravels as well as finer material in these areas. These stands are more susceptible to overbank flooding than mature *Populus* stands, but less so than *Populus* seedlings. Little erosion occurs at these sites from lateral channel migration due to their location on the inside of meander bends.

Successional Relationships These even-aged stands of young trees typically develop from *Populus* seedlings that were sexually derived in point bar settings. Although sediment has begun to accumulate around these trees, overflow channels (including point bar chutes) that penetrate the stands are common. These channels only conduct water during large flow events. The understory of these stands provides favorable habitat for exotic grass species, however these species do not appear to continue to dominate in the stands after the *Populus* canopy closes with maturity. Young *Populus* stands not located near point bars may have been asexually derived by root sprouting from mature *Populus* stands, especially when mature stands are located adjacent to cleared, moist or irrigated agricultural fields. However, asexual stands are usually easily identified since they typically are mixed-aged stands with progressively younger individuals present as the distance from the parent tree increases. Pressure from beaver herbivory can be intense on all young stands of *Populus*. In one stand sampled, 59% of the total stand had been harvested by beaver; of the harvested trees, 36% were resprouting from the cut stumps. Beaver herbivory can also result in mixed-aged stands, however, the spatial distribution of tree ages are randomly distributed throughout the stand when this occurs.

Figure 35. Mature *Populus angustifolia* (Plots 3, 5, 10, 15, 18, 27, 31, 32)

Geomorphic Setting These stands are only affected by overbank flooding during higher stream flows. Even during higher flows, the streamflow velocities are reduced at these sites and only fine sand, silt and clay are deposited. Usually there is little evidence of any recent alluvial deposition on the soil surface, with rich, loamy surface soils present. However, these stands are very susceptible to bank erosion from lateral channel migration processes at both moderate and high streamflows, since they are commonly located on the outside of meander bends.

Successional Relationships Although all of these stands exhibit a well-developed canopy of *Populus angustifolia*, the composition of the understory vegetation varies considerably. Stands that have experienced intensive grazing by livestock appear to be dominated by exotic grasses, while more pristine sites are dominated by woody shrubs and native herbaceous species in the understory. Variation of understory species composition within undisturbed forest stands may be a result of the height of the site relative to the water table, as well as the age of the stand. In all mature *Populus* forests, the composition of the understory largely determines the resulting seral stage which will ensue. When *Acer negundo* occurs as a dominant species in the subcanopy , it appears to replace the *Populus* canopy after the lifetime of the *Populus* has been exceeded. In *Populus* stands where *Cornus* is a dominant species in the understory, *Cornus* will persist and form dense, impenetrable stands after the canopy has opened up. However, *Cornus* and *Acer* never appear to codominate together after *Populus* has declined. Root sprouting of *Populus angustifolia* can also be prolific among some stands of mature *Populus* and when this occurs, *Acer* and *Cornus* appear to be infrequent in the understory. In these sites, mixed-aged stands of *Populus* result, and perhaps persist over long periods of time.

Figure 36. Overflow channels (Plots 8, 36)

Geomorphic Setting Overflow channels occur as a component of mature *Populus angustifolia* stands on older geomorphic surfaces. They may contain standing water during periods of the year when the water table elevation is higher than the bottom of the overflow channel. However, these channels remain hydraulically connected to the main stream channel during times of high streamflow. The fine textured organic soils that line these channels may completely dry out during droughty summers.

Successional Relationships These sites are almost completely shaded under the *Populus* canopy. Light gaps in the canopy may result in differences in plant species composition and a greater species diversity in the channel than in other shaded channel locations. These channels appear to be relatively stable from one year to the next because during times of high streamflow, water velocity in the channels is much slower than the main channel, and little erosion occurs. However, composition of the wetland vegetation can also vary considerably from one year to the next depending upon water depths in the channel during a given year. Presumably, the availability and distribution of propagules from previous high flow events may also influence species abundance from one year to the next.

Figure 37. *Acer negundo* forest (Plots 4, 19)

Geomorphic Setting *Acer negundo* forests occur on old geomorphic surfaces with loamy, rich soils in the surface horizon. Stands of *Acer* are only affected by overbank flooding during higher streamflows. Even during higher flows, the flow velocities are reduced at these sites and only fine sand, silt and clay are deposited. However, these stands are very susceptible to bank erosion by lateral channel migration processes at both moderate and high streamflows, since they are commonly located on the outside of meander bends.

Successional Relationships *Acer negundo* may be a dominant species in the subcanopy of mature *Populus* stands, frequently taking on a tall shrubby growth habit. After the eventual decline of the *Populus*, the *Acer* no longer competes for resources such as light and water, and *Acer* may form almost pure stands with a closed canopy. Among these stands, infrequent very old *Populus* trees may persist. It should be recognized that while *Acer* seedlings appear to establish beneath the canopy of mature *Populus* stands, not all stands of *Populus* provide appropriate habitat for the recruitment of *Acer* seedlings, but are instead dominated by other species.

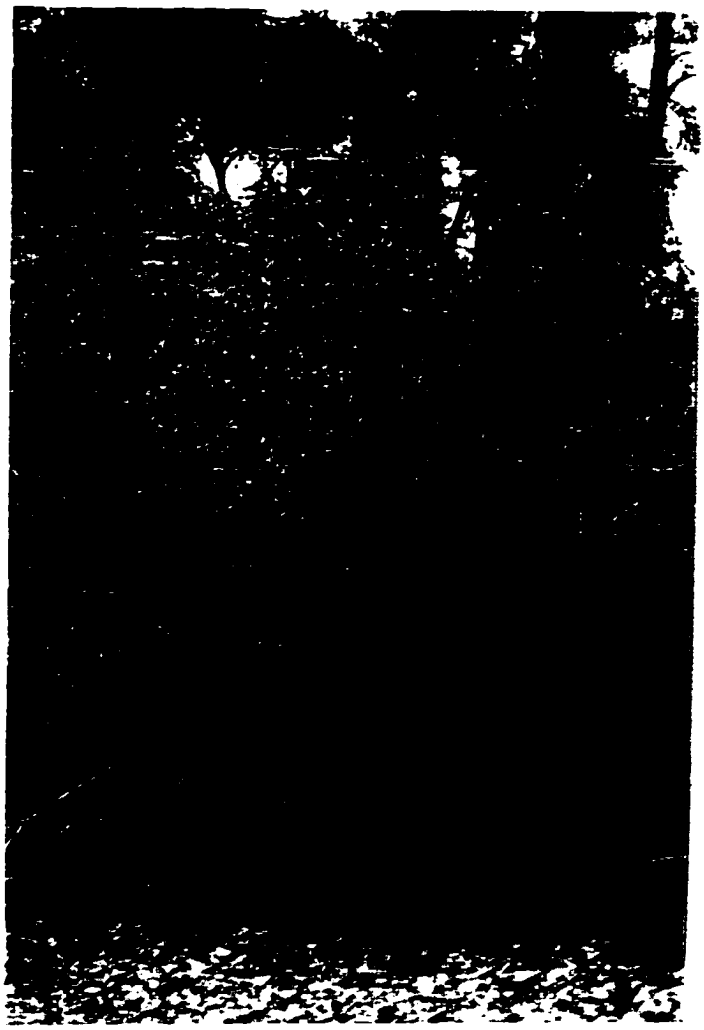

Figure 38. *Cornus sericea* (Plots 1, 14, 21)

Geomorphic Setting Dense stands of mature *Cornus sericea* occur on older geomorphic surfaces, similar to mature *Populus* and *Acer negundo* stands. These sites are only affected by overbank flood disturbance during higher streamflows. Even during these high flows, the streamflow velocities are reduced at these sites and only fine sand, silts and clays are deposited around the shrubs. However, sediment can commonly be observed "mounded' around the bases of these shrubs. These stands are also susceptible to erosion by lateral channel migration at moderate and high stream flows since they are commonly located on the outside of meander bends.

Successional Relationships *Cornus sericea* appears to regenerate best from seed under the canopy of mature *Populus* stands. Tall, dense stands of *Cornus* (with cover values ranging from over 50% to 95%) probably originated as the understory of previous *Populus* forests. Adventitious underground shoot growth or rhizomatous growth enables the scattered individuals of the previous understory to utilize the remaining available space and resources once the *Populus* canopy opens up with age. Apparently, *Acer negundo* was either not able to compete with *Cornus* at these sites or was not successful in establishing due to the environmental conditions present, or both. The herbaceous component in *Cornus* stands is very sparse, especially in the very dense thickets, due to little light penetration. Species richness is typically very low.

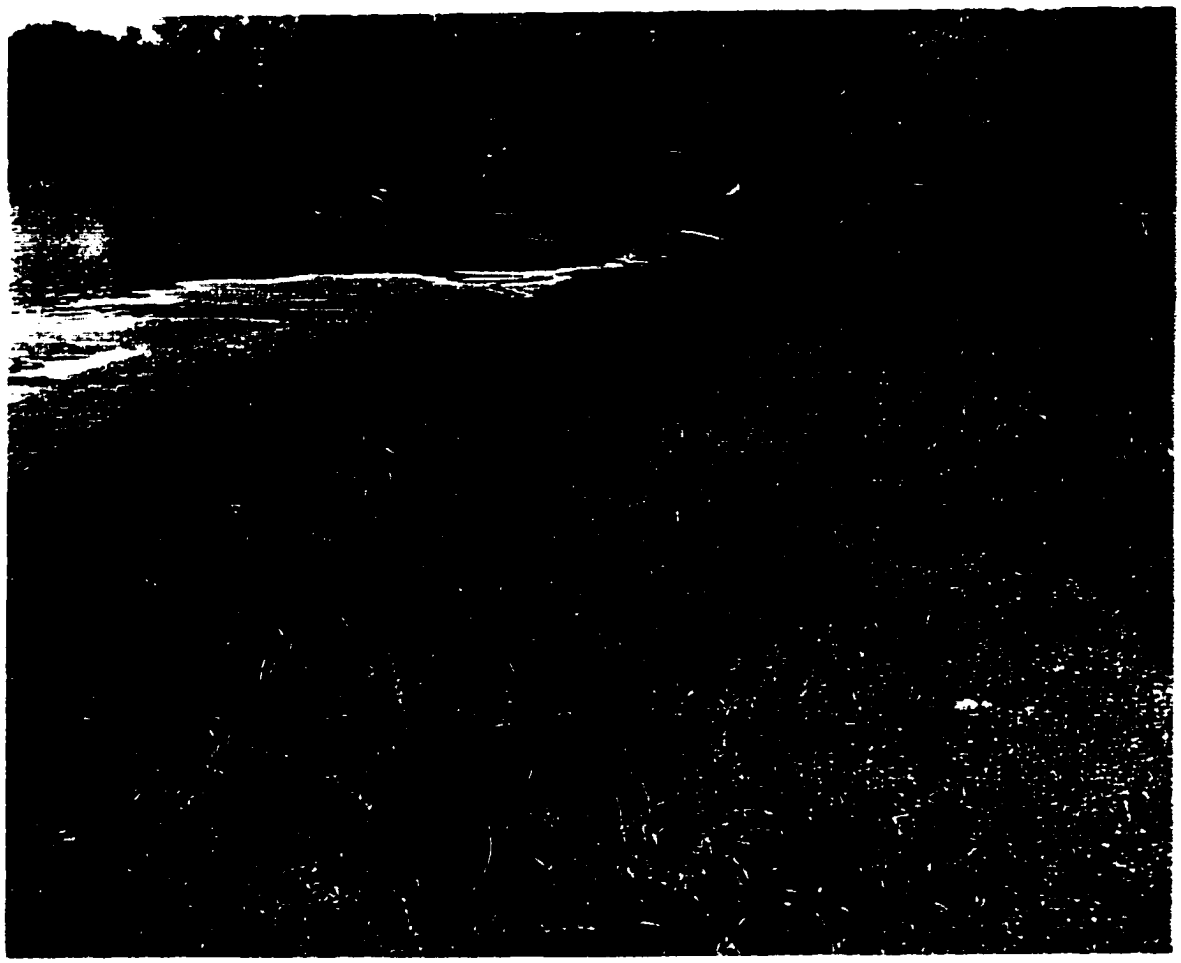

Figure 39. Riverine marsh (Plots 2, 13, 20, 38)

Geomorphic Setting These sites consist of low-lying, recently deposited, fine textured alluvial sediments, typically located downstream of point bars, islands, or other obstructions along the main stream channel. The elevation of these sites is very low relative to the stream channel (only about 1.5 m above the thalweg of the channel) and in most years these areas are barely above the water surface during the middle of the growing season.

Successional Relationships Species richness of the herbaceous component is typically very high in riverine marshes, except for those sites where *Phalaris arundinacea* dominates. These areas provide an important setting for the sexual regeneration of *Salix exigua*. *Salix* seedlings may in turn be largely responsible for capturing additional sediment after establishment, allowing sediment to increase the elevation of the surface over time. The marshes may provide an important source of propagules for many wetland herbaceous species. Propagules for these species may easily disperse from these streamside locations and be transported downstream, unlike other more hydraulically-isolated wetland settings within the ecosystem such as those associated with oxbow lakes and overflow channels.

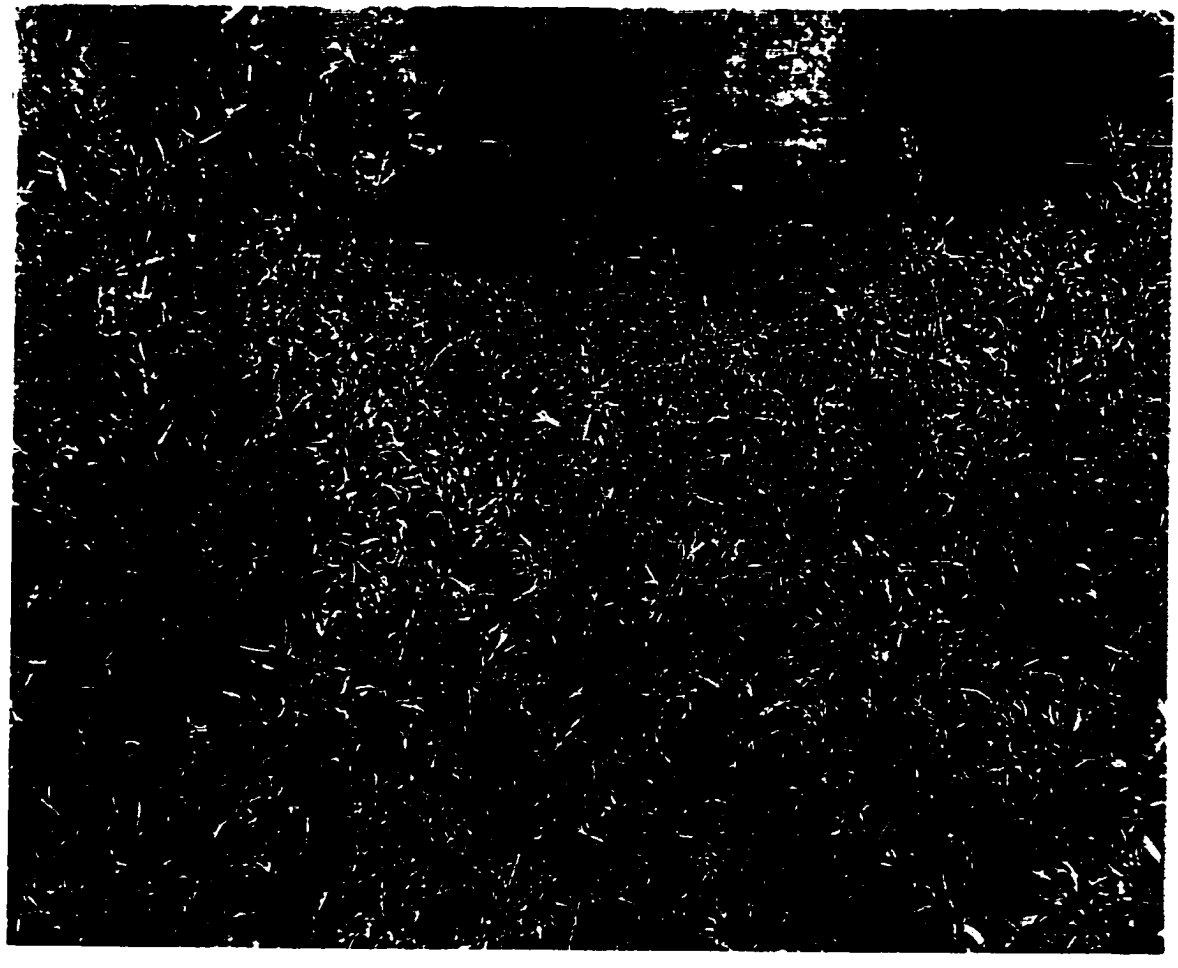

Figure 40. *Salix exigua* (Plots 9, 12, 16, 29)

Geomorphic Setting *Salix exigua* shrublands establish on sites where the deposition of fine sand, silt and clay has occurred along the main stream channel. Usually these sites are located in areas where streamflow velocities are reduced, such as the downstream end of point bars, islands, or where eddies in streamflow occur, allowing finer sediments to be deposited.

Successional Relationships These sites originally establish as low-lying riverine marshes that gradually entrap additional sediment over time as the vegetation matures. Eventually, the hydric herbaceous wetland species are no longer as well adapted to these sites as the deep rooted *Salix* shrubs, and the composition of the vegetation changes as the depth to the water table increases. However, *Phalaris arundinacea* does appear to be able to persist with *Salix* at these sites as the elevation of the ground surface increases. Few additional species invade the dense stands of *Salix* on these sandy soils after they are well-established, probably because they lack the ability to access the water table that the partially buried shrubs so greatly benefit from.

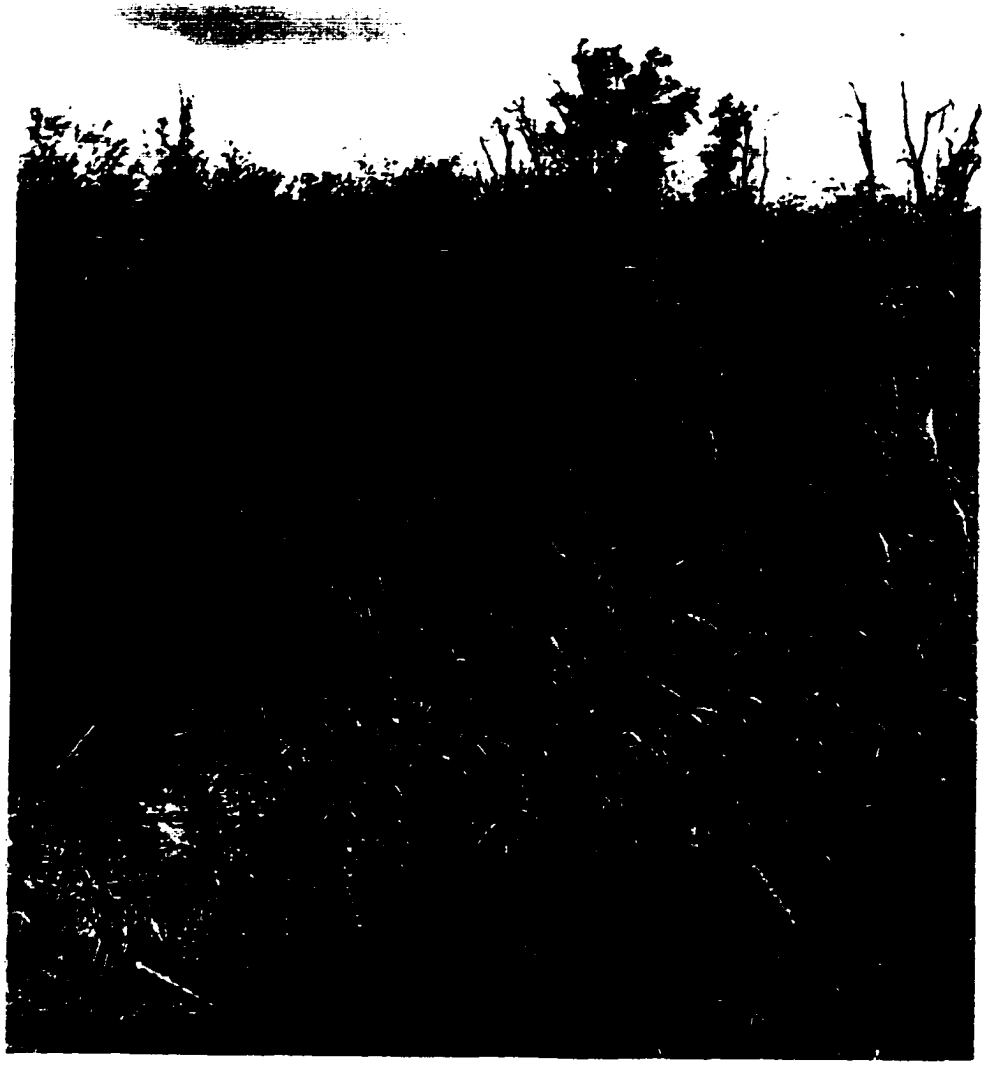

Figure 41. Oxbow lake banks (Plots 39, 40)

Geomorphic Setting These sites occur along the banks of abandoned channels of the Yampa River. They result from meander-cutoff of the main channel during flood events. After a channel has been abandoned, it will begin to fill with sediment at both ends of the abandoned segment, until the "oxbow" is no longer hydraulically connected to the main channel except during the highest streamflows.

Successional Relationships Once the river has abandoned its channel, vegetation along the banks of the newly created oxbow lake is no longer subjected to the erosive streamflow velocities associated with the main channel. This allows establishment of many new woody and herbaceous wetland species along the banks. Beaver play a very important ecological role in these areas as well. By creating dams across the oxbows, they may locally raise surface water and groundwater levels, diversifying habitat for plant species in the process. Species richness is typically very high in these areas while the abundance of any one species remains fairly low except for *Salix exigua* and/or *Phalaris arundinacea*. Although *Populus* saplings may be found among the diverse assemblage of species, these are most likely a product of asexual root sprouting from mature stands of trees that are adjacent to the old, abandoned channel.

Figure 42. Emergent marsh (Plots 23, 41)

Geomorphic Setting Extensive stands of *Typha latifolia* occur within certain portions of oxbow lakes. These oxbow lakes retain standing water because they intercept the water table, and during high streamflow events they may be hydraulically connected to the main stream channel. *Typha* only occurs in areas where the oxbow lake is deep enough to intercept the water table for almost the entire growing season. However, this species cannot endure water depths of greater than approximately one m for long periods of time. Also, this species is vulnerable to mechanical injury as a result of even fairly low water velocities, therefore, suitable habitat for this species only occurs in portions of the oxbow lake most protected from high flow velocities during flood events.

Successional Relationships *Typha latifolia* occurs in almost monospecific stands in these sites. This species requires bare, exposed soil for germination but after becoming established has good flood tolerance. Few other local species can tolerate water inundation as well as *Typha*, so little interspecific competition occurs. These stands may persist for relatively long periods of time unless the hydrologic regime changes, allowing other species to effectively compete. Some emergent marshes also appear to be dominated by species of *Scirpus*, instead of *Typha latifolia*.

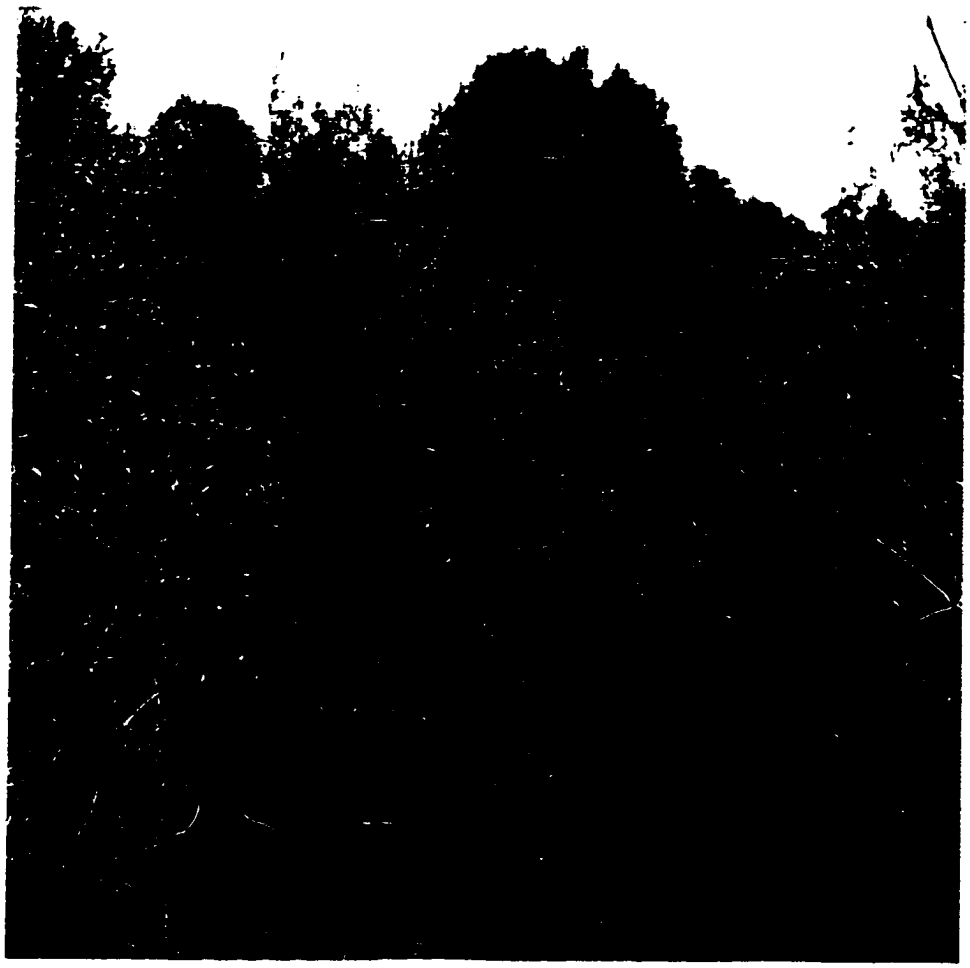

Figure 43. *Salix lasiandra* slough (Plots 22, 26)

Geomorphic Setting Examination of aerial photo sets indicate that *Salix lasiandra* shrublands establish on bare alluvium located within recently abandoned stream channels of the Yampa River. These depositional sites are similar to *Populus* recruitment sites except that *Populus* sites are a product of alluvial deposition by lateral channel migration, and *Salix lasiandra* recruitment sites result from deposition associated with meander cut-off / channel abandonment. Areas where *Salix lasiandra* have established may hold standing water when the water table is high in the spring, and they may still conduct water from the main channel during high streamflows. Although Salix lasiandra stands originate on fairly coarse alluvial sediments, the input of finer sediment from subsequent flooding occurs over time resulting in a silty, mucky soil horizon at the surface in the older stands. Aerial photographs and age dating of *Salix* shrubs indicate that these stands can persist for at least 30 years.

Successional Relationships Stands of *Salix lasiandra* appear to be relatively long-lived. The individuals in these stands reach heights of several meters and attain trunks of one decimeter or more in diameter. While herbaceous species, such as *Carex*, may dominate in the understory, there does not appear to be any other species that replace *Salix lasiandra* over time. Species composition of the understory may be variable and may reflect the amount of sedimentation that has occurred since channel abandonment, and sediment textures characteristic of the abandoned channel. In many areas of the floodplain, it appears that these sloughs have been fragmented by agricultural operations and only disjointed remnants remain.

APPENDIX F: TREE AGE DATA

Table 22. Stem radii and estimated establishment years of sexually-derived *Populus* seedlings located in different geomorphic settings along the Yampa River.

Stem radii of point bar seedlings (units of .01 mm) / estimated year of establishment	Stem radii of lateral bar and island seedlings (units of .01 mm) / estimated year of establishment
1418 / 1985	1339 / 1984
1500 / 1986	910 / 1984
1636 / 1984	1037 / 1985
2409 / 1985	1442 / 1989
1463 / 1983	931 / 1987
2472 / 1984	990 / 1988
3457 / 1986	1415 / 1986
	747 / 1987
	898 / 1988
	1254 / 1987

Table 23. Estimated ages of cored and slabbed trees along the Yampa River.

Acer negundo n=18	Populus angustifolia: post-settlement establishment period n=68		Populus angustifolia: pre-settlement establishment period n=32
45	53	61	104
39	57	55	97
61	37	47	99
37	59	46	98
28	57	54	95
48	68	50	119
57	39	65	159
50	60	66	96
45	69	66	96
55	57	63	109
70	50	55	100
54	55	48	93
56	56	54	98
70	57	43	123
68	31	34	134
33	31	54	116
48	68	19	105
33	9	55	159
	56	49	161
	54	68	92
	67	62	93
	39	65	98
	60	63	123
	44	66	134
	57	63	116
	51	58	137
	51	40	112
	56	54	90
	57	44	110
	31	56	103
	56	48	112
	54	58	111
	47	59	
	46	63	

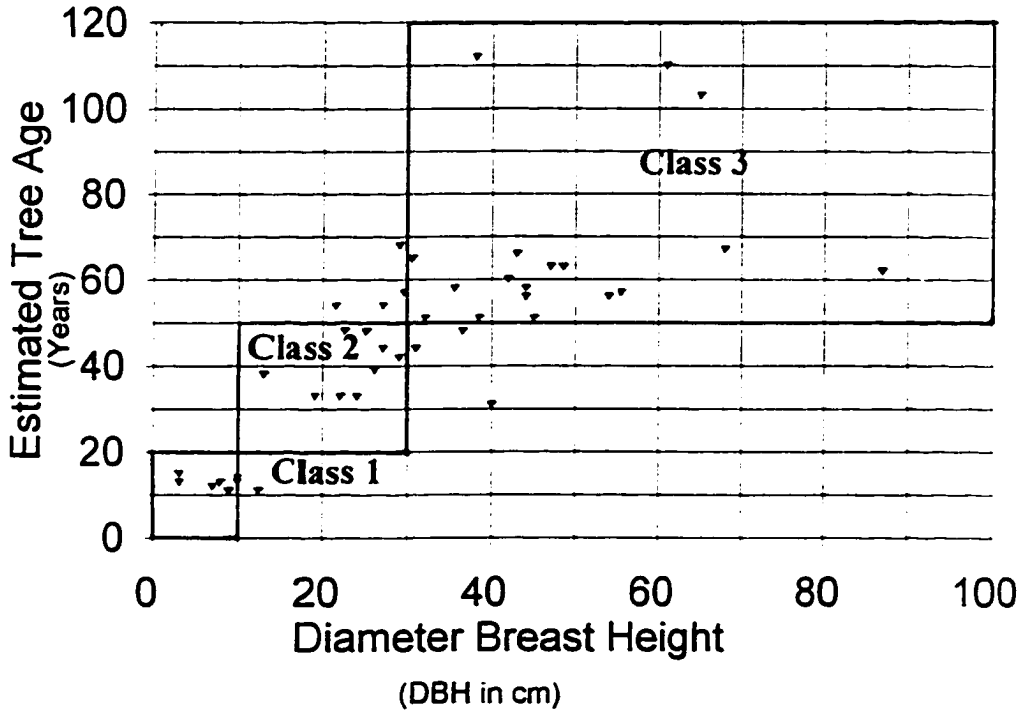

Figure 44. Tree core data were used to establish an approximate relationship between actual tree age and dbh (0-10 cm= 0-20 yrs, 10-30 cm= 20-50 yrs, +30 cm=+50 yrs). By establishing this general relationship, dbh could be used to express the approximate ages of trees in the correlation matrix in Chapter 4. A significant relationship was found between these two variables (r^2=.59, p=≤.01).

APPENDIX G: MODEL SUCCESS- PROGRAM CODE, DRIVER FILE, INPUT FILE, OUTPUT, SENSITIVITY ANALYSIS

```
c       Program SUCCESS
c
c...Simulates dynamics of: Yampa River ecosystem
c
c...Programmer Holly Richter, 1995
c
c...State Variables
c       ASC= Active stream channel
c       CSE= Populus seedlings
c       YCO= Young Populus
c       MCO= Mature Populus
c       COR= Cornus sericea
c       RIV= Riverine marsh
c       BOX= Acer negundo forest
c       WIL= Salix exigua
c       OXL= Oxbow lake
c       HMA= Emergent marsh
c       BAA= Bare alluvium
c       SLS= Salix lasiandra slough
c       OXB= Oxbow lake banks
c
c...Parameters
c       Floodpk= peak daily flow of year
c       Bankfds= % of days each year at or above 125% of
c                bankfull discharge
c...Run control
c       endyr= ending year of simulation
c       startyr= beginning year of simulation
c
        real ASC, CSE, YCO, MCO, BOX, WIL, OXL, HMA, BAA,
     +  OXB, RIV, COR, SLS
        real floodpk,bankfds,total
        integer startyr, endyr, year
c
        open (6,file='input')
        open (7,file='driver7.prn')
        open (8,file='diag.out')
        open (9,file='output')
c
c...enter starting and ending years for simulation
        read(6,20)startyr
        write(8,*)'start year is ', startyr
c
        read(6,20)endyr
        write(8,*)'end year is ', endyr
c
   20   format(8X,I4)
c
c...initialize state variables
        read(6,21)ASC
        write(8,*)'initial value for active stream channel is ',ASC
c
        read(6,21)CSE
        write(8,*)'initial value for cottonwood seedlings is ',CSE
c
        read(6,21)YCO
        write(8,*)'initial value for young cottonwoods is ',YCO
c
        read(6,21)MCO
        write(8,*)'initial value for mature cottonwood is ',MCO
```

```
c
        read(6,21)BOX
        write(8,*)'initial value for boxelder is ',BOX
c
        read(6,21)WIL
        write(8,*)'initial value for willow is ',WIL
c
        read(6,21)OXL
        write(8,*)'initial value for oxbow lake is ',OXL
c
        read(6,21)HMA
        write(8,*)'initial value for herbaceous marsh is ',HMA
c
        read(6,21)BAA
        write(8,*)'initial value for bare alluvium is ',BAA
c
        read(6,21)SLS
        write(8,*)'initial value for salix lasiandra slough is ',SLS
c
        read(6,21)OXB
        write(8,*)'initial value for oxbow lake banks is ',OXB
c
        read(6,21)RIV
        write(8,*)'initial value for riverine marsh is ',RIV
c
        read(6,21)COR
        write(8,*)'initial value for cornus sericea is ',COR
c
   21   format(8X,F4.1)
c
c...    Write  headings of state variables to output file
        write(9,23)'year','asc','cse','yco','mco','box','wil',
     +  'oxl','hma','baa','sls','oxb','riv','cor'
   23   format(a4,13a6)
c
c
c...    Read driver variables for current year
        do 30 i=startyr,endyr
           read(7,24)YEAR,FLOODPK,BANKFDS
   24      format(I4,F10.1,F3.0)
c
        BANKFDS=(BANKFDS/365)*100
c
c... CALCULATE BIOTIC SUCCESSION RATES BETWEEN STATE VARIABLES
c
c... Flow from BAA to CSE (90% of BAA is suitable habitat
c    for establishment of CSE)
           FBAACSE=(0.9*BAA)
c
c... Flow from BAA to RIV (10% of BAA is suitable habitat
c    for establishment of RIV)
           FBAARIV=(0.10*BAA)
c
c... Flow from RIV to WIL (one-eighth of total RIV patch area will
c    develop into WIL, it takes 10 years on average)
           FRIVWIL=(RIV*0.0125)
c
c... Flow from CSE to YCO (takes 8 years on average)
           FCSEYCO= (CSE*0.125)
c
```

```
c... Flow from YCO to MCO (17 more years, 25 total age)
      FYCOMCO=(YCO*0.059)
c
c... Flow from MCO to BOX (one-tenth of total MCO patch area will
c    develop into BOX, it takes 150 years on average)
      FMCOBOX= (MCO*0.0007)
c
c... Flow from MCO to COR (one-tenth of total MCO patch area will
c    develop into COR, it takes 150 years on average)
      FMCOCOR=(MCO*.0007)
c
c... CALCULATE PARTITIONING OF RECENTLY ABANDONED CHANNELS
c    (Assumes the area occupied by new meander cut-offs is approximately
c     equal to the area occupied by abandoned channels)
c
c... Flow from ASC to OXL (54% of abandoned channels go to OXL)
      FASCOXL=0.54*(-3.33+(0.00051*floodpk))
c
c... Flow from ASC to HMA (6% of abandoned channels go to HMA)
      FASCHMA=0.06*(-3.33+(0.00051*floodpk))
c
c... Flow from ASC to SLS (6% of abandoned channels go to SLS)
      FASCSLS=0.06*(-3.33+(0.00051*floodpk))
c
c... Flow from ASC to OXB (34% of abandoned channels go to OXB)
      FASCOXB=0.34*(-3.33+(0.00051*floodpk))
c
c... CALCULATE DEPOSITION FROM LATERAL CHANNEL MIGRATION
c... Flow from ASC to BAA (Equation developed by Vosen)
c
      FASCBAA=((2208120.92*BANKFDS)+4865.979)/4976300
c
c... CALCULATE EROSION OF PATCHES FROM LATERAL CHANNEL MIGRATION
c    AND MEANDER CUT-OFF (sum of erosion flows by lateral channel
c    migration must equal FASCBAA)
c
c... Flow from MCO to ASC (85.79% of all erosion from lateral
c    channel migration and 92% of all erosion from meander
c    cut-off occurs in MCO)
      FMCOASC=(0.8579*FASCBAA)+(0.92*(-3.33+(0.00051*floodpk)))
c
c... Flow from BOX to ASC (4.5% of all erosion from lateral channel
c    migration and 8% of all erosion from meander
c    cut-off occurs in BOX)
      FBOXASC=(0.045*FASCBAA)+(0.08*(-3.33+(0.00051*floodpk)))
c
c... Flow from COR to ASC (4% of all erosion from lateral channel
c    channel migration occurs in COR)
      FCORASC=(0.04*FASCBAA)
c
c... Flow from HMA to ASC (0.5% of all lateral channel migration
c    occurs in HMA)
      FHMAASC=(0.005*FASCBAA)
c
c... Flow from SLS to ASC (0.5% of all lateral channel migration
c    occurs in SLS)
      FSLSASC=(0.005*FASCBAA)
c
c... Flow from OXB to ASC (4% of all lateral channel migration
c    occurs in OXB)
```

```
            FOXBASC=(0.04*FASCBAA)
c
c... Flow from OXL to ASC (.01% of all lateral channel migration
c    occurs in OXL)
            FOXLASC=(0.0001*FASCBAA)
c
c... Flow from WIL to ASC (0.7% of all lateral channel migration
c    occurs in WIL)
            FWILASC=(0.007*FASCBAA)
c
          write(8,25)'flows for',i
   25     format(a9,3x,i4)
c
          write(8,26)'FBAACSE',FBAACSE
          write(8,26)'FBAARIV',FBAARIV
          write(8,26)'FCSEYCO',FCSEYCO
          write(8,26)'FYCOMCO',FYCOMCO
          write(8,26)'FMCOBOX',FMCOBOX
          write(8,26)'FMCOCOR',FMCOCOR
          write(8,26)'FASCOXL',FASCOXL
          write(8,26)'FASCHMA',FASCHMA
          write(8,26)'FASCSLS',FASCSLS
          write(8,26)'FASCOXB',FASCOXB
          write(8,26)'FASCBAA',FASCBAA
          write(8,26)'FMCOASC',FMCOASC
          write(8,26)'FBOXASC',FBOXASC
          write(8,26)'FCORASC',FCORASC
          write(8,26)'FOXLASC',FOXLASC
          write(8,26)'FHMAASC',FHMAASC
          write(8,26)'FSLSASC',FSLSASC
          write(8,26)'FOXBASC',FOXBASC
          write(8,26)'FWILASC',FWILASC
   26     format(a7,3x,f10.2)
c
c
c... Update bare alluvium
c
          BAA=BAA+(FASCBAA-FBAARIV-FBAACSE)
          if(BAA.lt.0.01)BAA=0.01
c
c... Update remaining state variables
c
          CSE=CSE+(FBAACSE-FCSEYCO)
          if(CSE.lt.0.01)CSE=0.01
c
          YCO=YCO+(FCSEYCO-FYCOMCO)
          if(YCO.lt.0.01)YCO=0.01
c
          MCO=MCO+(FYCOMCO-FMCOBOX-FMCOCOR-FMCOASC)
          if(MCO.lt.0.01)MCO=0.01
c
          BOX=BOX+(FMCOBOX-FBOXASC)
          if(BOX.lt.0.01)BOX=0.01
c
          COR=COR+(FMCOCOR-FCORASC)
          if(COR.lt.0.01)COR=0.01
c
          OXL=OXL+(FASCOXL-FOXLASC)
          if(OXL.lt.0.01)OXL=0.01
c
```

```
         HMA=HMA+(FASCHMA-FHMAASC)
         if(HMA.lt.0.01)HMA=0.01
c
         SLS=SLS+(FASCSLS-FSLSASC)
         if(SLS.lt.0.01)SLS=0.01
c
         OXB=OXB+(FASCOXB-FOXBASC)
         if(OXB.lt.0.01)OXB=0.01
c
         RIV=RIV+(FBAARIV-FRIVWIL)
         if(RIV.lt.0.01)RIV=0.01
c
         WIL=WIL+(FRIVWIL-FWILASC)
         if(WIL.lt.0.01)WIL=0.01
c
         ASC=ASC+(FCORASC+FBOXASC+FMCOASC+FOXBASC+
     +   FSLSASC+FHMAASC+FOXLASC+FWILASC-FASCBAA-
     +   FASCOXL-FASCHMA-FASCSLS-FASCOXB)
         if(ASC.lt.0.01)ASC=0.01
c
c
c... Add all patch type percentages together
         total=CSE+YCO+MCO+BOX+COR+OXL+HMA+SLS+OXB+RIV+WIL+ASC+
     +   BAA
c... Write values of state variables to file named 'output'
c
         write(9,27)year,asc,cse,yco,mco,box,wil,oxl,hma,baa,sls,oxb,
     +   riv,cor
   27    format(i4,13(1x,f5.2))
c
         write(8,28)i,total
   28    format(i4,3x,f6.1)
c
   30    continue
c
         end
```

Table 24. Yampa River ecological model driver file.

Simulation Year	Peak Daily Flow of the Year in cfs (FLOODPK)	% of Days Each Year at or Above 125% of Bankfull Discharge (BANKFDS)
1937	6269.9	0
1938	7248.9	10
1939	5127.8	0
1940	5771.9	0
1941	7389.9	3
1942	6756.6	1
1943	5639.8	0
1944	5802.9	0
1945	6434.6	0
1946	4800.1	0
1947	7205.2	5
1948	7954.8	6
1949	6617.8	0
1950	5543.9	0
1951	6396.2	0
1952	9811.3	17
1953	6984.6	3
1954	3513.5	0
1955	4667.5	0
1956	6970.9	3

Simulation Year	FLOODPK	BANKFDS
1957	10363.6	28
1958	8617.2	17
1959	4891.8	0
1960	5398.0	0
1961	4499.9	0
1962	8132.1	8
1963	3883.4	0
1964	6439.2	0
1965	8360.6	9
1966	4000.0	0
1967	6330.0	0
1968	7800.0	6
1969	4970.0	0
1970	8000.0	12
1971	7500.0	11
1972	7000.0	1
1973	7780.0	6
1974	11500.0	15
1975	7830.0	4
1976	5250.0	0
1977	2440.0	0
1978	8990.0	15
1979	10300.0	14
1980	6470.0	0

Simulation Year	FLOODPK	BANKFDS
1981	4810.0	0
1982	5600.0	0
1983	9630.0	14
1984	12500.0	46
1985	8000.0	6
1986	8670.0	13
1987	3894.1	0
1988	6067.6	0
1989	3175.4	0

Table 25. Yampa River ecological model input values.

Variable Name	Initial Value Used
First simulation year (startyr)	1938
Last simulation year (endyr)	1989
% Area in active stream channel (ASC)	16.4
% Area Populus angustifolia seedlings (CSE)	3.5
% Area Populus angustifolia pole stand (YCO)	4.0
% Area mature Populus angustifolia (MCO)	42.9
% Area Acer negundo forest (BOX)	8.6
% Area Salix exigua (WIL)	.95
% Area oxbow lake (OXL)	1.1
% Area emergent marsh (HMA)	1.4
% Area bare alluvium (BAA)	5.9
% Area Salix lasiandra slough (SLS)	1.4
% Area oxbow lake banks (OXB)	11.2
% Area riverine marsh (RIV)	.95
% Area Cornus sericea (COR)	1.7

Table 26. Yampa River ecological model output file

Year	Active Stream Channel	Populus Seedlings	Young Populus	Mature Populus	Acer negundo	Salix exigua	Oxbow Lake	Emergent Marsh	Bare Alluvium	Salix lasiandra	Oxbow Lake Banks	Riverine Marsh	Cornus sericea
1938	16.4	8.37	4.2	43.2	8.64	0.96	1.03	1.39	0	1.39	11.15	1.53	1.73
1939	16.4	7.33	5	42	8.59	0.97	1.23	1.41	1.22	1.41	11.23	1.51	1.71
1940	16.4	7.51	5.62	42.9	8.67	0.99	0.84	1.37	0	1.37	10.99	1.61	1.74
1941	16.4	6.57	6.23	43.52	8.73	1.01	0.63	1.34	0	1.34	10.86	1.59	1.77
1942	16.4	5.75	6.68	43.11	8.71	1.03	0.87	1.37	0.37	1.37	10.99	1.57	1.79
1943	16.4	5.36	7.01	43.23	8.73	1.05	0.93	1.37	0.12	1.37	11.03	1.59	1.81
1944	16.4	4.8	7.26	44	8.79	1.07	0.69	1.35	0	1.35	10.87	1.58	1.84
1945	16.4	4.2	7.43	44.71	8.86	1.09	0.49	1.32	0	1.32	10.75	1.56	1.87
1946	16.4	3.68	7.52	45.13	8.89	1.11	0.46	1.32	0	1.32	10.73	1.54	1.9
1947	16.4	3.22	7.54	46.32	8.99	1.13	0	1.27	0	1.27	10.43	1.52	1.94
1948	16.4	2.82	7.49	45.86	8.97	1.14	0.19	1.29	0.61	1.29	10.52	1.5	1.94
1949	16.4	3.01	7.4	44.94	8.91	1.15	0.58	1.33	0.73	1.33	10.74	1.55	1.95
1950	16.4	3.29	7.34	45.27	8.94	1.17	0.6	1.33	0	1.33	10.76	1.6	1.98
1951	16.4	2.88	7.32	46.11	9.01	1.19	0.33	1.3	0	1.3	10.58	1.58	2.01
1952	16.4	2.52	7.25	46.54	9.05	1.21	0.29	1.29	0	1.29	10.56	1.56	2.04
1953	16.4	2.21	7.14	43.58	8.85	1.22	1.2	1.38	2.07	1.38	11.05	1.54	1.99
1954	16.4	3.79	6.99	43.42	8.85	1.24	1.32	1.4	0.37	1.4	11.11	1.73	2.01
1955	16.4	3.65	7.05	45.18	9	1.26	0.49	1.3	0	1.3	10.59	1.74	2.04
1956	16.4	3.19	7.09	46.41	9.11	1.28	0	1.25	0	1.25	10.27	1.72	2.07
1957	16.4	2.79	7.07	46.24	9.11	1.3	0.12	1.26	0.37	1.26	10.33	1.7	2.09
1958	16.4	2.77	7.01	41.87	8.83	1.3	1.18	1.36	3.4	1.36	10.86	1.72	1.98
1959	16.4	5.49	6.94	39.48	8.68	1.3	1.75	1.41	2.07	1.41	11.14	2.03	1.93
1960	16.4	6.67	7.22	40.6	8.78	1.33	1.3	1.36	0	1.36	10.85	2.22	1.96
1961	16.4	5.83	7.62	41.5	8.85	1.36	0.99	1.33	0	1.33	10.66	2.19	1.99
1962	16.4	5.11	7.9	42.84	8.96	1.38	0.43	1.27	0	1.27	10.3	2.16	2.02
1963	16.4	4.47	8.08	41.66	8.88	1.4	0.87	1.31	0.97	1.31	10.54	2.13	2.01

Output File, continued

Year	Active Stream Channel	Populus Seedlings	Young Populus	Mature Populus	Acer negundo	Salix exigua	Oxbow Lake	Emergent Marsh	Bare Alluvium	Salix lasiandra	Oxbow Lake Banks	Riverine Marsh	Cornus sericea
1964	16.4	4.79	8.16	43.32	9.02	1.43	0.14	1.23	0	1.23	10.08	2.2	2.04
1965	16.4	4.19	8.27	43.78	9.05	1.46	0.12	1.23	0	1.23	10.07	2.18	2.07
1966	16.4	3.67	8.31	42.41	8.96	1.48	0.62	1.28	1.1	1.28	10.34	2.15	2.05
1967	16.4	4.19	8.28	44.02	9.09	1.5	0	1.2	0	1.2	9.9	2.23	2.08
1968	16.4	3.67	8.31	44.54	9.13	1.53	0	1.19	0	1.19	9.87	2.21	2.11
1969	16.4	3.21	8.28	43.75	9.08	1.55	0.35	1.23	0.73	1.23	10.06	2.18	2.12
1970	16.4	3.47	8.19	44.91	9.17	1.58	0	1.18	0	1.18	9.79	2.22	2.15
1971	16.4	3.04	8.14	43.39	9.08	1.6	0.4	1.22	1.46	1.22	9.99	2.2	2.12
1972	16.4	3.97	8.04	42.2	9.01	1.62	0.67	1.24	1.34	1.24	10.1	2.31	2.1
1973	16.4	4.68	8.07	42.29	9.02	1.64	0.8	1.25	0.12	1.25	10.18	2.42	2.12
1974	16.4	4.2	8.17	41.49	8.96	1.67	1.15	1.29	0.73	1.29	10.36	2.4	2.12
1975	16.4	4.34	8.22	38.02	8.7	1.69	2.51	1.43	1.82	1.43	11.15	2.44	2.08
1976	16.4	5.44	8.27	37.42	8.66	1.71	2.87	1.47	0.49	1.47	11.36	2.6	2.08
1977	16.4	5.19	8.47	38.46	8.73	1.75	2.52	1.43	0	1.43	11.14	2.61	2.11
1978	16.4	4.55	8.62	40.82	8.93	1.78	1.39	1.31	0	1.31	10.43	2.58	2.14
1979	16.4	3.98	8.68	38.56	8.77	1.8	2.07	1.37	1.82	1.37	10.78	2.55	2.09
1980	16.4	5.12	8.66	35.78	8.57	1.82	3.11	1.48	1.7	1.48	11.37	2.7	2.05
1981	16.4	6.02	8.79	36.27	8.6	1.85	3.09	1.48	0	1.48	11.36	2.83	2.08
1982	16.4	5.26	9.02	37.54	8.69	1.89	2.62	1.42	0	1.42	11.06	2.8	2.1
1983	16.4	4.61	9.15	38.46	8.76	1.92	2.36	1.4	0	1.4	10.9	2.76	2.13
1984	16.4	4.03	9.19	36.03	8.58	1.95	3.22	1.48	1.7	1.48	11.37	2.73	2.09
1985	16.4	5.06	9.15	28.92	8.11	1.94	4.86	1.64	5.59	1.64	12.18	2.87	1.89
1986	16.4	9.46	9.24	28.1	8.04	1.97	5.27	1.68	0.73	1.68	12.41	3.39	1.88
1987	16.4	8.94	9.88	26.25	7.9	2	5.86	1.74	1.58	1.74	12.71	3.42	1.84
1988	16.4	9.24	10.41	28.03	8.03	2.05	5.13	1.65	0	1.65	12.26	3.54	1.85
1989	16.4	8.09	10.95	28.82	8.06	2.09	5	1.64	0	1.64	12.18	3.49	1.87

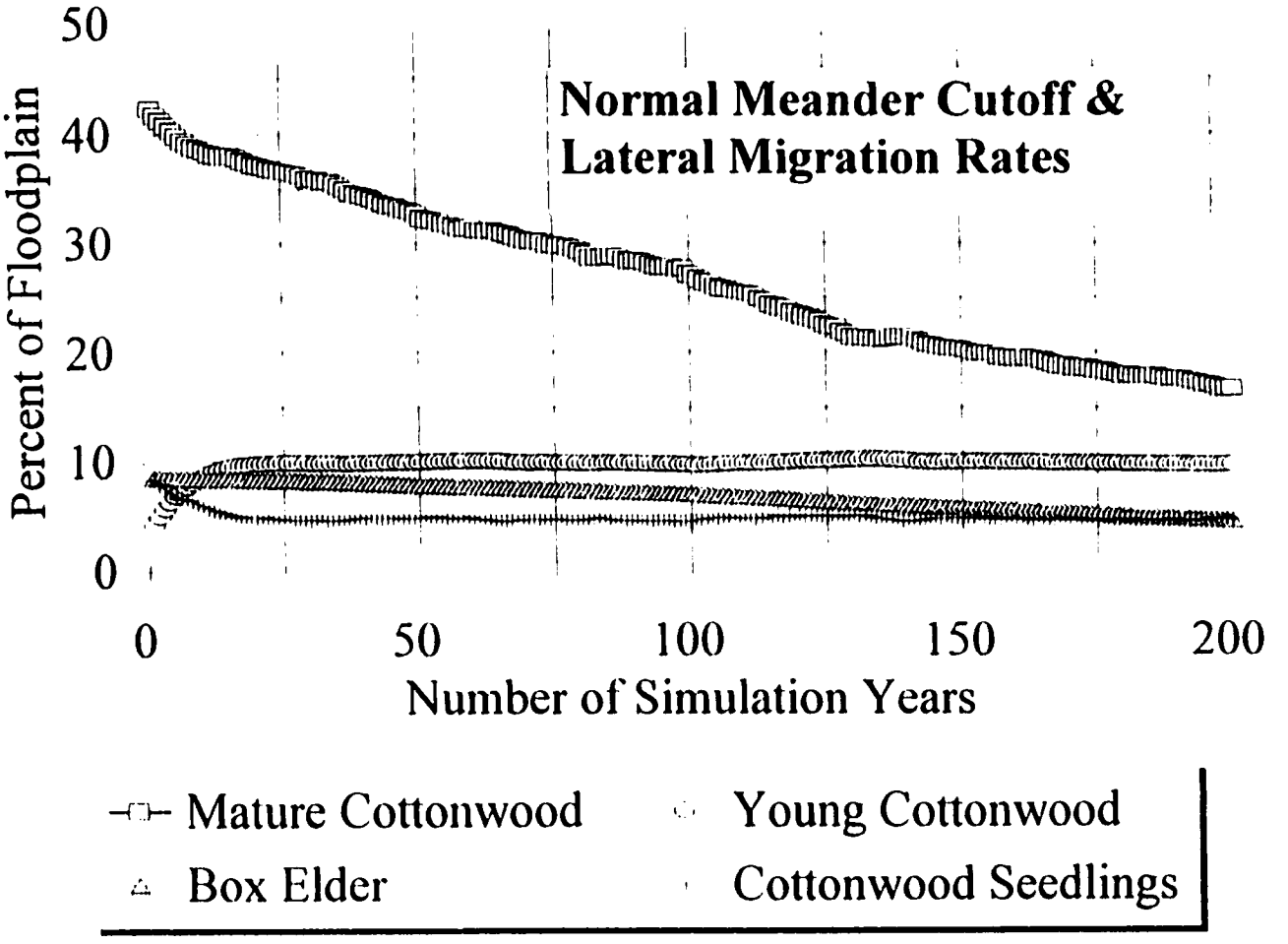

Figure 45. Sensitivity analysis: normal meander cut-off and lateral migration rates

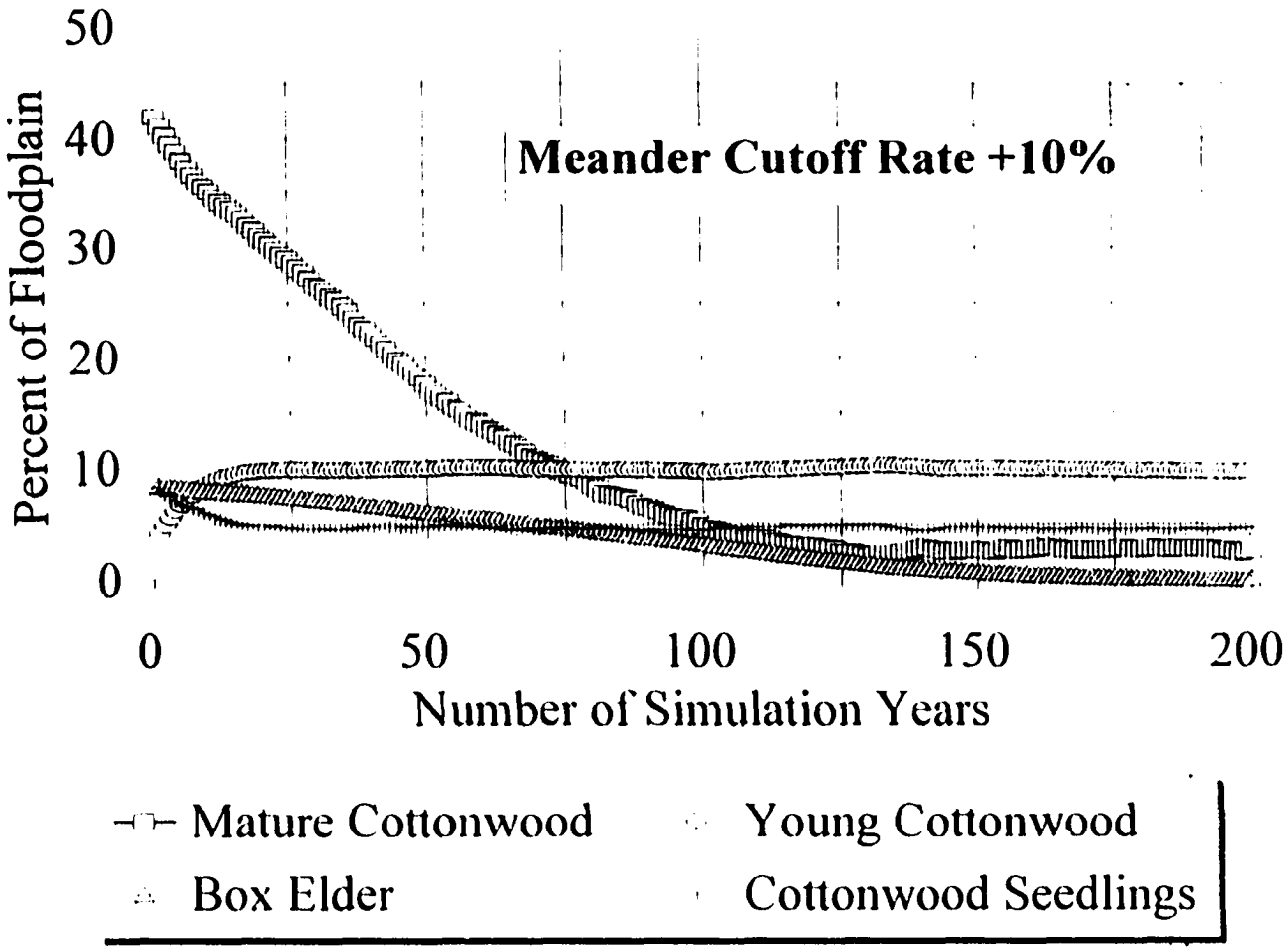

Figure 46. Sensitivity analysis: meander cut-off + 10%

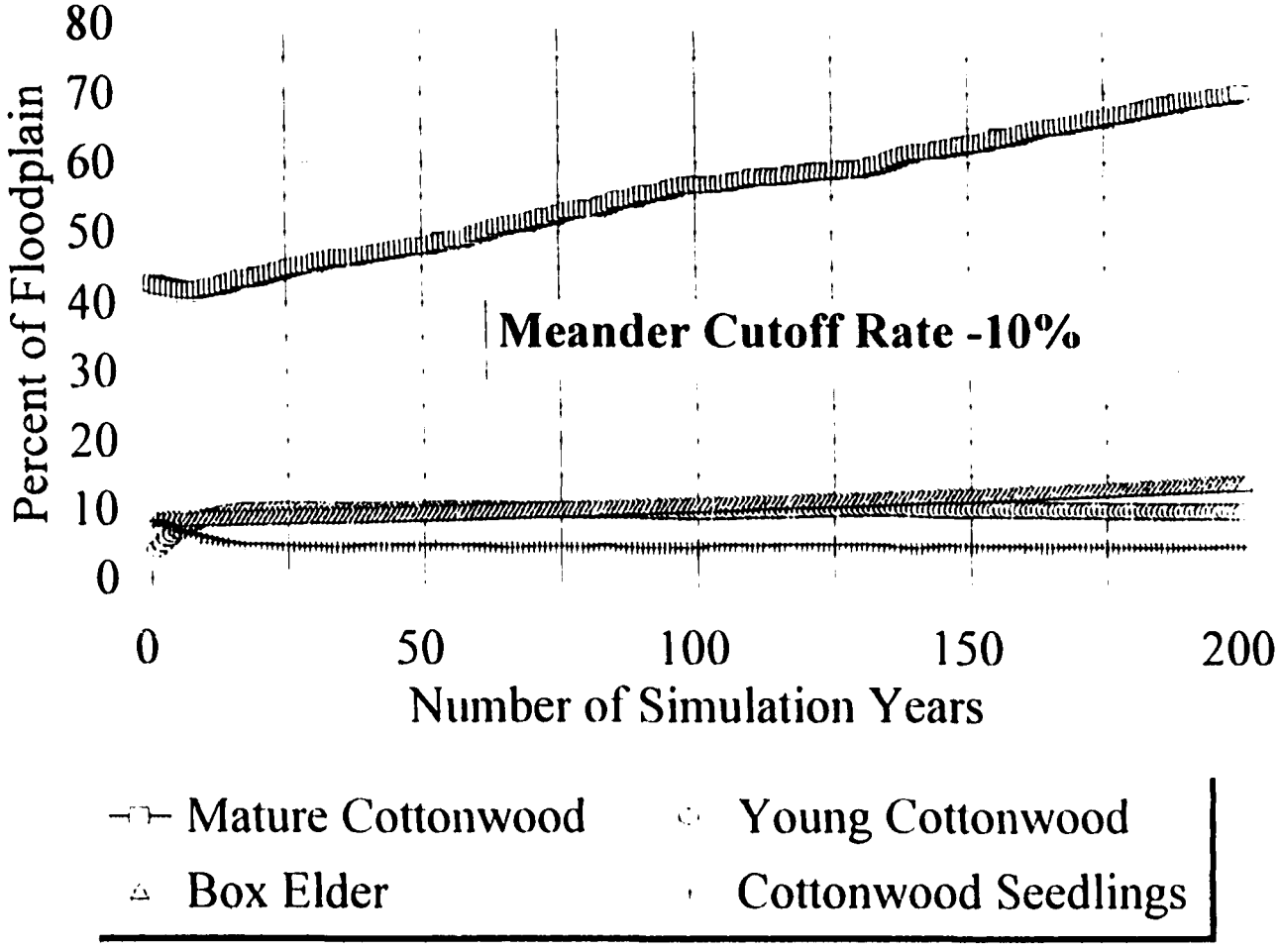

Figure 47. Sensitivity analysis: meander cut-off -10%

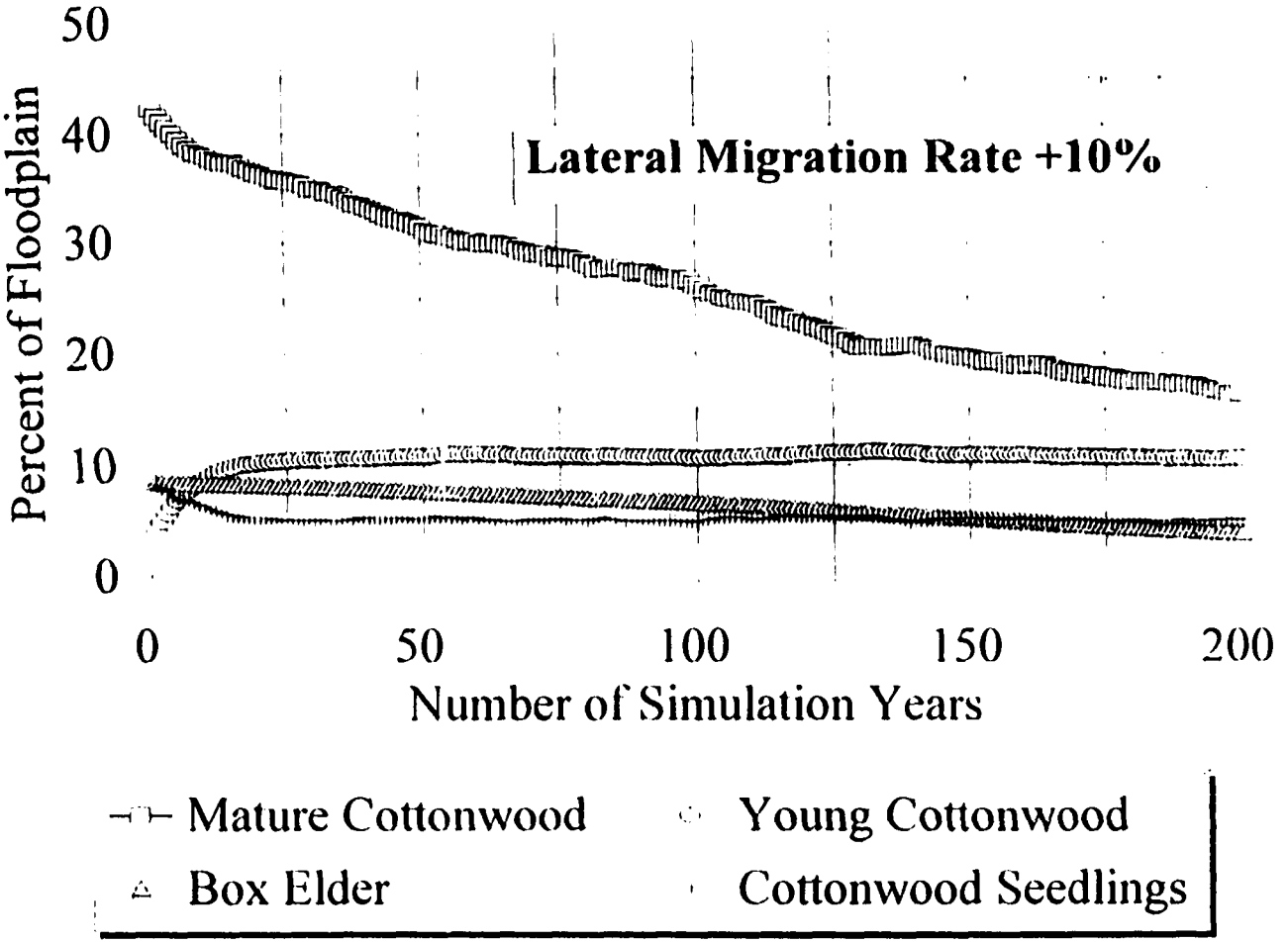

Figure 48. Sensitivty analysis: lateral migration +10%

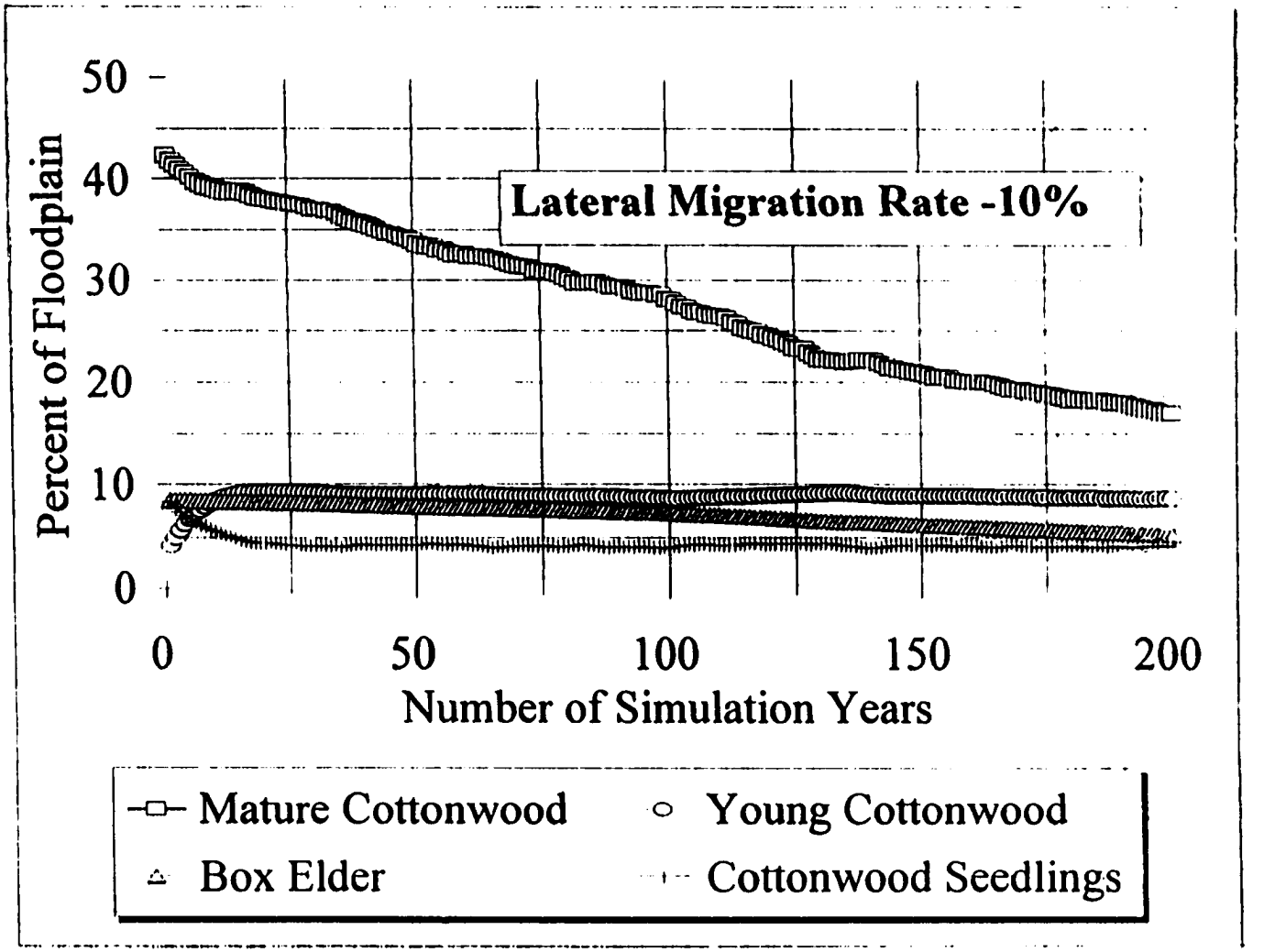

Figure 49. Sensitivty analysis: lateral migration -10%