1996

Water yield recovery in the northern Rockies

C. Paul Callahan
The University of Montana

Recommended Citation

Callahan, C. Paul, "Water yield recovery in the northern Rockies" (1996). *Graduate Student Theses, Dissertations, & Professional Papers*. 7734.
https://scholarworks.umt.edu/etd/7734

WATER YIELD RECOVERY IN THE NORTHERN ROCKIES

C. Paul Callahan
1996

Presented in partial fulfillment of the requirements for the degree of
Master of Science in Forestry

University of Montana
School of Forestry
Missoula, Montana

Approved by:

Committee Chairperson

Dean, Graduate School

MAY 8, 1996

Date

Callahan, C. Paul, B.A. Chemistry, Gettysburg College 1986

Water Yield Recovery In the Northern Rockies DFP

Committee Chairperson: Dr. Donald F. Potts, Associate Dean and Professor of Watershed Management, University of Montana, School of Forestry

The effect of timber harvest on aquatic ecosystems has been the subject of much debate. One of the pivotal aspects of this debate is hydrologic recovery times after clearcut logging. It is theorized here that the hydrologic recovery curves currently in use in the Northern Rockies overestimate the time to complete recovery. This study will clarify some of the terminology used in the discussion of hydrologic recovery, present new recovery curves, and will report the results of a new technique, using leaf area estimation and increment cores, by which land managers in the Northern Rockies could easily predict one component of hydrologic recovery, namely annual water yield recovery.

I can foretell the way of celestial bodies, but can say nothing about the movement of a small drop of water.

Galileo Galilei
as quoted by Daniel Hillel (1980)

ACKNOWLEDGEMENTS

There have been many individuals who have influenced me in the researching and writing of this thesis. I would first like to thank my Committee members. Drs. Kelsey Milner, Bob Pfister, and my committee chairman, Dr. Don Potts have challenged and encouraged me throughout our acquaintance. Dr. Ragan Callaway was generous enough to step in at the last minute to fill a vacated seat on my committee and has offered a fresh and welcome viewpoint.

During my time researching and preparing this paper I had the opportunity to work with numerous hydrologists in the region and have benefitted greatly from my interaction with them. These include: Leigh Bailey, Vito Ciliberti, Mike Collette, Gary Frank, Al Galbraith, Nick Gerhardt, Liz Hill, Steve Johnson, and Bill Schultz.

There have been other resource professionals whom I am lucky enough to call my friends. They have offered perceptive insight, criticisms, and unwavering support during this project and have helped me in other ways of which I am sure they are not all fully aware. These include Mike Biltonen, Ken Brewer, and Dr. Wendel Hann as well as all my former colleagues at the Intermountain Fire Science Lab in Missoula.

Finally, I would like to thank my family. My wife Lynn, mother Margie, and father Lawrence, as well as all my brothers and sisters continue to be my touchstones on the cobbly road of life.

Thanks to all of you.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

Recovery of the hydrologic regime after timber harvest is a function of a multitude of processes. The term itself, "hydrologic recovery", means different things depending on which group of processes one is considering. Strictly speaking, any discussion of hydrologic recovery must consider the effect of roads, ditches, and skid trails as these features have a tremendous effect on the hydrology of a site. To many, a site can never recover hydrologically as long as roads are present. There is much validity to this argument but one must keep in mind the scope of the discussion.

The current study does not address the relationship of roads to streamflow, it is limited to recovery of annual water yield from unroaded, naturally regenerating sites. It is recognized, also, that skid trails will prolong recovery times. This issue, however, was left to the judgement of the hydrologist. Where there are extensive skid trails, as where there is poor regeneration, the curves presented here would underestimate recovery times.

It is the hope of this researcher that the results given below will help land managers in the Northern Rockies gain insight into the temporal effects of timber harvest on water yield. However there are many factors involved in producing cumulative, detrimental effects on water resources and an appropriate policy would be to consider them all.

The major objective of this study is to propose recovery curves for groupings of habitat types of Western Montana (Pfister and others 1977) which are supported by a review of published literature and by the results of a procedure utilizing leaf area estimates and increment cores to predict the annual water yield recovery of a stand.

Numerous studies throughout the world have investigated hydrologic recovery over time. To paraphrase Cook and Reeves (1976), it is easy to become “perplexed by the shifting current of conflicting arguments, the discharge of unsubstantiated assertions, the pools of controversy, and the shoals of abandoned hypotheses.” In addition there is the concern over extrapolation of results from geographical areas outside the Northern Rockies. Data specific to Western Montana concerning hydrologic recovery do not exist other than anecdotally.

Most hydrologists in this region use the methods outlined in *Forest Hydrology Part II* (USDA Forest Service 1973a) to conduct cumulative effects analyses for proposed forest management activities. In this method the past and proposed activities are equated to an “equivalent clearcut area” which brings about an increase in water yield. This increase recovers back to pre-disturbance levels along one of nine curves depending on the habitat type of the site. There have been many attempts at refining the habitat type groupings for each of these curves but the underlying assumptions of the curves have rarely been disputed.

One reason for the unwavering acceptance of these curves is perhaps that they are very protective of the resource. Hydrologists concerned with the impact of multiple harvest activities in a drainage have pointed to the recovery times of 100 years or more as an argument for less harvest. This concern is often well-founded, however, the use of water yield recovery curves, which have not been validated in over 25 years of use, as a tool to limit harvest activities is inappropriate. A goal of this study is to present a more quantitative approach to the issue of water yield recovery.

Practically speaking, annual water yield recovery can be viewed as a function of two processes, evapo-transpiration (ET) recovery (i.e. vegetative regrowth) and the recovery of snow accumulation pattern and process (Figure 1). In the current study, the first process is quantified using leaf area index and heartwood formation. An estimate of leaf area growth over time is made using the ecosystem model FOREST-BGC (Running and Gower 1991). Two field measurements of leaf area index (LAI) are compared to the model results, which are considered to most accurately reflect stand level LAI over time, to determine where the stand falls on the leaf area recovery curve. In addition, heartwood formation is linked to the complete utilization of growing season moisture.

Recovery of snow accumulation processes is dealt with through a comprehensive review of current literature, a discussion of the relevant climatological conditions prevalent in the study area, and a discussion of relevent stand structure characteristics and their response to harvest.

BACKGROUND

Water Yield Recovery Curves

The most comprehensive water yield recovery data sets are from work done in Colorado at the Fraser Experimental Forest (see below for a synopsis of these studies). The prediction of water yield recovery times coming from these studies was the foundation for the seminal work, in Montana, of Al Galbraith and Dale Pfankuch in the early 1970's (personal communication with Al Galbraith, Hydrologist - Bridger-Teton National Forest, Jackson, WY). Water yield recovery curves presented in the documents *Forest Hydrology Part II* (USDA Forest Service 1973a) (Figure 2) and *Vegetation Manipulation Guide for the Lolo National Forest* (USDA Forest Service 1973b) (Figure 3a-c) were based solely on the intuition and personal experience of silviculturalists and hydrologists. The methods outlined in *Forest Hydrology Part II* have been incorporated into the cumulative effects model WATSED and are still widely used.

Of the lasting contributions which this document has made, perhaps the most important is the idea that water yield recovery estimates should be made on a site specific basis and that a suite of different curves should be used to reflect different site, hydrologic characteristics. By presenting multiple curves and grouping sites by the productivity of the habitat type one can more accurately predict recovery times. Galbraith's (USDA Forest Service 1973a) curves remain the basis for most water yield recovery estimates being made in the Northern Rockies.

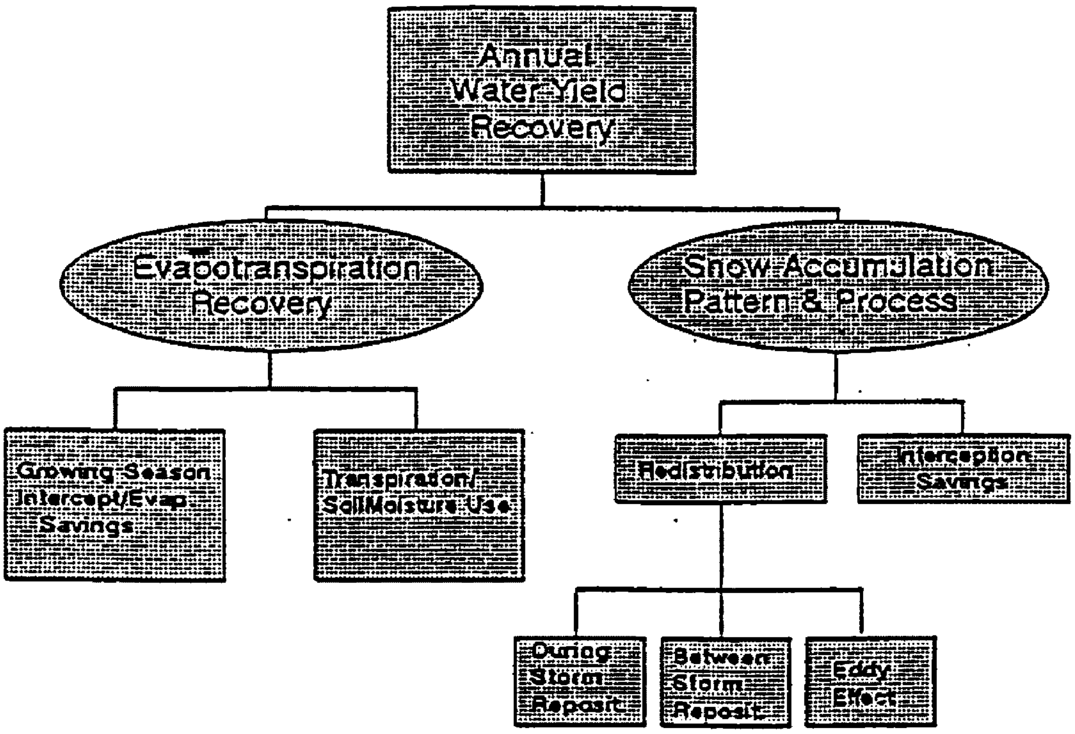
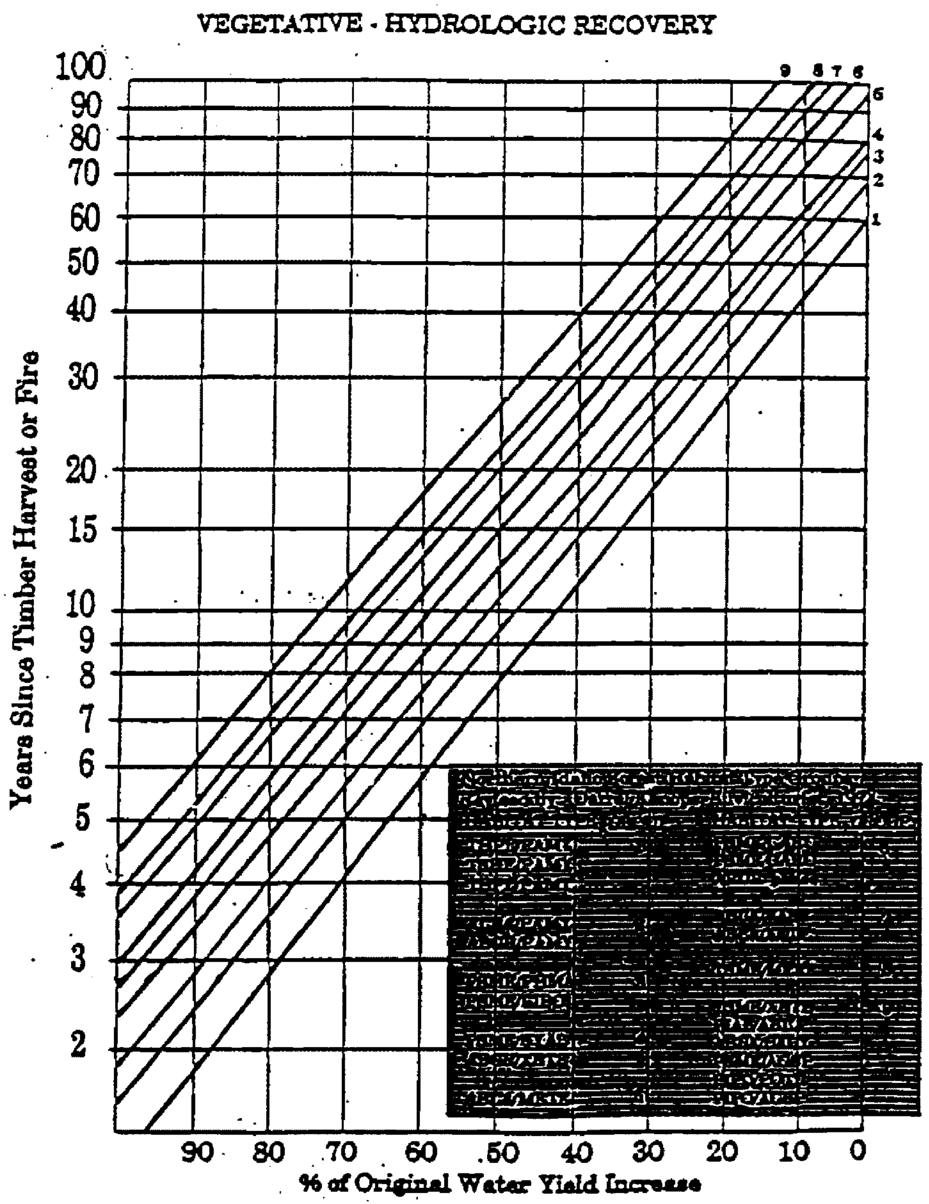


Figure 1. Processes involved in the recovery of annual water yield

In order to set the context within which the current study was undertaken a close look at the water yield recovery curves in both of the previously mentioned Forest Service documents is warranted. First, however, an explanation of the conventional presentation of water yield recovery curves. Water yield recovery curves, as generally shown, may be misleading to some. The log-normal axes, which have become the norm, obscure the

actual relationships which are at work in nature. Figure 4a shows a water yield recovery curve without transformed axes. The recovery occurs quickly in the years immediately following disturbance and slows as time passes. Galbraith (USDA Forest Service 1973a) reversed the axes, putting recovery on the x-axis and years since disturbance on the y-axis, yielding a curves of the form shown in Figure 4b. This curve has a logarithmic form which can then be plotted as a straight line on log-normal axes. The reasoning behind these transformations is unclear, however, the convention will be followed in this study.



Fiigure 2. Water yield recovery curves developed by Al Galbraith (USDA For. Ser. 1973a)

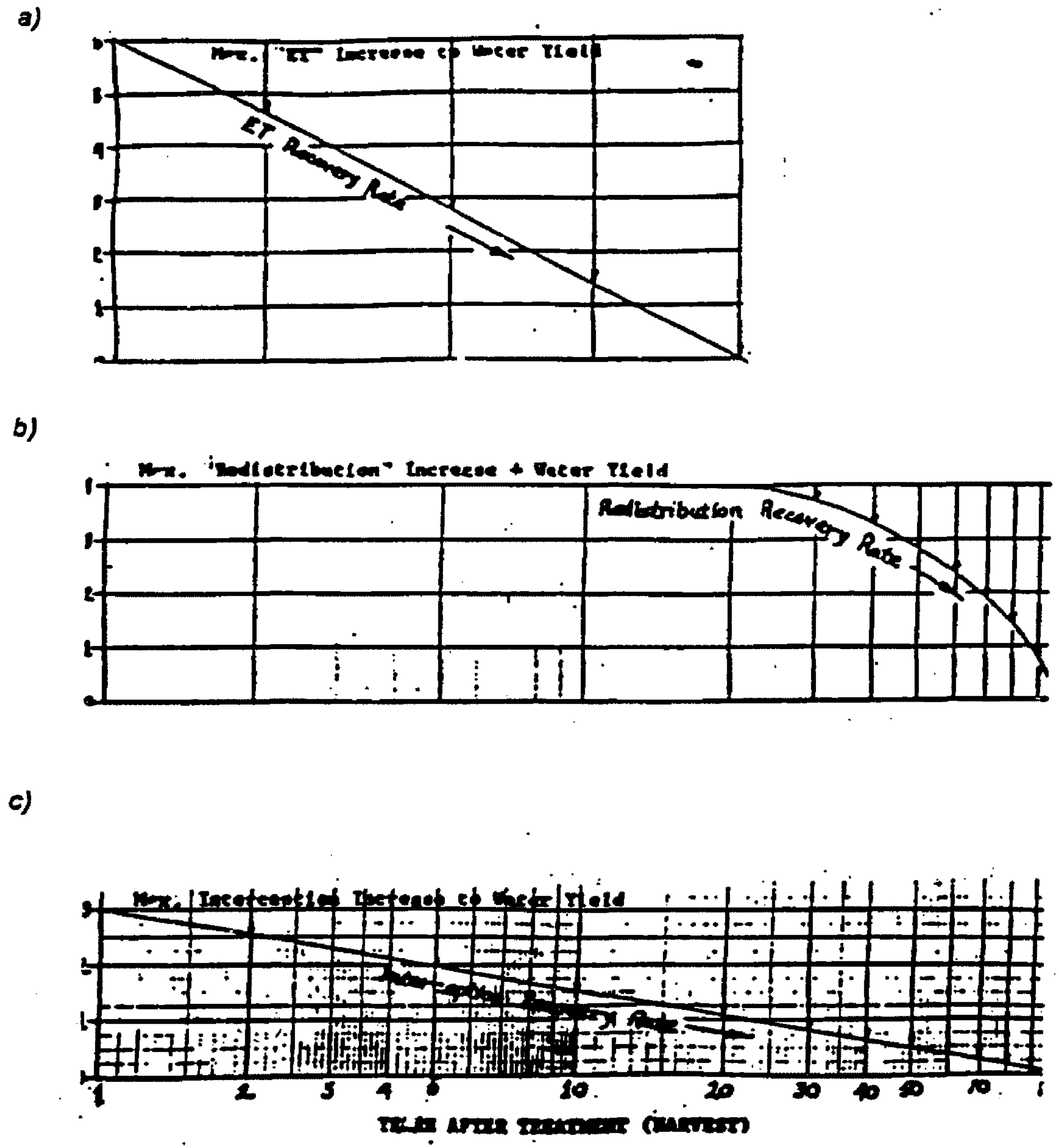


Figure 3. The three factors in water yield recovery (USDA For. Serv. 1973b): a) Evapotranspiration recovery; b) recovery of snow redistribution processes; and c) recovery of snow interception processes.

A close look at the recovery curves in *Forest Hydrology Part II* (USDA Forest Service 1973a) reveals some inconsistencies. These curves seem to grossly overestimate the time of ET recovery which accounts for approximately 70-85% of the water yield recovery (e.g. Gary and Troendle 1982). For instance, the slowest type to recover in Figure 2 is shown by line 9. The slope of this line indicates that it takes more than 50 years for the ET to return to predisturbance levels, an estimate which is without foundation in current literature.

Another example of a recovery estimate based on inconsistent logic is that presented in *Vegetation Manipulation Guidelines* (USDA Forest Service 1973b) for the Lolo National Forest, headquartered in Missoula, Montana. In this document the author recognized that ET recovers quickly (~20 years) (Figure 3a) but projects the time of

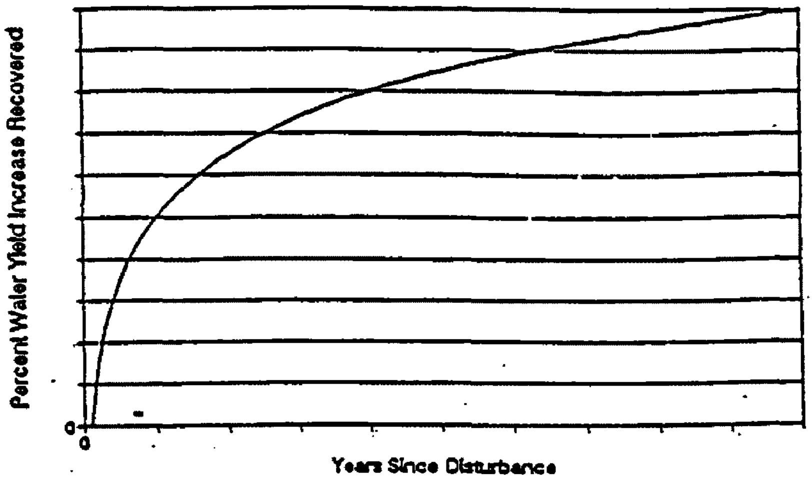


Figure 4a. Generic water yield recovery curve before transforming the axes.

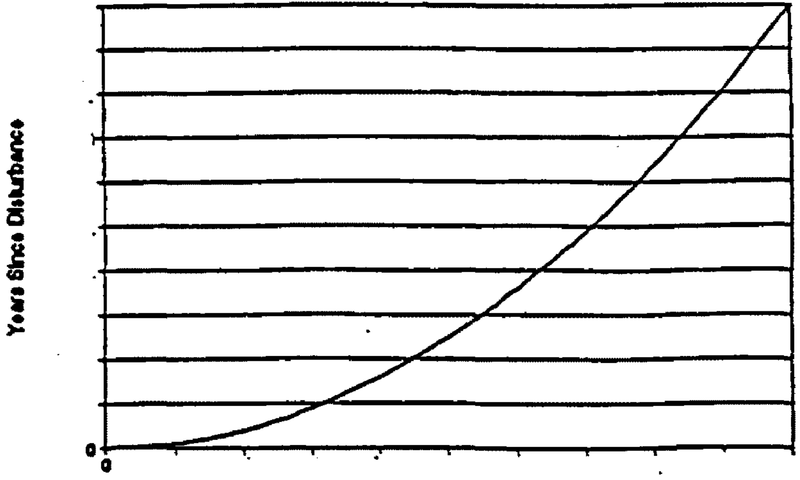


Figure 4b. Generic water yield recovery curve with axes switched to yield a logarithmic curve.

complete hydrologic recovery to be 100 years because of differential snow accumulation (Figure 3b,c). Here, the majority of the water yield increase after 20 years is shown to be from redistribution of snow. As will be discussed below, however, strong evidence indicates that redistribution is not an important factor in differential snow accumulation.

Evapotranspiration Recovery

One of the major foci of this study is the investigation of the theory that heartwood forms in unsuppressed trees at the time of complete site utilization of moisture. Confirmation of this idea would establish the time of ET recovery, one of the two factors in water yield recovery (Figure1).

Evapotranspiration is defined as evaporation from soil, water bodies, and plant surfaces, along with water losses through plant leaves. The relationship of ET to streamflow is shown in the water budget equation for a watershed:

$$Q = P - ET - S - L \tag{1}$$

where Q (mm) is streamflow, ET (mm) is evapotranspiration, P (mm) is precipitation over a time period, S is the amount of storage (recharge capacity) in the watershed,

and L is deep seepage (the difference between seepage into and seepage out of the watershed).

It can be seen from this equation, and research throughout the world has demonstrated, that removing vegetation (i.e. reducing ET) increases water available for streamflow. This increase in available water results from 1) reduced transpiration which leaves a greater amount of soil moisture at the end of the growing season reducing recharge capacity for the following spring melt and 2) savings from growing season rain interception/evaporation (this second component, however, rarely makes its way to the stream because it is quickly utilized by regrowing vegetation or stored as soil moisture (Brooks and others 1990)).

My approach to the investigation of ET recovery is through the relationship between leaf area, heartwood formation, and available moisture.

Leaf Area/Heartwood/Moisture Relationship

Leaf area index (leaf area per unit ground area) is probably the single most important structural property of forests for use in quantifying energy and mass exchange. LAI is directly proportional to canopy interception, transpiration, and net photosynthesis and is, as McNaughton and Jarvis (1983) demonstrated, important in determining canopy-scale estimates of evapotranspiration.

Long and Turner (1975) and Grier and Running (1977) were the first to show that a forested site has a leaf area carrying capacity dependent on water balance and independent of stand density (Knight and others 1981). I interpret their findings to mean that, for water-limited sites, maximum site leaf area index (LAI) will occur at the time of complete site utilization of moisture.

Related to the above theory is the assumption that heartwood forms as a result of competition for light, moisture, or nutrients or a combination of these inputs. Given that, in general, the Northern Rockies is a water-limited environment (McMinn 1952) and given the fact that, by sampling only unsuppressed trees, light is not limited, it seems reasonable to state that the competition for moisture is the impetus of heartwood formation.

Support of this assertion is as follows: Shinozaki and others (1964) observed that sapwood basal area is proportional to leaf area. Subsequent studies have confirmed this relationship, dubbed the "pipe model" theory (e.g. Kaufmann and Troendle 1981, Ryan 1989). It follows that, on individual trees, maximum leaf area will coincide with maximum sapwood basal area (i.e. heartwood formation will begin). This assertion, along with the above statement that maximum site LAI is an indicator of complete site utilization of moisture leads to the postulation that the onset of heartwood formation coincides with complete site utilization of moisture. Leaf area on a site may be mostly in the form of shrubs and herbaceous vegetation early in a stands development but, on forest-potential sites, will gradually become, primarily, conifer leaf area.

Riparian areas, by definition, may not be water-limited and trees in these locations may begin to form heartwood as a result of some other limiting factor or combination of factors (i.e. structural, physiological, light). Sub-alpine sites, as well, may not be water-limited (McMinn 1952, Daubenmire 1968) but could experience water stress due to low soil temperatures which restrict rates of water uptake (Hinckley and Ritchie 1972).

Heartwood formation in an individual tree or a subsample of trees may not, of course, indicate that the entire stand is being stressed by water limitation. To address this complication, the trees sampled in this study were only those which were thought to be the last on the stand to experience water stress, that is, only dominants and co-dominants.

This raises the question: does heartwood form differentially across crown class? This issue was informally investigated by coring individual trees across crown class within a single stand. It was theorized that the suppressed and intermediate trees would experience water limitation and begin heartwood formation first, the co-dominants next, and the dominant individuals would be last. This, however, was not a distinct trend. The more dominant individuals certainly had much greater ring width than the more suppressed trees but the age of onset of heartwood seems consistent across crown class.

Heartwood formation is a poorly understood process. What we do know is rudimentary. The pipe model theory indicates that when a tree reaches the point where it has enough conducting tissue to support its maximum leaf area it will begin to turn the inner pith of the tree to heartwood (the new growth ring will be sapwood and the sapwood area will remain constant, therefore some tissue around the pith must become heartwood). As it grows out each year an additional ring of sapwood will be added to the perimeter while an additional amount of sapwood will be converted to that heartwood already present around the pith.

The formation of heartwood allows for the maintenance of a relatively constant sapwood basal area as growth rings (i.e. additional sapwood) are added annually. The number of annual rings of sapwood decreases as the tree diameter increases. For instance, say a tree experiences relatively constant growing conditions for 50 years and each growth ring is 0.2 inches in width. Let's say further that the tree is cored at age twenty and nineteen of the twenty growth rings are found to be sapwood. This would mean that the sapwood basal area (SWA) is ~49 in^2 (total basal area = 50.26 in^2, heartwood basal area = 1.26 in^2, sapwood basal area is (50.26 - 1.26 = 49 in^2). If the tree was cored again at age 50 and the SWA had remained constant there would only be four rings of sapwood (total basal area = 314.2 in^2, if SWA = 49 in^2 then HWA must be 265.2 in^2 which would be ~46 annual rings of heartwood, leaving 4 rings of sapwood).

Since the sapwood area has theoretically remained constant since reaching a maximum (i.e. since heartwood formation began) then a simple count of the number of sapwood rings will reveal the age at which heartwood on that tree began to form. This approach would be the most valid if the tree had begun heartwood formation in the recent past. The older and larger the tree gets the more potential error is introduced. In the example above, it would be safe to assume the tree had begun to form heartwood at age 19 if the tree core was observed at age 20.

Water Yield Recovery

The effect of silvicultural practices on water yield has been studied in a number of experiments on small, gauged watersheds. These studies, summarized by Hibbert (1967), Anderson and others (1976), and Bosch and Hewlett (1982), demonstrate that removing forest cover increases water yield and that the magnitude of increase depends mainly on water availability and is proportional to the amount of vegetation removed (Rothacher 1970, Reinhart and others 1963).

Troendle and Leaf (1981) presented the following description of the mechanism of water yield increase. During the growing season the evapotranspirational draft, and the resulting depletion of soil moisture, is reduced when vegetation is removed. As a result, soil in harvested areas has higher soil moisture at the beginning of the dormant season. During the winter, precipitation is stored on the ground in the snowpack. When, in the following spring, the snow begins to melt, the soil moisture recharge requirements are satisfied more quickly and the remaining snowmelt becomes available for streamflow. In addition, clearcut areas tend to store snow more efficiently due mainly to decreased surface area, resulting in less ablation.

The first paired catchment study in this country was conducted on the Wagon Wheel Gap watershed in the Fraser Experimental Forest near Fraser, Colorado. Between 1911 and 1926 Bates and Henry (1928) monitored streamflow before and after clearcutting. They observed that the increased streamflow, which was as much as 5 cm, diminished to pre-treatment levels in 5 years due to rapid aspen regrowth. Further work by scientists at Fraser has likely contributed more to the understanding of the effect of vegetation manipulation on forest hydrology than anyone.

Two other important paired catchment studies conducted at the Fraser Experimental Forest are the Deadhorse Creek (Troendle 1982, Troendle and King 1987) and Fool Creek (Troendle and King 1985) experiments (for an excellent synopsis of these three Fraser studies see Troendle and Kaufmann 1987).

Because of the rigor and lengthy period of record it is tempting to put great faith in the results of these studies. However, extrapolation to the Northern Rockies is risky. The headquarters of Fraser Experimental Forest lies at an elevation of 9500 feet. Precipitation on the Forest ranges from 15-30 cm. The snow which falls is generally lower in water equivalent (that is, it is more likely to be blown by wind) and the region receives much greater winter solar radiation than much of Western Montana. Nevertheless, these studies offer good insight into the fundamental relationships between forest hydrology and vegetation manipulation.

The Fool Creek watershed was harvested using a pattern of alternating clearcut and forested strips in 1956. Troendle and King (1985) estimate an 80-year hydrologic recovery (more accurately, *water yield* recovery, since they do not address peak flow problems or subsurface flow changes as a result of roads) period for this watershed and in a separate study based on basal area regrowth Kaufmann (1985) predicts hydrologic recovery in 70 to 80 years. This is for a watershed with a very short growing season and harsh environmental conditions. Elevations range from 9500 feet to 11,500 feet. In fact, the upper quarter of the drainage is alpine tundra.

In the Deadhorse Creek study Troendle (1982) and Troendle and King (1987) observed an average increase in peak water equivalent (PWE) of the snowpack (measured about April 1 each year) of 18 percent for the four years following clearcutting of 36 percent of the drainage. The average observed increase in flow was 24 percent but, interestingly, this increase had no detectable effect downstream. Troendle (1982) states, "The magnitude of the change would not cause a significant increase in either the wetted or evaporative surface along the channel, seepage to groundwater, or an increase in consumptive use by vegetation. It is assumed that the increase has not been "lost" but is simply not detectable at the main gaging station." This study is presented as an illustration of the potential pitfalls, due to observing at an inappropriate scale, which one must face when studying cumulative watershed effects. Potential problems such as severe channel scour can occur in first order streams while little change is detected downstream at a mainstem monitoring site.

As with other studies in Colorado (Troendle and Leaf 1981) and at the James River in Alberta (Golding 1981), the observed increase in flow appears on the rising side of the hydrograph. The increase results from a combination of advancing the spring melt by exposing the pack and smaller soil water deficits from the previous growing season. The peak volume, though advanced two days from the normal date of occurrence, was not increased (Golding 1987).

In more moderate climates, several studies have been conducted which indicate that the invasion of harvested sites by shrubs and grasses quickly brings about recovery of the soil moisture depletion regime. Hibbert (1969), working in the southern Appalachians, clearcut 22 acres and seeded fescue grass. He showed that in years when grass production was high, water yield was about the same as, or less than the expected yield from the original forest (in a rainfall-dominated area such as the southern Appalachians water yield increases would be expected to be attributed almost entirely to soil water savings, the increases in snow accumulation should be minor contributors, thus water yield recovery and ET recovery should correspond closely). A further observation was that the grass appeared to evaporate more water early in the spring and less water late in the summer than the original forest cover.

Closer to my study area, Cline and others (1977) working at the Priest River Experimental Forest in North Idaho showed that invading ninebark rapidly reoccupied a south slope clearcut, eliminating soil water savings (i.e. water yield increases due to reduced ET) within five years of harvest. In this same study a north slope clearcut was reoccupied more gradually by fireweed, a herbaceous species, and showed much slower recovery, though they failed to quantify it. They made no prediction of when the site would recover. Similar results were observed in the Douglas-fir zone of Southwest Oregon where vegetation recovered enough in less than five years after burning a clear-cut area, for soil moisture depletion to equal the rate of the adjacent old-growth forest (Schmidt 1970 as cited in Tobin-Scheer 1993).

Two other studies conducted in the Sierra Nevada found short recovery times for soil moisture depletion. After a selection cutting, soil water savings dropped by 50% in 4 years (Anderson 1963). Similarly, Ziemer (1964) predicted that increases in water stored in the soil would fall to zero by the 16th year following clearcut harvesting.

Others have made predictions of hydrologic recovery. In northeastern Utah four spruce stands at approximately 8400 feet elevation were clearcut. ET recovery was expected to take at least 50 years (Hart and Lomas 1979) and differential snow accumulation patterns were expected to persist for 80 to 160 years in the subalpine zone of Colorado (Leaf and Brink 1975). The later study, however, was based upon the premise that increased snow accumulation is due to redistribution (i.e. snow blowing from the canopy and from adjacent forested areas). Strong evidence, discussed in the following section, now disputes the notion of redistribution and favors the theory of interception savings as the main cause of increased snow accumulation. This issue is discussed in detail in the following section.

Recovery of Snow Accumulation Pattern and Process

It is difficult to separate the many processes which play a role in the differential snow deposition patterns which are observed between openings and forests. It seems clear, though, that in openings which are small enough to mitigate the effects of wind scour loss (less than about 3 tree heights; Golding 1982), the amount of snow water equivalent (SWE) will be greater than in the adjacent forest. Sources of this increased snow accumulation include 1) that which would normally accumulate under an undisturbed forest canopy, 2) that which would have been intercepted and evaporated/sublimated from the forest canopy if the trees were still there, 3) that which falls into the opening because of the canopy discontinuity created by the opening, and which otherwise would have fallen downwind (or even upwind) of the opening, and 4) that which is blown in, either from the canopy or from under the canopy of the adjacent forest (Haupt 1979).

Each of these sources will be addressed in turn. For the purposes of this discussion the first source of increased SWE can be ignored. If the snow would have been on the ground under an undisturbed canopy then its presence in a clearcut presents no change in the site water balance. The fourth source can be split into two: during storm repositioning and between storm repositioning. The amount of snow which is repositioned, from either under or in the forest canopy, into an opening between storms has been observed to be negligible (Troendle and others 1988, Meiman 1987). Snow repositioned into openings during a storm is indistinguishable from that which is deposited in the openings due to wind eddies. The significance of this source in increased water yield will depend on the meteorologic characteristics of each particular storm. The energy of the wind, as well as the density and moisture content of the snow, will affect how much is repositioned after settling on the ground or on a tree crown.

The second and third sources which Haupt (1979) has described are the ones about which the debate has centered. Most often, the term redistribution, used in the context of snow accumulation, refers to the process of increased deposition in clearings due to the aerodynamic effects caused by a break in the forest canopy. Snow which is blown along the shear plane just above the tree canopy may encounter an aerodynamic eddy which causes it to be deposited in the opening. This effect is dependent on clearing size and would persist until the regeneration in the openings is high enough to maintain the wind shear plane along the canopy.

The term “interception savings” refers to Haupt’s (1979) second source of increased SWE. The canopy of a forest intercepts snow which is then subjected to some degree of sublimation or evaporation. This loss occurs to a lesser extent when vegetation is removed. The amount of snow intercepted and evaporated/sublimated is greatly influenced by meteorologic and physiographic factors. Latitude, aspect, elevation, albedo, temperature, snowflake characteristics, and storm characteristics are all critical factors (for an excellent discussion of the factors influencing snow accumulation and runoff see Delk 1972).

The role of particular meteorological conditions on the interception of snow is a complex issue, mostly out of the scope of this study. After all, most of the forces at work would have equal influence on a mature and a young forest. For example the capability of a tree to intercept snow has been correlated with low specific gravity of the snow and storm size (Schmidt and Gluns 1991). These conditions would be the same for both a young stand and a mature forest. The question is whether the stand structure has any relationship to interception capabilities. McNay and others (1988) found that mean crown completeness (the proportion of the sky obscured by tree crowns within a specified angle view from the ground) and storm size were the factors most responsible for a particular stand's capability to intercept snow. They found crown length, crown width, basal area per hectare, tree height, and tree density to be less well-correlated.

Once the snow has accumulated in the tree crown its fate is dependent on a set of factors as complicated as those involved in interception. Snow can be evaporated directly from the canopy or fall in solid or liquid form to the ground. Mass transport of snow could occur due to strong wind conditions or by the process of snow melt and subsequent loss of cohesive strength. Several factors, such as wind velocity, albedo, and temperature, which affect the rate and magnitude of interception retention of snow in trees, also determine the amount of evaporation of that snow. As stated above, however, these factors should all act equally on mature and immature stands.

Regarding the relative effects of redistribution and interception savings as causes of the well documented, increased SWE, the scientific dogma has come full circle in the 50 years since the phenomenon was first investigated.

Wilm and Dunford (1948) studied the effect of differing harvest levels on snowpack accumulation in lodgepole pine (*Pinus contorta*) stands on the Fraser Experimental Forest. They observed an increase in peak water equivalent with increased intensity of harvest and concluded that the increase was due to interception savings.

This assertion was generally accepted until Hoover and Leaf (1967), also working at Fraser, concluded that the differences in snowpack accumulation between forest and clearcuts were a reflection of deposition and redistribution processes rather than interception savings. They further stated that any interception savings would be lost through increased evaporative loss from the snowpack. Several subsequent studies concurred (e.g. Gary 1974, Dietrich and Meiman 1974, and Leaf 1975). Of note is a study in the maritime climate of North Idaho which continued to point out the importance of winter loss by interception/sublimation (Haupt 1972).

While there is agreement that more snow accumulates in openings there is considerable debate about the opposing effect of higher ablation rates in openings. Troendle and King (1987) state that "ablation and differential deposition are inseparable." Nevertheless, it seems reasonable to suggest that slopes with south aspects or at high elevations will receive greater winter and spring solar energy and thus the ablation rate of the snowpack will be greater than that of the adjacent forest and will, to some degree, offset the higher accumulation resulting from redistribution and/or interception savings. This, in fact, was the interpretation made in several studies (e.g. Meiman 1968, Satterlund and Haupt 1972, Haupt 1979, Golding and Swanson 1986).

In contrast, however, Gary (1979) found the *greatest* differences in SWE accumulation between clearing and forest to be on south aspects and he explained the cause as exposure to prevailing southwest winds. This is a clear demonstration of the difficulty in making generalizations about the interwoven processes at work in snowfall accumulation patterns.

Those still holding the opinion that redistribution is the major process affecting differential accumulation argue that the combination of available energy and vapor pressure gradients are seldom adequate to account for the reported values of interception loss. Currently, however, the weight of the scientific evidence seems to support the theory that interception savings, not redistribution, is the major factor in differential snow accumulation (e.g. Gary 1979, Gary and Troendle 1982, Gary and Watkins 1985, and Meiman 1987).

Troendle and others (1988) saw little snow accumulation in openings between storms, agreeing with findings of Troendle and Meiman (1984, 1986) and Wheeler (1987). Troendle and King (1985) harvested a watershed using a strip clearcut method and observed a 9% *net* increase (significant at the 1% level) in snowpack *averaged over an entire watershed* in Colorado. They concluded that "it does not seem likely that depositional differences can play as significant a role as previously thought." This conclusion is supported by the work of Packer (1962) who reported a uniform increase of 10.7 cm snow water equivalent after harvest on the Priest River Experimental Forest.

The proportion of annual precipitation which is lost due to snow interception/evaporation has been estimated by Golding (1982) at 18.3% at Marmot Creek and 12.5% at James River, both in Alberta. Satterlund and Haupt (1970) working in northern Idaho estimated snow interception loss to be only 4.5% and 5.2% of total snowfall in Douglas-fir (*Pseudotsuga menziesii*) and western white pine (*Pinus monticola*) respectively. They found that more than 80% of the snow initially caught in the crowns ultimately reached the ground being washed off by the subsequent rain, falling by direct mass release, or dripping as melting snow. Anderson (1963) states that most studies show that interception losses amount to 10% or less of actual precipitation (USDA Forest Service 1973a). Haupt (1979) showed that PSME and PIPO saplings lost approximately 5% of total snowfall to evaporation.

METHODS

Plot Selection/Sampling Scheme

Habitat types were hypothetically categorized into theoretical slow, moderate, and fast recovery types based upon site a combination of productivity, length of growing season, and other stand development influences (for instance, high water table, high elevation, etc.) (Pfister and others 1977, Appendix E-3) (high productivity correlates with fast recovery of vegetation) and length of growing season. From each of these categories two habitat types were chosen (Table 1) that had a high frequency of occurrence in the study area. The chosen habitat types are quite common in Western Montana and are considered to be clearly representative of the recovery rate category into which they are placed. The selection of the PSME/PHMA moist and dry phases was based on more recent work (Arno and others 1993). Three stands in each habitat type were located from information provided by Champion International Corporation (CIC) and the U.S. Forest Service (Table 2).

As the availability of water, light, and/or nutrients (i.e. growing space) changes, the rate of growth of foliage and the associated sapwood (conducting tissue in the bole) willfluctuate. As a result of this it seems likely that heartwood may form intermittently through the lifespan of an individual tree. In other words, when a disturbance, either natural or anthropogenic, makes more growing space available, a tree that had been putting on heartwood for several years may, once again, add sapwood and cease heartwood formation for a period of time.

Because of this, the stands desired for this study were at an age where the codominant and dominant individuals were just beginning to put on heartwood.

Table 1. Habitat Type Recovery Classes west of the continental divide in the Northern Rockies.

FAST RECOVERY HABITAT TYPES

mountain hemlock/glacier lily (TSHE/CLUN)
western redcedar/glacier lily (THPL/CLUN)*
grand fir/glacier lily (ABGR/CLUN)*
grand fir/twinflower (ABGR/LIBO)
spruce/dwarf huckleberry (PICEA/VACA)
spruce/glacier lily (PICEA/CLUN)
subalpine fir/glacier lily (ABLA/CLUN)

MODERATE RECOVERY HABITAT TYPES

subalpine fir/sweetscented bedstraw (ABLA/GATR)
subalpine fir/*menzesii ferruginea* (ABLA/MEFE)*
sublapine fir/twinflower (ABLA/LIBO)
Most Douglas-fir types (PSME/PHMA moist phase)*

SLOW RECOVERY HABITAT TYPES

pinus albicaulus/subalpine fir (PIAL-ABLA)
subalpine fir/*luzula hitchcockii* (ABLA/LUHI)
subalpine fir/*calamagrostis canadensis* (ABLA/CACA)
sublapine fir/beargrass (ABLA/XETE)*
Douglas-fir/ninebark (PSMEPHMA dry phase)*
All ponderosa pine types (PIPO/****)

* chosen for this study

The age at which heartwood begins to form was initially hypothesized to be 30, 45, and 60 years for the fast, moderate, and slow recovery types, respectively. This was based on a general knowledge of the literature regarding ET recovery. Early in the data collection, however, it became apparent that heartwood formation occurs as early as 7 - 10 years on the fast types and no later than 25 years on the slow types. As a result of this late realization, some of the stands which were sampled early in the data collection process are not in the desired age range and some error in the determination of heartwood initiation ages may have been introduced.

Data Collection

Within each of the 19 stands (three each for each of five habitat types, four for ABLA/XETE) (Table 2) two tenth-acre fixed area plots were laid out aligned with the cardinal directions (on very dense, homogenous stands the plots were smaller). On each plot all trees were tallied in their respective DBH class. Increment cores were then taken from three trees of each of the two dominant species. Two cores were taken at right angles at collar height (15 cm or as low as the local duff and terrain permitted) to accurately determine the total age of the tree and the age at onset of heartwood. The latter being determined by counting the number of rings of sapwood. To accurately distinguish the heartwood-sapwood boundary several stains were tried but they were very species-specific and none were truly effective. The most effective method found was to hold the core up to a light sky. When the core was backlit properly the conducting sapwood tissue was translucent while the heartwood was opaque. In certain species (i.e. Douglas-fir) there is also a distinct color difference between heartwood and sapwood.

Within each tenth-acre plot a twentieth-acre circular plot was used to conduct an understory inventory (O'Brien and VanHooser 1983).

Table 2. Plot Name, location, ID code (for use on figures), physical setting, and age.

Plot Location	Plot ID	Habitat Type	Slope%	Elev. (ft)	Aspect (deg)	StandAge (yrs)
W.Fk. Schwartz Crk (Lolo NF)	PPD1	PSME/PHMA dry	55	3900	90	70
Windy Saddle (Lolo NF)	PPD2	"	32	4000	160	32
Antenna Rd./Windy Saddle (Lolo NF)	PPD3	"	30	4600	202	31
W.Fk. Gold Crk (CIC)	AX1	ABLA/XETE	65	5000	35	56
Sleeping Child Burn (Bitteroot NF)	AX2	"	25	7000	80	23
Sleeping Child Burn (Bitterroot NF)	AX3	"	30	7100	110	24
Sleeping Child Burn (Bitterroot NF)	AX4	"	32	7240	30	25
Park Creek (Lolo NF)	PPM1	PSME/PHMA moist	80	4200	0	42
Blue Mtn. (Lolo NF)	PPM2	"	26	5800	154	27
Snowbowl Rd. (Lolo NF)	PPM3	"	37	4900	325	26
W.Fk. Schwartz Crk. (Lolo NF)	AM1	ABLA/MEFE	33	4600	50	26
W.Fk. Schwartz Crk. (Lolo NF)	AM2	"	30	4700	115	24
W.Fk. Elk Crk. (Lolo NF)	AM3	"	20	5000	110	26
Whitetail Crk. (Kootenai NF)	TC1	THPL/CLUN	30	3850	90	23
W.Fk. Yaak R. (Kootenai NF)	TC2	"	24	4400	120	25
W. Fk. Yaak R. (Kootenai NF)	TC3	"	19	4200	90	24
Jewel Basin (Flathead NF)	AC1	ABGR/CLUN	55	3860	310	30
Jewel Basin (Flathead NF)	AC2	"	60	4000	180	30
Jewel Basin (Flathead NF)	AC3	"	50	4200	15	27

Leaf Area Index Estimation

Three methods were used to calculate leaf area index (LAI) for each stand. The first estimation was obtained from the forest growth simulation model FOREST-BGC (Running and Gower 1991). The second method utilized light attenuation as measured by a portable integrating radiometer (Decagon Devices 1987, Pierce and Running 1988). Finally, by piecing together relationships from several different studies I was able to develop an allometric calculation of LAI for each stand. Each of these methods will be discussed in turn below.

FOREST-BGC LAI Estimate

The most recent version of FOREST-BGC uses water and nitrogen limitations to alter the leaf/root/stem carbon allocation fraction dynamically at annual iterations (Running and Gower 1991). This model was used in the current application to "grow" a stand for 50 years, starting at an estimated age of 6 years. The leaf carbon output (kg) was then converted to leaf area using the specific leaf area of 25 m^2/kg carbon (Running and Hunt 1993). The dimensionless stand LAI was calculated by dividing leaf area (m^2) divided by ground area (m^2).

In order to run this model for a specific geographic area a number of initialization parameters are required. Default values for several of these parameters have been derived and tested in other applications (Running and Gower 1991, Running 1993) and these were applied here (see Appendix A). Certain stand specific values, however, were used to differentiate each of my sites.

Soil water holding capacity (SWC) is an important parameter to define for this model. Running (1993) states that :

> ...by far the most difficult important parameter to define is soil water-holding capacity available for water uptake by roots. Although, typically these measurements are made for the top 1 m of soil, in

> reality we have no way of knowing the depth and rooting extension of trees on these sites. The SWC measured by accepted techniques...ranged from 4 cm to 22.6 cm across the sites, yet measured SWCs are clearly inadequate to support the observed vegetation....it is clear that typical soil-sampling data is the wrong methodology to rely on for this parameterization.

A figure of 20% of the volume of the rooting zone is a reasonable estimate of soil water-holding capacity but, as stated above, there was no way of knowing the depth and rooting extension of the trees on these sites. Because of this uncertainty I decided to hold SWC constant at 2000 m^3 / hectare for all my sites. This corresponds to an estimate of 1m for the rooting zone for all of the study sites.

Another parameter for which the defaults were not used was the initial carbon allocation figures. In a previous study (Milner and Coble, pers. comm.) a 12-15 year old stand was assigned the carbon initialization values of 400 kg for foliage, 3320 kg for stem, and 820 kg for roots.

Since I wanted my BGC run to start with a stand younger than 12 years I used figures which were 50 percent of those values and assumed the starting age was 6 years. This age was chosen to reflect an average time it takes for a seedling to become established. As with SWC this value was held constant for all of the model runs.

The distinguishing parameter between sites was the climate data set. To obtain these I used the weather extrapolation model MT-CLIM (Running and others 1987). This model takes data from a base meteorological station and projects what the conditions would be at a different but nearby location, given the slope, elevation, and aspect. The base stations that were used for the various sites, along with the estimated yearly precipitation (USDA SCS 1970) are shown in Table 3.

Individual 50 year BGC runs were made for each location and the output value of leaf carbon (kg) was converted to LAI (specific leaf area = 25 m^2/kg). The LAI thus determined was all-sided. This value was then divided by 2.2 to arrive at projected LAI. Using the age of each stand a single LAI figure was determined from the appropriate LAI growth curve.

Ceptometer LAI Estimate

The second estimate of stand LAI was made using a portable integrating radiometer (ceptometer). Canopy transmittance of each plot was sampled using the sunfleck ceptometer on cloudless days between 20 July and 31 August in two field seasons, 1992 and 1993. Because of the travel distance and unusually cloudy weather not all plots have ceptometer measurements.

For each plot sampled, 3200 points were measured at each of three heights, soil surface, 1.5 feet, and 6.1 feet. This was easily accomplished because the instrument instantaneously integrates 80 radiometer measurements at once and stores them in a datalogger (Decagon Devices 1987). The 3200 measurements

Table 3. Weather Data Inputs to MTCLIM

Location	Base Station	Base Sta. PPT (cm)	Plot PPT (cm)
W.Fk.Schwartz Creek #1(Lolo NF)	Missoula	40	63.5
Windy Saddle (Lolo NF)	Missoula	40	63.5
Antenna Rd./Windy Saddle(LoloNF)	Missoula	40	76.0
W.Fk.Gold Creek (CIC)	Missoula	40	76.0
Sleeping Child Burn #1(Bitterroot NF)	Darby	44	70.0
Sleeping Child Burn #2	Darby	44	70.0
Sleeping Child Burn #3	Darby	44	70.0
Park Creek (Lolo NF)	Missoula	44	63.5
Blue Mountain (Lolo NF)	Missoula	40	63.5
Snowbowl Road (Lolo NF)	Missoula	40	64.0
W.Fk.Schwartz Creek (Lolo NF)	Missoula	40	51.0
W.Fk.Schwartz Creek (Lolo NF)	Missoula	40	51.0
W.Fk.Elk Creek (Lolo NF)	Missoula	40	51.0
Whitetail Creek (Kootenai NF)	Troy	90	127.0
W.Fk.Yaak River #1 (Kootenai NF)	Troy	90	127.0
W.Fk.Yaak River #2 (Kootenai NF)	Troy	90	114.0
Jewel Basin (Flathead NF)	Creston	51	89.0
Jewel Basin (Flathead NF)	Creston	51	89.0
Jewel Basin (Flathead NF)	Creston	51	89.0

at the soil surface were used to determine total plot LAI. The transmittance values for each plot were then averaged and converted to LAI using the Beer-Lambert Law:

[2] $$LAI = -\ln(Q/Q_o)/K,$$

where *LAI* is projected LAI, *K* is a light extinction coefficient, Q_i is the average below-canopy transmittance, and Q_o is the average total incoming transmittance.

An extinction coefficient is a value which is used to characterize the ability of vegetation to intercept solar radiation. The value may range from 0.3 to 1.5 (Landsberg 1986) but data collected by Jarvis and Leverenz (1983) indicate that the average value for both coniferous and deciduous forests is about 0.5. Following Pierce and Running (1988) I used a value of 0.52 except where a plot had a large deciduous component. In this case a value of 0.70 was used.

LAI Estimate Using Allometric Relationships

To calculate stand LAI using allometric equations several studies were utilized. Leaf area for each of the four lifeforms in each stand (trees, shrubs, forbs, and grasses) was calculated by a different method. Once the leaf area value for each of these components was calculated they were summed to give a total stand LAI.

Allometric Estimate of Overstory Conifer Leaf Area Index

To calculate conifer LAI, I first calculated tree foliage biomass using the regression statistics shown in Table 4 (the deciduous overstory component LAI was calculated using the shrub method described below). Using the tree tally by diameter class, a dry weight biomass was calculated for all conifers on each plot and a specific leaf area of 5 m^2/kg dry mass (note that this is different than the specific leaf area based on kg of carbon used in the BGC conversion) was used to calculate leaf area for each tree. These figures were summed to arrive at leaf area per plot area. Converting units appropriately yielded stand LAI for conifers.

Allometric Estimate of Shrub Leaf Area Index

In an unpublished study conducted in 1974 and 1984 at the Coram Experimental Forest near Columbia Falls, Montana, Schmidt and Fiedler (1984) derived regression equations for the biomass of several shrubs using foliage volume (Table 5). I used these relationships, as follows, to derive shrub biomass for each plot and applied a specific leaf area of 17m^2/kg (Running and Hunt 1993) to calculate LAI.

As mentioned previously, the understory was inventoried using the method of O'Brien and Van Hooser (1983). For each of the four most prevalent tree, shrub, forb, and grass species a cover class was visually estimated and assigned one of the following classes (Daubenmire 1959):

Crown canopy cover class codes	Percent crown canopy coverage
1	5
2	6-25
3	26-50
4	51-75
5	76-95
6	96-100

Likewise, the height layer was estimated ocularly. The height layers were as follows:

Layer 1 - (0-1.5 ft)
Layer 2 - (1.6-6 ft)
Layer 3 - (6.1+ ft)

Using the midpoints of these categories I was able to calculate volume of foliage.

In the case of some shrub and deciduous tree species I estimated the length of "canopy" instead of using the layer mid-point. For instance, many of the plots had geyers willow (*Salix geyerani*) as a prevalent component. This species often was called as being in layer 3 (greater than 6.1 feet) however, the foliage of this species is generally limited to only the upper 2-4 feet of the plant. In this case a canopy length of 3 feet (~10 dm) was used.

For many species the use of layer midpoints obviously overestimated or underestimated the actual foliage volume. However, it was assumed that these discrepancies would cancel each other, leading to a reasonable canopy volume estimate.

There were species present on certain plots for which no regression relationship was developed in Schmidt and Fiedler (1984). In these cases a species was chosen from Table 4 which had similar foliage characteristics and the regression equation for that species was used.

Biomass figures were calculated for all shrubs and deciduous trees. These were summed and multiplied by the specific leaf area and then divided by area to arrive at a plot LAI. Units were converted where appropriate.

Table 4. Statistics to Determine Conifer Foliage Biomass

Species	Regression Statistics			Reference
	a	b	r^2	
Douglas-fir	5.630	0.989	0.46	1
Ponderosa Pine	4.788	1.213	0.66	1
Western Red Cedar	5.314	1.363	0.96	1
Western Larch	4.986	1.046	0.98	1
Sub-alpine Fir	5.970	1.185	0.90	1
Grand Fir	6.108	0.961	0.81	1
Lodgepole Pine <1000 TPA	10.300	0.016	0.96	2
Lodgepole Pine 1000-1500 TPA	-1.000	0.034	0.83	2
Lodgepole Pine 1500-2500 TPA	-0.500	0.031	0.84	2
Lodgepole Pine >9000 TPA	-0.140	0.025	0.84	2

1 Snell and Brown (1978;
Model: $\ln(wt) = a + b \ln(d)$;
wt is foliage biomass in grams, *d* is DBH in cm

2 Pearson and others (1984);
Model: $wt = a + b\,(tba)$;
wt is foliage biomass in kg, *tba* is tree basal area in cm^2

Allometric Estimate Forb and Grass Leaf Area Index

Studies conducted to determine biomass of forbs are few. The one conducted closest geographically to my study area was that of Olson and Martin (1981) working in north-central Washington. Fortunately, this paper also presented a relationship for pinegrass (*Calamagrostis rubescens*), the most common grass on my plots. Unfortunately, the Olson and Martin study was limited in scope, only testing three forbs (Table 6).

Table 5. Regression Statistics To Determine Shrub Foliage Biomass

Species	b	r^2
Rocky Mountain Maple (*Acer globularis*)	0.2619	0.97
Alder (*Alnus sinuata*)	0.1775	0.93
Serviceberry (*Amalancher alnifolia*)	0.1403	0.96
False Huckleberry (*Menziseii feruginea*)	0.2292	0.87
Ninebark (*Physocarpus malvaceus*)	0.1477	0.93
Prickly Currant (*Ribes montigenum*)	0.1311	0.97
Scouler willow (*Salix scouleriana*)	0.0450	0.92
Buffalo-berry (*Sheperdia canadensis*)	0.3265	0.95
Mountain Ash (*Sorbus Scopulina*)	0.1156	0.98
Spirea (*Spirea betulafolia*)	0.1266	0.91
Snowberry (*Symphoricarpus albus*)	0.1117	0.95
Big Huckleberry (*Vaccinium membranaceum*)	0.2532	0.92
Huckleberry (*Vaccinium globularus*)	0.3497	0.87

Schmidt and Fiedler (1984);
Model: wt = b(vol)
wt = foliage biomass in grams, vol = foliage volume in dm^3

Given the dearth of information on this subject I was forced to use one of these equations for each of the forbs on my plots. I chose the species from Table 6 which most closely resembled each of my forbs and used that regression equation to calculate foliage biomass.

The biomass figures were summed and multiplied by specific leaf area and divided by area of the plot to arrive at forb LAI.

The foliage biomass for all grass species was calculated using the equation for pinegrass. The specific leaf area of 5 m^2/kg dry mass was applied to arrive at plot leaf area and, again, divided by plot area to arrive at stand LAI.

Table 6. Statistics to Determine Forb and Grass Foliage Biomass

Species	a	b	r^2
Sidebells pyrola (*Pyrola secunda*)*	-0.23194	0.06348	0.95
Meadowrue (*Thalictrum occidentale*)	0.10045	0.00639	0.96
Western Rattlesnake plantain (*Goodyera oblongifola*)	0.39309	0.30382	0.83
Pinegrass (*Calamagrostic rubescens*)*	0.78009	0.25822	0.70

Olson and Martin (1981);
Model: wt = a + b(cov) * (ht)
wt = foliage biomass (g/0.5m^2), cov = percent ground cover, ht = plant height in cm
*Model for *Pyrola* and *Calamagrostis* was wt = a + b (cov)

RESULTS

Figure 5 shows the average age of onset of heartwood for the study plots in each habitat type. The Slow recovery types (ABLA/XETE and PSME/PHMA dry phase) had an average onset age of 17 and 26 years, respectively. The moderate recovery types both averaged 15 years and the Fast recovery types (ABGR/CLUN and THPL/CLUN) averaged 12.5 and 11 years respectively.

The LAI growth curves, as estimated by FOREST-BGC, for each study site are shown in Figures 6a-c, 7. It was expected that the large differences in site precipitation levels would be reflected by significant differences between the leaf area recovery curves. This was not the case, however. The similarity of these curves between stands may be explained by the fact that all the model runs were initialized with exactly the same values with the exception of the climate data. The climate data which was used for MT-CLIM varied in the annual precipitation and the physiographic characteristics of the stands (i.e. slope, elevation, aspect, latitude, longitude). The range of elevations for the plots in this study is from 3850 feet on the Kootenai National Forest in northwest Montana to 7240 feet on the Bitterroot National Forest in west-central Montana. The difference in latitude, with the lowest site being the furthest north and the highest site being the furthest south could account for the low variability in LAI estimations calculated from model runs. Using the approximate age of each stand (Table 2), as determined by increment cores, the BGC-predicted LAI was obtained from the LAI recovery curve (Figures 6a-c). For all stands modeled the LAI reaches

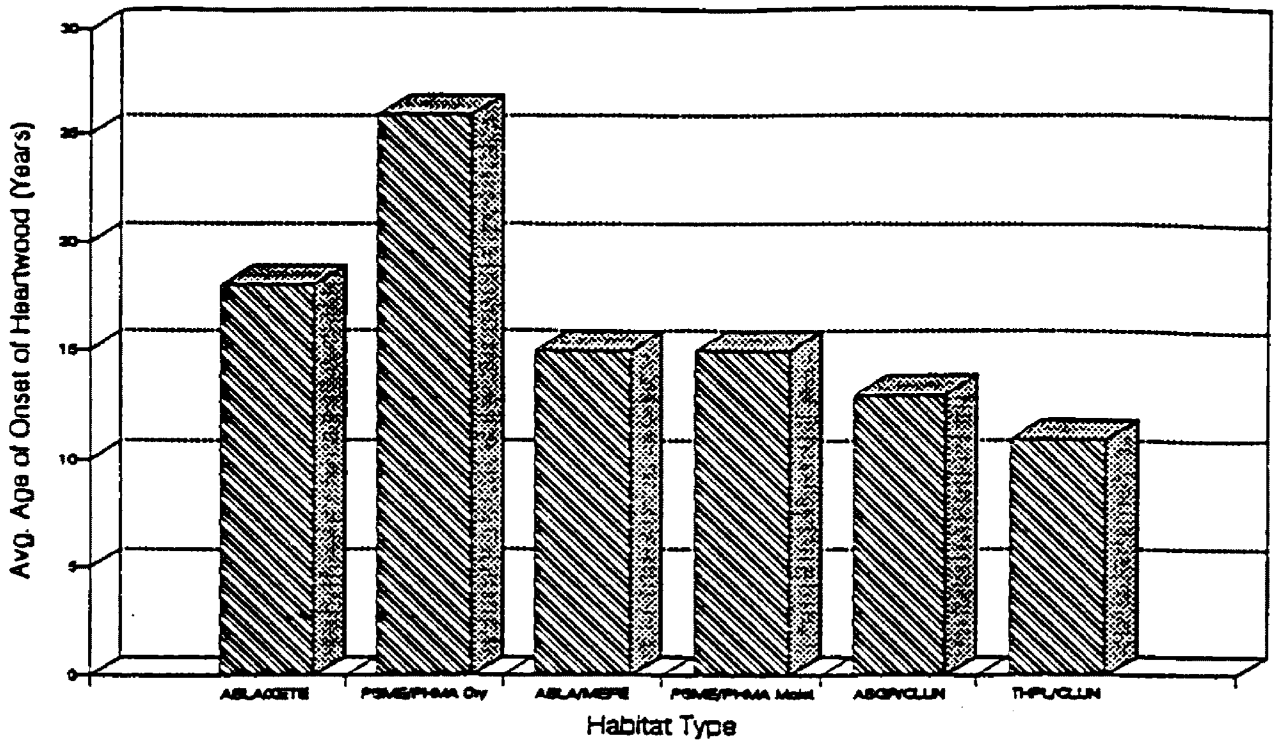


Figure 5. Average age of onset of heartwood for each of the studied habitat types.

a maximum of approximately 3.5 to 4.5 between the age of 20 and 25. After reaching this maximum the LAI drops slightly to a plateau of approximately 3.0 to 4.0. These values are graphed with ceptometer LAI measurements and allometric LAI estimations in Figures 8a-c.

The allometric LAI values are notably out of agreement with the other two estimates. They are higher than BGC-predicted LAI in 32 of the 38 plots. The lodgepole pine allometric is the cause of the large discrepancies found for the ABLA/XETE plots 2 through 4. These stands were extremely dense and the allometric equation may, in fact, be the most accurate calculation of actual LAI. Another possible explanation for the high allometric LAI could be that, because these stands were so heavily stocked, tallying the trees on the plot was more difficult and some error could have been introduced.

The allometric LAI values for the ABGR/CLUN stands are also very much higher than the ceptometer or model values. There seems to be no good explanation for this other than the fact that allometrics have been shown to overestimate leaf area (relative to other estimates) inprevious studies (K.Milner, pers.comm.). The ceptometer LAI observations were the lowest of the three estimations in every stand.

DISCUSSION AND CONCLUSIONS

There should be little argument over the fact that the factor delaying annual water yield recovery for long periods of time is not the return of predisturbance ET levels. Rather, it is changes in the pattern and process of snow accumulation which cause lingering effects.

Recovery of ET to predisturbance levels has been observed to occur quickly due to invasion of shrubs and herbaceous vegetation (e.g. Anderson 1963, Ziemer 1964, Hibbert 1969, Cline and others 1977). On the other hand, water yield increases attributed to changes in the snowmelt regime have been expected to remain detectable for 80 (Troendle and King 1985) to 160 years (Leaf and Brink 1975). The major objective of this study was to present water yield recovery curves supported by scientific evidence. A part of this objective was to present evidence that, by obtaining increment cores for a representative sample of trees on a site, one could establish annual water yield recovery. It seems clear, as will be shown in the following discussion, that increment cores can be utilized to determine if a stand has reached a maximum LAI. If the stand has done so that should establish ET recovery. However, the snow accumulation processes must be dealt with separately and so water yield recovery, *per se*, can not be determined solely by the establishment of ET recovery.

The approach utilized to determine ET recovery is to use stand-level leaf area and heartwood formation as indicators. The reasoning behind this

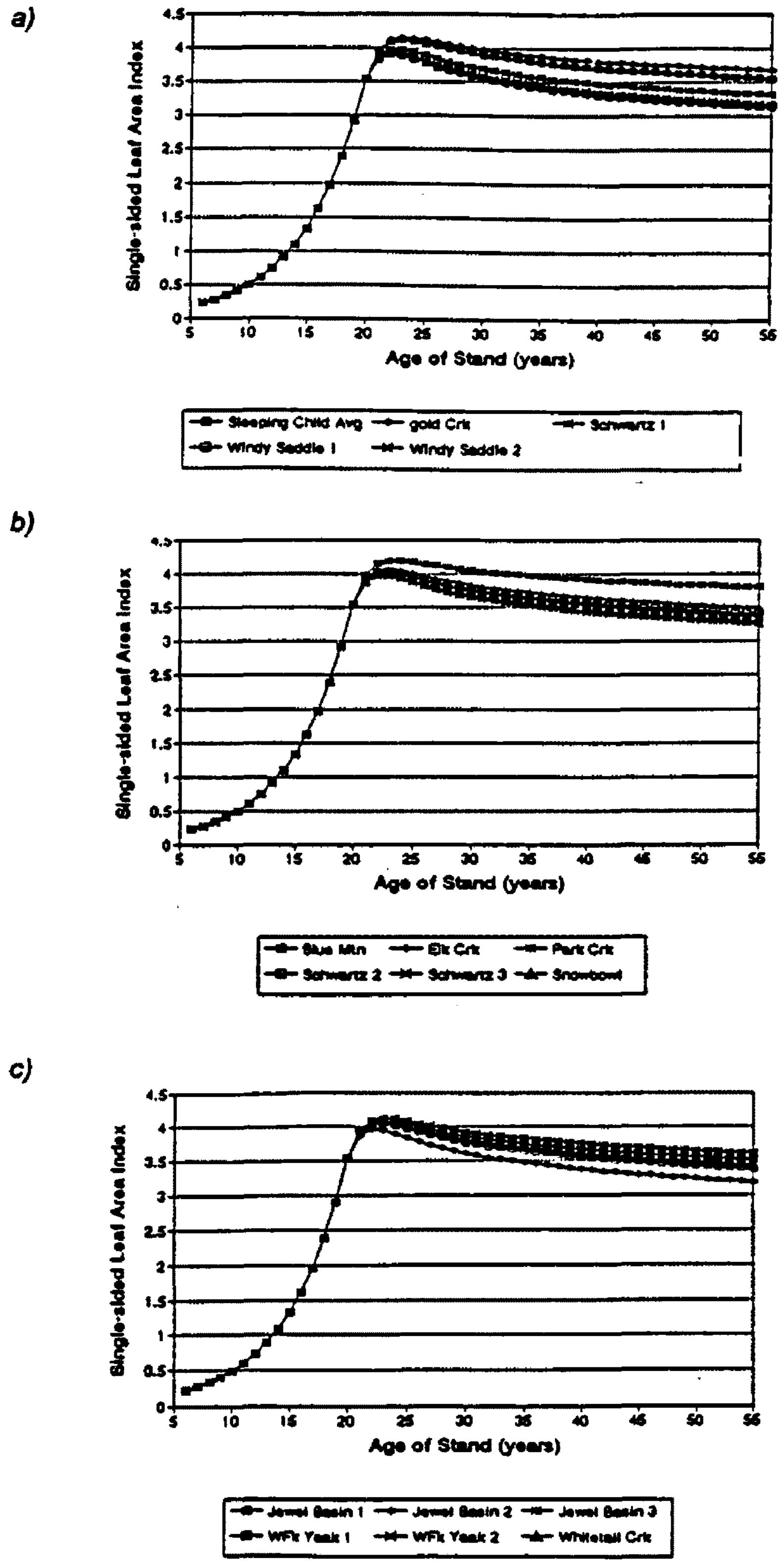


Figure 6. Single-sided (projected) LAI recovery as modeled by FOREST-BGC for slow (a), moderate (b), and fast recovery types

The approach utilized to determine ET recovery is to use stand-level leaf area and heartwood formation as indicators. The reasoning behind this approach is as follows: leaf area has been shown to be proportional to sapwood basal area (Shinozaki and others 1964) and maximum leaf area occurs at the time of complete site utilization of moisture (Grier and Running 1977). Therefore, heartwood formation should coincide with maximum site utilization of growing season moisture (i.e. evapotranspiration recovery). Average, observed ages of onset of heartwood are shown in Figure 5. These ages are in agreement with numerous studies indicating ET recovery in 5 to 30 years.

LAI recovery was estimated using three methods, allometric equations, FOREST-BGC ecosystem model, and a portable, integrating ceptometer. The large variability in the three LAI estimates (Figures 8a-c) made it untenable to draw a clear conclusion, based on my results alone, that leaf area had reached a maximum and thus, that ET had recovered. Nevertheless, a certain degree of confidence may be placed in the LAI recovery curves as modeled by FOREST-BGC. Use of this model in numerous other studies has confirmed it's accuracy in predicting ecosystem carbon allocation and, thus, leaf area. The curves from the model indicate that LAI recovery occurs in 20 to 25 years. This, along with published research and the heartwood onset ages, provides significant credence to the theory that ET recovers in 10-30 years, depending on site productivity.

Evapotranspiration, technically speaking, would also include ablation of a snowpack. In the context of water yield increases, however, the processes

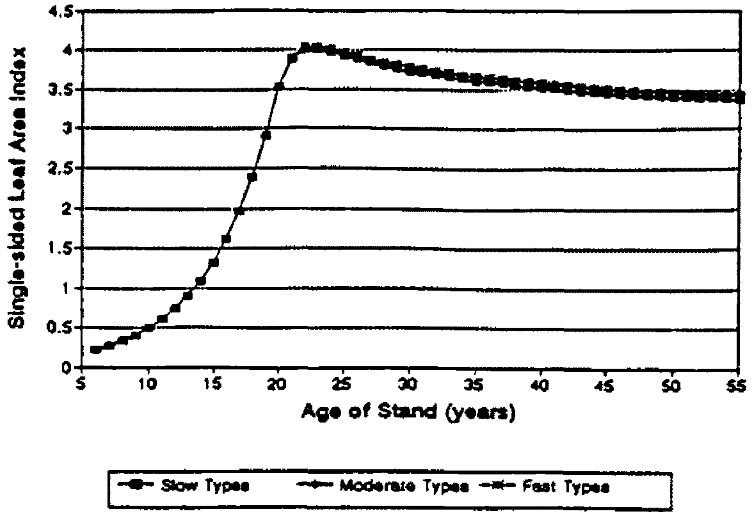


Figure 7. Average Single-sided LAI as modeled by FOREST-BGC for slow, moderate, and fast recovery habitat types.

involving snow must be dealt with separately from ET. The reason for this is that a significant portion of the snowmelt runoff in the Northern Rockies occurs before the vegetation is transpiring in the spring. If there is an increase in the amount of snow accumulation over predisturbance levels there will be an increase in water yield which is not subject to use by regrowing vegetation.

The recent research into snow accumulation processes indicates that interception, rather than redistribution, is the dominant cause of the observed increase in snow water equivalent in openings. McNay and others (1988) showed that the canopy completeness was the best stand characteristic at predicting the amount of snow intercepted. Canopy closure in forest types of this region can be expected sometime between age 17 (Wilford 1987) and 40 (K. O'Hara, pers. comm. as cited in Tobin-Scheer 1993). An estimate of 20-25 years to canopy closure is reasonable for all but the low productivity sites. Other studies lend these estimates credence (Osawa 1990, Raison and others 1992).

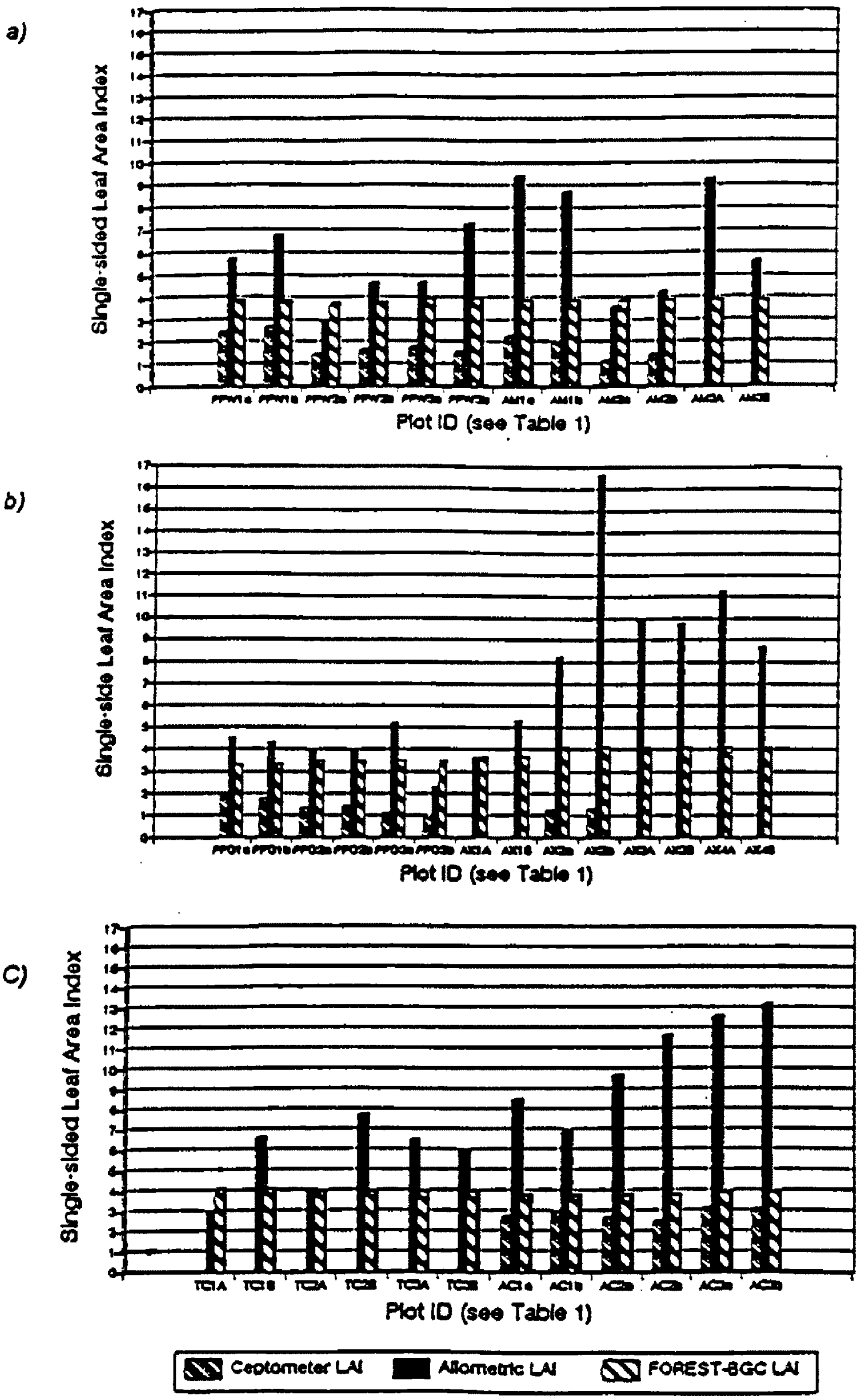


Figure 8. Estimated single-sided, stand LAI for slow (a), moderate (b), and fast (c) recovery types. The three methods used to estimate LAI are ceptometer, allometric equations, and ecosystem model, FOREST-BGC.

Though it is likely that the stand must return to pre-disturbance structure for the aerodynamic regime to return to a pre-disturbance state (Hoover and Leaf 1967) there are numerous current studies (i.e. not superceded by more recent work) which indicate that redistribution due to altered aerodynamics is a minor cause of increase snow-water equivalent (see Troendle and King 1985).

Given these conclusions, I propose the hydrologic recovery curves shown in Figure 9. These are presented as reasonable estimates for Slow, Moderate, and Fast recovery types. They take into account only slight regeneration delays (1 to 2 years). Any delay in vegetative regrowth would delay recovery for a corresponding amount of time. As a comparative tool, the curves are presented with the comparable curves from *Forest Hydrology Part II* (USDA Forest Service 1973). An initial categorization of habitat types in western Montana into the three recovery classes is made in Table 1. The category of any given habitat type may change for a particular area based on local knowledge.

Evidence does not exist to substantiate every point along these curves. There is little hard data to precisely say when a site will recover hydrologically. The y-intercept values for the curves are somewhat arbitrary. As stated above, the curves will shift up and down, while keeping the same slope, depending on the regeneration of the site. The most precise points on the curves are those near 70-80% recovery. Numerous studies, as pointed out above, have shown that ET savings account for approximately 70-80% of the water yield increases, and these

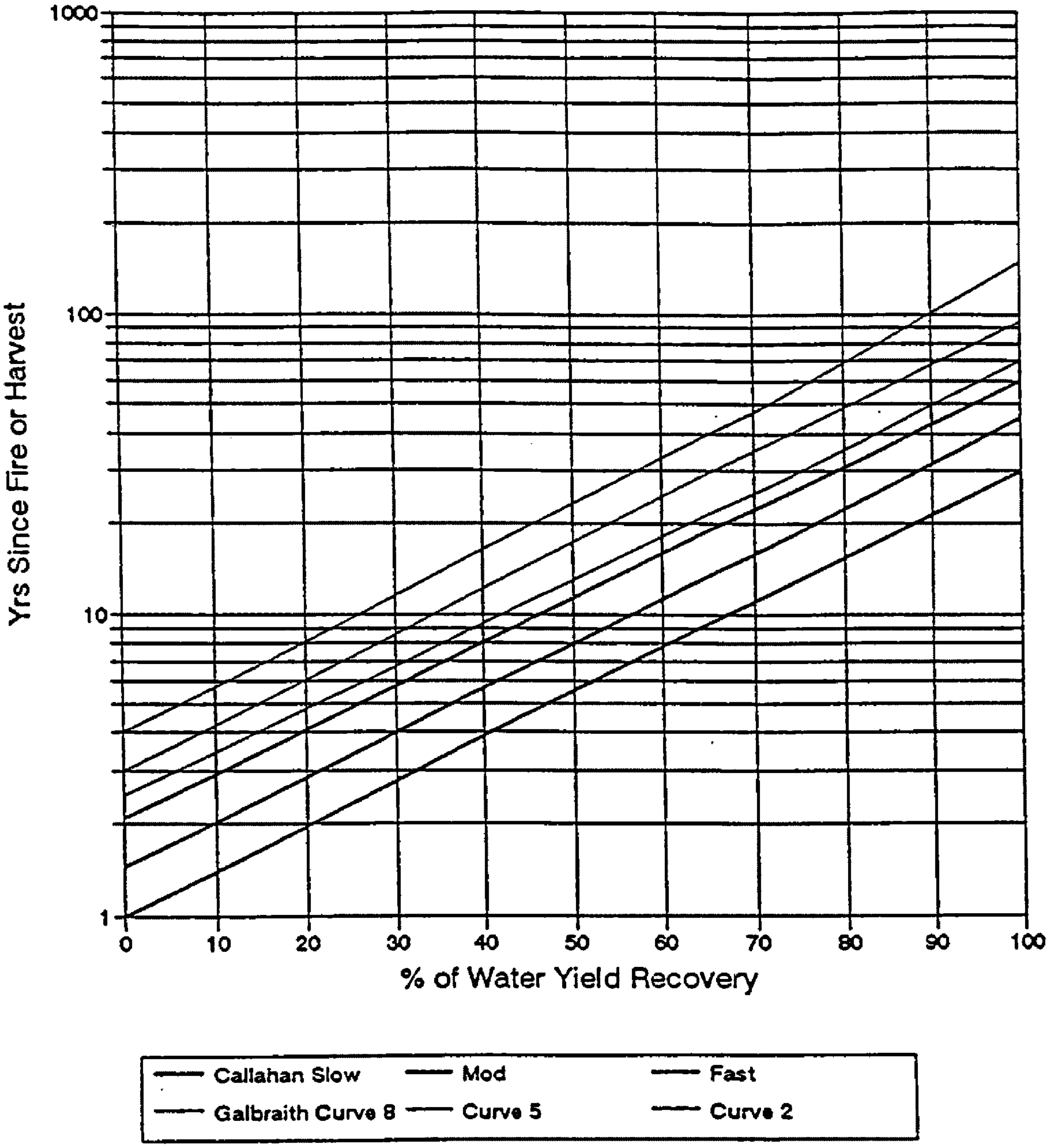


Figure 9. Proposed water yield recovery curves (bold lines). Light lines are curves2, 5, and 8 (moving bottom to top) from Forest Hydrology, Part II (USDA For. Ser. 1973a).

increases recovery in between 10 and 30 years. The curves presented here agree with these approximations. The points of complete water yield recovery (60, 45, and 30 years for the slow, moderate, and fast types, respectively) were chosen as reasonable estimates which are conservative (i.e. conservative) and yet more substantiated than those currently in use. Based on the evidence presented here, these curves represent a more substantiated set of curves to use in cumulative effects assessments, and they, hopefully, will provide a new benchmark from which to continue research on this subject.

Though the present study has proposed hydrologic recovery times which are much shorter than previously thought there are many factors which could prolong actual recovery times. Skid trails, poor regeneration, and, certainly, roads all have a profound effect on site water balance and the routing of water to the stream. Consideration of all of all of these factors is essential.

REFERENCES

Alexander, R.R., C.A. Troendle, M.R. Kaufmann, W.D. Shepperd, G.L. Crouch, R.K. Watkins. Fraser Experimental Forest, CO: research program and published research. 1937-1985. 1985. USDA For. Serv. Gen. Tech. Rep. RM-118. Rocky Mountain Forest and Range Exper. Sta., Fort Collins, CO.

Anderson, H.W. 1963. Managing California's snow zone lands for water. USDA For. Serv. Res. Pap. PSW-6. Pacific Southwest Forest and Range Exper. Sta., Berkeley, CA. 28 pp.

Anderson, H.W., M.D. Hoover, and K.G. Reinhart. 1976. Forests and water: Effects of forest management on floods, sedimentation, and water supply. USDA For. Serv. Gen. Tech. Rep. PSW-18. Pacific Southwest Forest and Range Exper. Sta., Berkeley, CA.

Bates, C.G. and A.J. Henry. 1928. Forest and streamflow experiment at Wagon Wheel Gap, Colorado. Supp. 30. U.S. Weather Service, Washington, D.C. 71 pp.

Bosch, J.M. and J.D. Hewlett. 1982. A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration. J. Hydrol. 55:3-23.

Brooks, K.N., P.F. Ffolliott, H.M. Gregersen, J.L. Thanes. 1991. Hydrology and the management of watersheds. Iowa State University Press. Ames, IA.

Cline, R.G., H.H. Haupt, and G.S. Campbell. 1977. Potential water yield response following clearcut harvesting on north and south slopes in northern Idaho. USDA For. Serv. Res. Pap. INT-191. Intermountain Forest and Range Exper. Sta., Ogden, UT.

Cooke, R.U., and R.W. Reeves. 1976. Arroyos and environmental change in the American Southwest. Oxford Res. Studies in Geog., Claredon Press, 213 pp.

Daubenmire, R. 1959. A canopy-coverage method of vegetational analysis. Northwest Science 33(1):43-69.

Daubenmire, R. 1968. Soil moisture in relation to vegetation distribution in the mountains of northern Idaho. Ecology 49(3):431-438.

Decagon Devices. 1987. Sunfleck ceptometer users manual. Decagon Devices, Pullman, Washington.

Delk, R. 1972. Probable hydrological effects of clear-cutting on the Flathead National Forest. USDA For. Ser., Flathead National Forest. Kalispell, MT.

Dietrich, T.L. and J.R. Meiman. 1974. Hydrologic effects of patch cutting of lodgepole pine. Colorado State Univ. Hydrol. Pap. 66. 31 pp.

Gary, H.L. 1979. Duration of snow accumulation increases after harvesting in lodgepole pine in Wyoming and Colorado. USDA For. Serv. Res. Note RM-366. Rocky Mountain Forest and Range Exper. Sta., Ft. Collins, CO. 7 pp.

Gary, H.L. and C.A. Troendle. 1982. Snow accumulation and melt under various stand densities in lodgepole pine in Wyoming and Colorado. USDA For. Serv. Res. Note RM-417. Rocky Mountain Forest and Range Exper. Sta., Ft. Collins, CO. 6 pp.

Gary, H.L. and R.K. Watkins. 1985. Snowpack accumulation before and after thinning a dog-hair stand of lodgepole pine. USDA For. Serv. Res. Note RM-450. Rocky Mountain Forest and Range Exper. Sta., Ft. Collins, CO. 4 pp.

Golding, D.L. 1981. Hydrologic relationships in interior Canadian watersheds. *In:* Interior West Watershed Management; Symposium, April 8-10, 1980. Spokane, Washington, Washington State University, Pullman, WA. pp. 107-116.

Golding, D.L. 1982. Snow accumulation patterns in openings and adjacent forest. Canadian Hydrology Symposium:82. National Research Council of Canada, Fredericton, New Brunswick

Golding, D.L. and R.H. Swanson. 1978. Snow accumulation and melt in small forest openings in Alberta. Can. J. For. Res. 8(4):380-388.

Grier, C.C. and S.W. Running. 1977. Leaf area of mature northwestern coniferous forests: relation to site water balance. Ecology 58:893-899.

Hart, G.E. and D.A. Lomas. 1979. Effects of clearcutting on soil water depletion in an Engelmann Spruce stand. Water Res. Res. 15(6):1598-1602.

Haupt, H.F. 1972. The release of water from forest snowpacks during winter. USDA For. Serv. Res. Pap. INT-114. Intermountain Forest and Range Exper. Sta., Ogden, UT. 17 p.

Haupt, H.F. 1979. Effects of timber cutting and revegetation on snow accumulation and melt in North Idaho. USDA For. Serv. Res. Pap. INT-224. Intermountain Forest and Range Exper. Sta. Ogden, UT.

Hibbert, A.R. 1967. Forest treatment effects on water yield. *In:* Proceedings, International Symposium on Forest Hydrology. W.E. Sopper, H.W. Lull, eds. Pergamon, New York, N.Y. pp. 527-543.

Hibbert, A.R. 1969. Water yield changes after converting a forested catchment to grass. Water Resour. Res. 5(3):634-640.

Hillel, D. 1980. Fundamentals of Soil Physics. Academic Press, New York. 413 pp.

Hinckley, T.M. and G.A. Ritchie. 1972. Reaction of mature ABIES seedlings to environmental stresses. Trans. Mo. Acad. Sci. 6:24-37.

Hoover, M.C. and C.F. Leaf. 1967. Process and significance of interception in Colorado and subalpine forest. *In:* Forest Hydrology, International symposium on forest hydrology, Aug.-Sept., 1967, University Park, PA. W.E. Sooper and H.E. Lull, eds. Pergamon Press, New York, N.Y. 813 p.

Jarvis, P.G. and J.W. Leverenz. 1983. Productivity of temperate, deciduous and evergreen forests. *In:* Ecosystem processes: mineral cycling, productivity and man's influence. O.L. Lange, P.S. Novel, C.B. Osmond, and H. Ziegler, eds. Volume 12D. Physiological plant ecology: new series. Springer-Verlag, New York, New York. pp. 233-280.

Kaufmann, M.R. Modelling transpiration of subalpine trees in the central Rocky Mountains. *In:* Proceedings of the Symposium on Watershed Management. American Society of Civil Engineers, New York, N.Y. pp. 61-68.

Kaufmann, M.R. and C.A. Troendle. 1981. The relationship of leaf area and foliage biomass to sapwood conducting area in four subalpine tree species. For. Sci. 27(3):477-482.

Knight, D.H., T.J. Fahey, S.W. Running, A.T. Harrison, and L.L. Wallace. 1981. Transpiration from 100-year-old lodgepole pine forests estimated with whole-tree potometers. Ecology 62:717-726.

Landsberg, J.J. 1986. Physiological ecology of forest production. Academic Press, New York, New York.

Leaf, C.F. 1975. Watershed management in the Rocky Mountain subalpine zone: The status of our knowledge. USDA For. Serv. Res. Pap. RM-137. Rocky Mountain Forest and Range Exper. Sta., Fort Collins, CO. 31 pp.

Leaf, C.F. and G.E. Brink. 1975. Land use simulation model of subalpine coniferous forest zone. USDA For. Serv. Res. Pap. RM-135. Rocky Mountain Forest and Range Exper. Sta., Fort Collins, CO.

Long, J.N. and J. Turner. 1975. Above-ground biomass of understory and overstory in an age sequence of four Douglas-fir stands. J. App. Ecol. 12:179-188.

Lundberg, A. and S. Halldin. 1994. Evaporation of intercepted snow: Analysis of governing factors. Water Resour. Res. 30(9):2587-2598.

MacDonald, L. 1987. Forest harvest, snowmelt and streamflow in the central Sierra Nevada. *In:* Proceedings: Forest hydrology and watershed management. August 1987. Vancouver, B.C. pp. 273-283.

McMinn, R.G. 1952. The role of soil drought in the distribution of vegetation in the northern Rocky Mountains. Ecology 33(1):1-15.

McNaughton, K.G. and P.G. Jarvis. 1983. Predicting effects of vegetation changes on transpiration and evaporation. *In:* Water deficits and plant growth. T.T. Kozlowski, ed. Volume 7. Academic Press, London, England. pp. 41-47.

McNay, R.S., L.D. Peterson, J.B. Nyberg. 1988. The influence of forest stand characteristics on snow interception in the coastal forest of British Columbia. Can. J. For. Res. 18:566-573.

Meiman, J.R. 1987. Influence of forests on snowpack accumulation. USDA For. Serv. Res. Note RM-149. Rocky Mountain Forest and Range Exper. Sta., Fort Collins, CO. pp. 61-67.

O'Brien, R.O. and D.D. Van Hooser. 1983. Understory vegetation inventory: An efficient procedure. USDA For. Serv. Res. Pap. INT-323. Intermountain Forest and Range Exper. Sta., Ogden, UT. 6 p.

Olson, C.M. and R.E. Martin. 1981. Estimating biomass and shrubs and forbs in central Washington Douglas-fir stands. USDA For. Serv. Res. Note PNW-380. Rocky Mountain Forest and Range Exper. Sta., Fort Collins, CO. 6 p.

Osawa, A. 1990. Reconstructed development of stem production and foliage mass and its vertical distribution in Japanese larch. Tree Physic. 7(1/4):189-200.

Packer, P.E. 1962. Elevation, aspect and cover effects on maximum snowpack water content in a western white pine forest. For. Sci. 8:225-235.

Pfister, R.D., F.L. Kovalchik, S.F. Arno, and R.C. Presby. 1977. Forest habitat types of Montana. USDA For. Serv. Gen. Tech. Rep. INT-34. Intermountain Forest and Range Exper. Sta., Ogden, UT. 174 pp.

Pierce, L.L. University of Montana. School of Forestry, Missoula, MT. Research Assistant.

Pierce, L.L. and S.W. Running. 1988. Rapid estimation of coniferous forest leaf area index using a portable integrating radiometer. Ecology 69(6):1762-1767.

Raison, R.J., P.K. Khanna, M.L. Benson, B.J. Myers, R.E. McMurtrie, and A.R.G. Lang. 1992. Dynamics of Pinus radiata foliage in relation to water and nitrogen stress: II. Needle loss and temporal changes in total foliage mass. Forest Ecology and Management 52(1/4):159-178.

Reinhart, K.G., A.R. Eschner, and G.R. Trimble, Jr. 1963. Effect on streamflow of four forest practices in the mountains of West Virginia. USDA For. Serv. Res. Pap. NE-1. Northeast Forest Exp. Sta., Upper Darby, PA. 79 pp.

Rothacher, J. 1970. Increases in water yield following clear-cut logging in the Pacific Northwest. Water Resour. Res. 6(2):653-658.

Running, S.W. and S.T. Gower. 1991. FOREST-BGC, A general model of forest ecosystem processes for regional applications. II. Dynamic carbon allocation and nitrogen budgets. Tree Physic. 9:147-160.

Running, S.W. and E.R. Hunt, Jr. 1993. Generalization of a forest ecosystem process model for other biomes, BIOME-BGC, and an application for global-scale models. *In:* Scaling Physiological Processes: Leaf to Globe. Academic Press, London, England. pp. 141-157.

Running, S.W., R.R. Nemani, and R.D. Hungerford. 1987. Extrapolation of synoptic meteorological data in mountainous terrain and its use for simulating forest evapotranspiration and photosynthesis. Can. J. For. Res. 17(6):472-483.

Ryan, M.G. 1989. Sapwood volume for three subalpine conifers: predictive equations and ecological implications. Can. J. For. Res. 19(11):1397-1401.

Satterlund, D.R. and H.H. Haupt. 1970. The deposition of snow caught by conifer crowns. Water Resour. Res. 6(2):649-652.

Satterlund, D.R. and H.H. Haupt. 1972. Vegetation management to control snow accumulation and melt in the northern Rocky Mountains. *In:* Proceedings, National Symposium on Watersheds in Transition. Ccallany, S.C., T.G. McLaughlin, W.D. Striffler, eds. June 19-22. Fort Collins, CO. Colorado State Univ., Fort Collins, CO.

Schmidt, W.C., C. Fielder. unpublished data. Foliage biomass study at the Coram Experimental Forest, Montana.

Schmidt, R.A., D.R. Gluns. 1991 Snowfall interception on branches of three conifer species. Can. J. For. Res. 21:1262-1269.

Schmidt, W.C. 1970. The effects of vegetative manipulation on stream flow, water quality, and water available for plant growth (unpublished).

Shinozaki, K., K. Yoda, K. Hozumi, T. Kira. 1964. A quantitative analysis of plant form - the pipe model theory. I. Basic analyses. Jpn. J. Ecol. 14:133-139.

Thompson, D.C. 1989. The effect of stand structure and stand density on the leaf area - sapwood area relationship of lodgepole pine. Can. J. For. Res. 19(3):392-396.

Tobin-Scheer, J. 1992. Literature review of water-yield recovery. University of Montana, School of Forestry (unpublished).

Troendle, C.A. 1982. The effects of small clearcuts on water yield from the Deadhorse Watershed: Fraser, Colorado. *In:* Proceedings 50th Western Snow Conference. Reno, Nevada. April 19-23. Colorado State University, Fort Collins, CO. pp.75-83.

Troendle, C.A. and M.R. Kaufmann. 1987. Influence of forests on the hydrology of the subalpine forest. USDA For. Serv. Gen. Tech. Rep. RM-149. Rocky Mountain Forest and Range Exper. Sta. Fort Collins, CO. pp. 68-78.

Troendle, C.A. and R.M. King. 1985. The effect of timber harvest on the Fool Creek Watershed, 30 years later. Water Resour. Res. 21(12):1915-1922.

Troendle, C.A. and R.M. King. 1987. The effect of partial and clearcutting on streamflow at Deadhorse Creek. Colorado. J. Hydrol. 90:145-157.

Troendle, C.A. and C.F. Leaf. 1980. Hydrology, an approach to water resources evaluation of non-point source pollution. EPA 60018-80-012. Athens, GS: Environmental Protection Agency: III.1-III.173.

Troendle, C.A. and C.F. Leaf. 1981. Effects of timber harvest in the snow zone on volume and timing of water yield. *In:* Interior West Watershed Management; Symposium, Spokane, Washington, April 8-10. Washington State University, Pullman. pp. 231-243.

Troendle, C.A. and J.R. Meiman. 1984. Options for harvesting timber to control snowpack accumulation. *In:* Proceedings, 52nd Western Snow Conference; Sun Valley, Idaho, April 10-15. Colorado State University, Fort Collins. pp. 86-97.

Troendle, C.A. and J.R. Meiman. 1986. The effect of patch clearcutting on the water balance of a subalpine forest slope. *In:* Proceedings, 54th Western Snow Conference; Phoenix, Arizona, April 15-17. Colorado State University, Ft. Collins, CO. pp. 93-100.

Troendle, C.A., R.A. Schmidt, and M.H. Martinez. 1988. Snow deposition processes in a forest stand with a clearing. *In:* Proceedings, 56th Western Snow Conference, April 19-21. Kalispell, Montana. Colorado State University, Ft. Collins, Colorado. pp. 78-86.

USDA Forest Service. 1973a, Forest Hydrology: hydrologic effects of vegetation manipulation, Part II.

USDA Forest Service. 1973b. Lolo National Forest Vegetation Manipulation Guidelines.

USDA Soil Conservation Service. 1970. Isohyets for Montana. Bozeman, Montana.

Wheeler, K.R. 1987. Interception and redistribution of snow in a subalpine forest on a storm by storm basis. *In:* Proceedings, 55th Western Snow Conference, Colorado State University, Fort Collins, Colorado.

Wilford, D.J. 1987. Watershed workbook. Forest hydrology sensitivity analysis for coastal British Columbia watersheds. B.C. Ministry of Forests and Lands. Prince Rupert Forest Region. Smithers, B.C. V0J 2N0.

Wilm, H.G. and E.G. Dunford. 1948. Effect of timber cutting on water available for streamflow from a lodgepole pine forest. USDA Technical Bulletin 968, 43 p. Washington, D.C.

Yang, K.C., G. Hazenberg, G.E. Bradfield, and J.R. Maze. 1985. Vertical variation of sapwood thickness in Pinus banksian Lamb. and Larix laricina (Du Roi) K. Koch. Can. J. For. Res. 15:822-828.

Ziemer, R.R. 1964. Summer evapotranspiration trends as related to time after logging of forests in Sierra Nevada. J.Geophys. Res. 69:615-620

Appendix A. Sample input file used for FOREST-BGC model.

```
GOLD CREEK (GOLDCRK.DAT)

1      KSTART =  START SIMULATION LOOP COUNTER
18250 STOP   =  STOP SIMULATION LOOP, DAY
0      DAY    OUTPUT CONTROL: 1 MEANS  YES; 0 MEANS  NO
1      GRW    OUTPUT CONTROL: 1 MEANS  YES; 0 MEANS  NO
0      LNG    OUTPUT CONTROL: 1 MEANS  YES; 0 MEANS  NO
365    KPRINT =  IF KPRINT = 10 THEN OUTPUT ONCE EVERY 10 ITERATIONS
0      KBEGIN =  BEGIN PRINTING AFTER ITERATION > KBEGIN
365    LOOP   =  LOOP TO THE CARBON/NIT SUBMODEL EVERY xx DAYS
0      LIFE CYCLE REDEFINE B CONSTANTS WITH LOOP # (1=YES, 0=NO, *.LIF
FILE)
0      SEASONALLY REDEFINE B CONSTANTS WITH YEARDAY (1=YES, 0=NO, *.SEA
FILE)
0      NEGX   =  PRINT ERROR MESSAGES WHEN X(I) IS NEGATIVE: 1 MEANS YES.
20            NUMX   = NUMBER OF X VALUES TO READ
1850.0        X(  1)   SNOWPACK                ( M**3 )
1000.0        X(  2)   SOIL WATER CONTENT      ( M**3 )
0.0           X(  3)   WATER OUTFLOW           ( M**3 )
0.0           X(  4)   TRANSPIRATION           ( M**3 )
0.0           X(  5)   EVAPORATION             ( M**3 )
0.0           X(  6)   PSN                     ( KG )
0.0           X(  7)   RESPIRATION AUTOTROPHIC ( KG )
200.00        X(  8)   LEAF CARBON   1200      ( KG )
1660.0        X(  9)   STEM CARBON   10000     ( KG )
410.00        X( 10)   ROOT CARBON   2500      ( KG )
3000          X( 11)   LEAF/ROOT LITTER CARBON ( KG )
000           X( 12)   RESPIRATION DECOMP, C   ( KG )
40000         X( 13)   SOIL CARBON             ( KG )
200.0         X( 14)   AVAILABLE NITROGEN      ( KG )
18.0          X( 15)   LEAF NITROGEN (1.5% OF X8( KG )
100           X( 16)   STEM NITROGEN           ( KG )
18.0          X( 17)   ROOT NITROGEN .75% OF X10( KG )
300.0         X( 18)   L/R LITTER NITROGEN 1%X11( KG )
2000          X( 19)   SOIL NITROGEN           ( KG )
000           X( 20)   NITROGEN LOSS           ( KG )
50            NUMB   = NUMBER OF B CONSTANTS TO READ
25.0          B(  1)   SPECIFIC LEAF AREA      (M**2/KG C)
-0.5          B(  2)   CANOPY LIGHT EXTINCTION COEFFICIENT
800.0         B(  3)   SOIL WATER CAPACITY 2350 (M**3)
0.0005        B(  4)   INTERCEPTION COEFF      (M/LAI/DAY)
10000         B(  5)   GROUND SURFACE AREA     (M**2 / HA )
0.0007        B(  6)   SNOWMELT COEFF          (M/DEG C/DAY)
47.0          B(  7)   LATITUDE                (DEG)
0.8           B(  8)   1 - SURFACE ALBEDO
0.5           B(  9)   SPRING MIN. PMS         (MPA)
3000          B( 10)   RAD. RED LC THRESHOLD   (KJ/M**2/DAY
0.0016        B( 11)   MAX CANOPY AVG. LC      (M/SEC)
1.65          B( 12)   LWP AT STOMATAL CLOSURE (MPA)
```

```
0.05           B( 13)   SLOPE ABS HD REDUCTION    (M/SEC/ABSHD)
432            B( 14)   PSN LIGHT COMP PT.        (KJ/M**2/DAY)
9720           B( 15)   PSN I                     (KJ/M**2/DAY)
0.0008         B( 16)   MAX LC(CO2)               (M/SEC)
0              B( 17)   MIN TEMP. PSN             (DEG C)
40             B( 18)   MAX TEMP. PSN             (DEG C)
0.0002         B( 19)   LEAF RESPIRATION COEFF
0.0010         B( 20)   STEM RESPIRATION COEFF
0.0002         B( 21)   ROOT RESPIRATION COEFF
0              B( 22)
4.0            B( 23)   TEMP. EFFECT  MESOPHYLL COND. ADJUSTMENT
COEFFICIENT.
0              B( 24)
0.085          B( 25)   Q10=2.3 CONSTANT FOR EXPONENTIAL RESPIRATION
SURFACE
0.044          B( 26)   MAXIMUM CAN AVE LEAF NITROGEN CONC  (%x 2.2
C/CH2O)
0.0132         B( 27)   MINIMUM CAN AVE LEAF NITROGEN CONC
0.50           B( 28)   MAX LEAF NITROGEN RETRANSLOCATION FRACTION  (DIM)
1.0            B( 29)   SOIL WATER DECOMP RATE FACTOR {0-1} (DIM)
0.5            B( 30)   N/C DECOMP RELEASE FRACTION (DIM)
12.0           B( 31)   MAXIMUM LEAF AREA INDEX, ALL SIDES  (DIM)
3.0            B( 32)   LEAF TURNOVER RATE (YR)
0.25           B( 33)   LEAF LIGNIN FRACTION  (%/100)
0              B( 34)
1.0            B( 35)   NITROGEN AVAIL LEAF/ROOT ALLOCATION FACTOR (DIM)
0              B( 36)   DATE OF SPRING LEAF GROWTH (YEARDAY)
365            B( 37)   DATE OF FALL LEAF DROP (YEARDAY)
20.0           B( 38)   MOBILE N RETENTION TIME  (YR)
5.0            B( 39)   ATMOSPHERIC DEPOSITION N  (KG/HA/YR)
0.0            B( 40)   BIOLOGICAL FIXATION N  (KG/HA/YR)
0.00           B( 41)   STEM TURNOVER COEFF
0.40           B( 42)   ROOT TURNOVER COEFF
0.35           B( 43)   LEAF GROWTH RESP
0.30           B( 44)   STEM GROWTH RESP
0.35           B( 45)   ROOT GROWTH RESP
50.0           B( 46)   DECOMPOSITION TEMPERATURE OPT (DEG)
0.03           B( 47)   SOIL/LITTER C DECOMP FRACTION (DIM)
0.4            B( 48)   DECOMPOSITION RATE SCALAR (DIM)
0              B( 49)
0              B( 50)
0   NUMIZP =   NUMBER OF Z VARIABLES TO PRINT: CAN BE 0
14  NUMIGP = NUMBER OF G VALUES TO PRINT: CAN BE 0
```