

Seasonal and successional streamflow response to forest cutting and regrowth in the northwest and eastern United States

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[1] This study examined daily streamflow response over up to four decades in northwest conifer forest and eastern deciduous forest sites in the United States. We used novel methods to analyze daily observations of climate and streamflow spanning more than 900 basin years of record at 14 treated/control basin pairs where forest removal and regrowth experiments were underway in the period 1930–2002. In the 1 to 5-year period after forest removal, maximum daily increases ranged from 2 to 3 mm at deciduous forest sites, to 6 to 8 mm at conifer forest sites. Significant spring surpluses persisted for up to 35 years in conifer forest basins, but winter and spring streamflow deficits appeared after 10 to 15 years of forest regrowth in eastern deciduous forest basins. In all 5-yr posttreatment periods, absolute changes in daily streamflow were significantly more likely during moist, warm seasons, or during snowmelt seasons, but relative changes were more likely during warm seasons irrespective of moisture status. Both relative and absolute streamflow changes in the 1 to 5 and 15 to 25-year periods after forest removal were significantly positively related to the age of the forest at the time it was cut. Eastern deciduous forests had been disturbed by logging or hurricane 12 to 56 years prior to forest removal, while Pacific Northwest conifer forests had been not experienced logging or wildfire for 90 to 450 years. Paired basin experiments provide a continuous, and continuously changing, record of vegetation structure, composition, and climate, and their effects on streamflow. **INDEX TERMS:** 1860 Hydrology: Runoff and streamflow; 1803 Hydrology: Anthropogenic effects; 1863 Hydrology: Snow and ice (1827); **KEYWORDS:** Caspar Creek experimental forest, Coweeta experimental forest, Coyote Creek, Fernow experimental forest, H. J. Andrews Forest, Hubbard Brook experimental forest

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1. Introduction

[2] Paired-basin forestry experiments are a major source of data on climate, streamflow, and vegetation for testing of theoretical propositions in hydrology. Yet to date, the hydrologic implications of paired basin experiments have been largely examined for individual experiments, or in reviews or meta-analyses [e.g., *Bosch and Hewlett*, 1982; *Robinson et al.*, 2003] combining results from studies using disparate methods. Hydrologic modeling efforts frequently employ paired-basin data, but inferences are limited by uncertainty about many parameters, including vegetation-climate-soil interactions [*Beven*, 2002].

[3] Studies of eco-physiology, global change, and stream ecology are providing hydrologists with challenging hypotheses about vegetation and climate coupling to hydrology. Eco-physiology studies argue that forest structure and composition develop during succession to reduce stress on plants and optimally use resources, including moisture [*Eagleson*, 2002]. Studies of global change, including

climate change, indicate that streamflow responds to changes in temperature and rainfall [*Hodgekins et al.*, 2003] with concurrent changes in vegetation cover and species composition [e.g., *Shafer et al.*, 2001]. Stream ecologists advocate restoration policies based on streamflow variability [*Poff et al.*, 1997], as well as habitat structure. Results from paired-basin experiments can contribute to these issues, by revealing the coupling among vegetation, atmosphere, soil, and streamflow at spatial and temporal scales intermediate between plot- and reach-scale studies characteristic of eco-physiology and stream ecology, and the coarse scales of climate and land use change modeling.

[4] In paired basin experiments, both increases and decreases in streamflow may occur in both relative and absolute terms at different seasons or time periods after treatment, providing clues about causal mechanisms, and geomorphic and ecological consequences, of vegetation change. In published studies, the largest relative changes in streamflow occurred in summer months after removal of eastern deciduous forest [*Douglass and Swank*, 1972, 1975; *Swank et al.*, 2001; *Hornbeck et al.*, 1997; *Martin et al.*, 2000] and western conifer forest [*Rothacher*, 1975; *Harr et al.*, 1979, 1982]. However, in conifer sites, the largest absolute streamflow increases occurred during wet winter months [*Rothacher*, 1970; *Lewis et al.*, 2001]. Lags of

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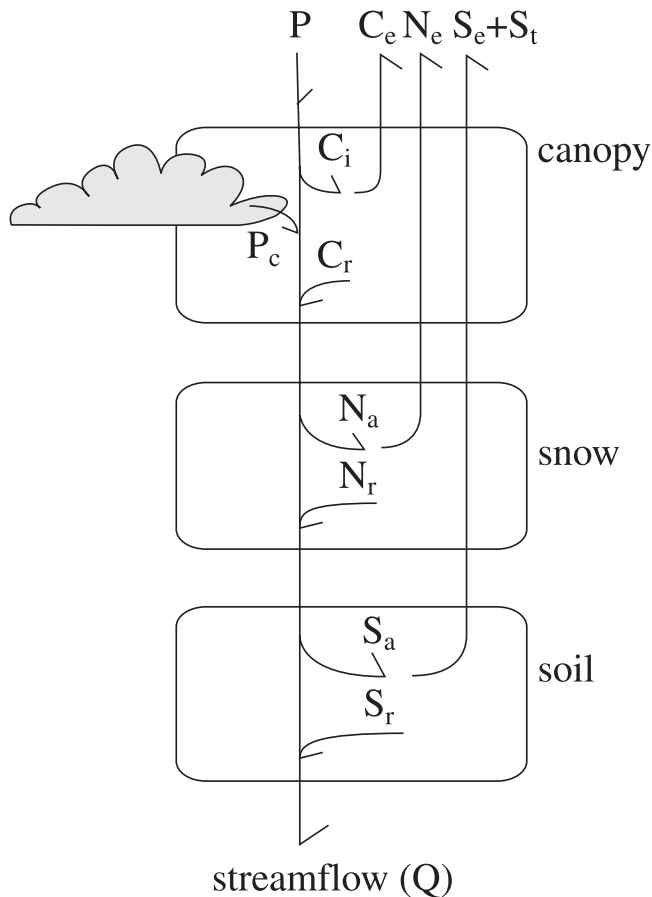


Figure 1. Ten fluxes involving moisture storage reservoirs (boxes) in vegetation canopies, snowpacks, and soils in forested basins. Inputs to the system are from precipitation (P) and cloudwater interception (P_c); output is streamflow (Q). Fluxes into and out of the canopy are interception (C_i), throughfall (C_r) and evaporation (C_e). Fluxes into and out of the snowpack are snow accumulation (N_a), sublimation and evaporation (N_e), and snowmelt (N_r). Fluxes into and out of the soil are soil water accumulation (S_a) and release (S_r), evaporation (S_e) and transpiration (S_t).

several months between periods of vegetation water use and streamflow responses have been reported from southeastern deciduous forest sites [Swank *et al.*, 1988].

[5] Both hydrologic and ecological causal mechanisms have been invoked to explain varied streamflow responses in paired basin experiments. In the northwestern United States, conifer forest removal may modify cloudwater interception [Harr, 1982] as well as snowpack dynamics [Harr, 1981; Berris and Harr, 1987] during wet (winter) seasons. In the eastern United States, vegetation species in early succession may be higher water users per unit leaf area than the species removed, reducing summer streamflows [Hornbeck *et al.*, 1997; Swank *et al.*, 2001]. Also, conifers may use more water over greater periods of the year than deciduous forests, reducing fall, winter, or spring flows [Swank and Douglass, 1974; Swank *et al.*, 1988].

[6] Differences among basins where forest removal experiments have been conducted lend themselves to testing the generality of hypotheses about causes and consequences of vegetation change for streamflow. The eastern US has a

mesic climate with wet summers whereas the northwestern US has a xeric climate with dry summers. Northern and high-elevation basins have seasonal snow, but basins at lower latitudes or elevations have transient snowpacks or no snow. Basins in the eastern US have deciduous forests mostly regenerating from logging or other disturbances in the early 20th century, whereas basins in the northwestern US have conifer forests that have been protected from logging and wildfire since at least 1900. Thus season, forest type, and forest age, both time since treatment and age of the forest when it was removed, all may influence streamflow response to forest removal.

[7] Technological developments also lend themselves to a broad analysis of paired-basin forest removal experiments [Jones and Swanson, 2001]. Records of up to sixty years of continuous streamflow and associated measurements now are available from many sites [Post *et al.*, 1998]. Many of these records are available through online data harvesters (e.g., hydro-DB [Baker *et al.*, 2000]). New methods are being developed for testing hypotheses with long-term streamflow data sets [e.g., Jones and Grant, 1996; Jones, 2000; Post and Jones, 2001]. Finally, increased computer power and growth of the Internet now permit data sets from many sites to be readily compiled and analyzed in one location.

2. Conceptual Model

[8] Hydrologic responses to forest canopy removal and regrowth can be predicted from the hydrologic cycle (Figure 1). Because forest vegetation is coupled to the atmosphere, the snowpack, and the soil, three major classes of hydrologic responses to forest removal and regrowth involve changes in forest canopy interactions with: (1) the atmosphere and soils (i.e., cloudwater interception P_c , canopy interception C_i , evaporation from the canopy and soils C_e and S_e , and transpiration S_t , Figure 1), (2) snowpack accumulation and melt (i.e., snow accumulation N_a , sublimation N_e , and snowmelt N_r , Figure 1), and (3) soil moisture storage (i.e., additions and losses S_a and S_r , Figure 1).

[9] We tested the following hypotheses.

[10] H1. Forest vegetation affects streamflow through evapotranspiration, interception, and soil moisture storage. Therefore streamflow responses to forest removal should occur when temperature is conducive to evapotranspiration, or during periods of snowmelt. Evapotranspiration effects are large in absolute terms at times of year when soils are moist (S_e , S_t , S_a and S_r are large), but they are large in relative terms at times of year when temperature is conducive to transpiration irrespective of soil moisture (S_e and S_t are large but S_a and S_r are small). Snow interception effects are large in absolute terms at times of year when soils are moist and snowmelt is occurring (S_a , S_r , and N_r are large). In sites with cold snowpacks, young deciduous forests produce smaller snowpacks (N_a , N_e , and C_e increase) compared to older deciduous forests, but in sites with warm snowpacks, young conifer forests produce larger snowpacks (N_a , N_e , and C_e decrease) compared to older conifer forests. Alternatively, streamflow responses to forest removal may occur during times of year when neither evapotranspiration nor snowmelt is occurring, because soil moisture storage reservoirs exert a lagged effect.

[11] H2: The forest vegetation effect on streamflow depends upon forest structure and composition, which vary with the age of vegetation. Two measures of forest age are relevant: the age of the forest in the treated basin (time since treatment) and the difference in ages of the forests between the treated and control basins (which is equivalent to the time since most recent pre-treatment forest disturbance). Young forests use more water than older forests at times of year when temperature is conducive to transpiration, irrespective of soil moisture (S_e and S_t are larger relative to S_a and S_r for young than older forests). Therefore streamflow response will decline rapidly in the first few decades of forest regrowth, and forests aged 10 to 30 years will produce summer streamflow deficits relative to older forests. However, as forests age, structure and composition change so as to better utilize water available at times of year when transpiration is temperature- or moisture-limited. Therefore streamflow responses will be positively related to the difference in forest age between the treated and control basins.

3. Study Sites

[12] Study sites were located in six experimental forests, three in the Pacific Northwest of the United States, and three in the eastern United States (Table 1). As of 2002, Pacific Northwest sites (the Andrews, Coyote Creek, and Caspar Creek Experimental Forests) had conifer forests up to 500-yr old and dry summers. Eastern sites (the Hubbard Brook, Fernow, and Coweeta Experimental Forests) had <100 yr old deciduous forests and wet summers. The northernmost sites (Andrews, Hubbard Brook) had seasonal snowpacks. Mean annual precipitation ranged from 1000 mm to over 2000 mm at both conifer and deciduous sites (Table 1).

[13] Forest age was determined as the time since the most recent severe disturbance documented at that site (Table 1). The most recent disturbances included wildfire and logging in conifer forests, and hurricane and logging in deciduous forest (Table 1). Conifer forest types included western hemlock (Andrews), mixed-conifer (Coyote Creek) and redwood forests (Caspar Creek). Deciduous forest types included northern hardwoods (Hubbard Brook) and oak-hickory forests (Fernow, Coweeta) (Table 1).

[14] Each site consisted of one or more paired-watershed experiments in which 100% of forest cover had been harvested and an unharvested control basin exists (Table 1). Forest harvest treatments at the fourteen treated basins occurred over more than half a century, from the 1930s to 1990 (Figure 2). In ten of these cases forest harvest occurred in a single year, but in four cases harvest occurred over several years (Table 1, Figure 2). Treatment involved logging (removal of wood products) in ten treated watersheds. In four cases wood products were not removed, and in two of these four cases herbicide was applied for several years after logging (Table 1). Because of differing disturbance histories, 90 to 450 yr-old forests were removed in the conifer sites, but 12 to 56 yr-old forests were removed in the deciduous forest sites (Table 1).

[15] Long-term records of streamflow and climate have been collected at 26 basins (14 treated, 12 control) from the six study sites. Basin size ranged from 9 to 96 hectares, and streamflow and climate records span periods ranging from 17 years to 63 years (Figure 2). Pre-treatment records were

6 or more years in length in all but one treated basin, and posttreatment records ranged from 11 to over 40 years (Figure 2). Most of the basins ranged in size from 20 to 50 ha, and the ages of most harvested forest ranged from 30 to 125 years (Table 2, Figure 2).

4. Methods

4.1. Datasets and Data Collection

[16] Mean daily streamflow, precipitation, minimum and maximum temperature, and snowpack data from five of the six sites are publicly available on the worldwide web and were collected electronically through Hydro-DB, an automated data harvester <http://www.fsl.orst.edu/hydrodb/>. Data from the sixth site (Coweeta Experimental Forest) are not publicly available, but they were provided by U.S. Forest Service scientists (L. Swift and W. Swank) for periods of record through 1995. The resulting primary data set consisted of over 750,000 observations spanning more than 900 watershed-years of streamflow records. Original streamflow data in units of L/s were converted to mm/day (unit area discharge):

$$\frac{\text{mm}}{\text{day}} = 8.64 \cdot \frac{\text{L}}{\text{s}} \cdot A$$

where A is basin area in hectares. We used a water year from 1 October to 30 September. For Caspar Creek many values from late April to early November were missing values.

[17] The initial data set comprised records from 26 basins (14 treated, 12 control). We present results from 14 treated/control pairs (Table 2). In 11 of these 14 pairs we used the treated/control pairs established by the original researchers. In three cases, we used an alternative to the original control basin (Table 2). In these three cases, Coweeta 7/34 (7/2), Coweeta 13/14 (13/18), and Andrews 10/2 (10/9), the original control basins (in parentheses) were less than 15 ha in size. The average standard deviation of daily flow at control basins in mm (y) was significantly negatively related to basin size in hectares (x) ($y = 2.29 \exp(-0.034x)$; $r^2 = 0.84$; $n = 12$). Therefore streamflow changes were not detectable using the original (<15 ha) basins, but they were detectable when the same treated basins were compared to larger, nearby control basins. Moreover, in one case (Andrews 10/9) the original treated/control relationship was suspect because a flume change 15 months prior to the treatment produced significant changes in streamflow at the control basin (Andrews 9).

4.2. Calculating Streamflow Responses to Forest Removal and Regrowth

[18] The change in streamflow in the treated basin relative to the pretreatment treated/control relationship was calculated by day of year and averaged for 5-yr periods after forest removal, following Jones and Grant [1996] and Jones [2000]. The treated/control relationship was

$$c_{ij} = \ln \left[\frac{(b_{ij})}{(a_{ij})} \right]$$

where c_{ij} = the (ln-transformed) ratio of streamflow at the treated and control basins, day i , year j ; a_{ij} and b_{ij} = unit area

Table 1. Vegetation Cover, Disturbance History, Treatments, and Ages of Forest in Fourteen Treated/Control Basin Pairs in This Study

Basin Pair	Disturbance	Treatment		Age ^a		MAP, ^a mm
		Type	Date	Treated ^b	Control ^c	
<i>Western Hemlock</i> ^d						
Andrews 1/2	severe wildfire in 1500s	100% clearcut, logged, burn	1962–66	450	500	2270
Andrews 6/8	wildfire in 1500s, 1850s	100% clearcut, logged, road	1974	125	150	2178
Andrews 10/2	"	100% clearcut, logged	1975	125	500	2282
<i>Mixed Conifer</i> ^e						
Coyote 3/4	wildfire in 1500s, 1850s	100% clearcut, logged	1970	120	145	984
<i>Redwood</i> ^f						
Caspar C/I	clearcut, logged 1860–1904	96% clearcut, logged	1991	90	100	1190
Caspar E/I	"	100% clearcut, logged	1991	90	100	1190
<i>Northern Hardwood</i> ^g						
Hubbard Brook 2/3	logged 1800s–1910, hurricane/salvage 1938	100% clearcut, herbicide	1965	27	64	1312
Hubbard Brook 4/3	"	100% clearcut, logged	1970–74	32	64	1312
Hubbard Brook 5/3	"	100% clearcut, logged	1983	45	64	1312
<i>Oak-Hickory</i> ^h						
Fernow 1/4	logged 1905–1910	100% clearcut, logged	1957	50	95	1438
Fernow 7/4	"	100% clearcut, herbicide	1963	56	95	1450
<i>Oak-Hickory</i> ⁱ						
Coweeta 7/34	grazing, burning 1840–1906; logged 1919–27	100% clearcut, logged	1977	50	75	1962
Coweeta 13/14	"	100% clearcut	1939	12	75	1934
Coweeta 37/36	"	100% clearcut	1963	35	75	2191

^aAge of forest (time since last forest disturbance) and mean annual precipitation (mm) at the control basin for the period of record used in the analysis. Forest ages are based on *Weisberg and Swanson* [2003] (Andrews), *Lewis et al.* [2001] (Caspar Creek), *Douglass and Hoover* [1988] (Coweeta), *Harr et al.*, [1979] (Coyote), Fernow Experimental Forest website (<http://www.fs.fed.us/ne/parsons/fehome.htm>), *Schwarz et al.* [2001] (Hubbard Brook). Ages of 500-year old forest have error margins of ± 25 years due to uncertainty in dating prehistorical events. Forest ages were log-transformed in analyses in part to account for increasing uncertainty of dates with forest age.

^bAge (time since last forest disturbance) of forest in treated basin at time of treatment.

^cAge (time since last forest disturbance) of forest in control basins in 2002.

^dForests dominated by Douglas-fir (*Pseudotsuga menziesii*) with western hemlock (*Tsuga heterophylla*) and red cedar (*Thuja plicata*) [*Rothacher et al.*, 1967].

^eForests dominated by Douglas-fir (*Pseudotsuga menziesii*), ponderosa pine (*Pinus ponderosa*), and sugar pine (*Pinus lambertiana*) [*Harr et al.*, 1979].

^fForests dominated by coast redwood (*Sequoia sempervirens*), Douglas-fir (*Pseudotsuga menziesii*), grand fir (*Abies grandis*) and western hemlock (*Tsuga heterophylla*) [*Lewis et al.*, 2001].

^gForests dominated by American beech (*Fagus grandifolia*), sugar maple (*Acer saccharum*), and yellow birch (*Betula alleghaniensis*) [*Schwarz et al.*, 2001].

^hForests dominated by northern red oak (*Quercus rubra*), sugar maple (*Acer saccharum*), and tulip poplar (*Liriodendron tulipifera*) (Fernow web site).

ⁱForests dominated by chestnut oak (*Quercus prinus*), scarlet oak (*Quercus coccinea*), northern red oak (*Quercus rubra*), red maple (*Acer rubrum*), and tulip poplar (*Liriodendron tulipifera*) with abundant rhododendron (*Rhododendron maximum*) [*Day et al.*, 1988].

streamflow (mm) at the control basin and the treated basin, respectively, on day i , year j . The period of record was divided into periods $k = 1, 2, \dots, n$, such that the pretreatment period was noted 1, and 5-year posttreatment periods were noted 2 and higher. The average treated/control relationship was

$$c_{ik} = \bar{c}_{ij}$$

for years j in period $k = 1, 2, \dots, n$. The percent change in the treated/control relationship in a given posttreatment period relative to the treated/control relationship in the pretreatment period, for each period k , was

$$d_{ik} = \left(\exp^{(c_{ik} - c_{i1})} - 1 \right) \cdot 100$$

for periods $k = 2, \dots, n$ and where d_{ik} = percent change on day i , years j in period k , c_{ik} = treated/control relationship on day i , years j in 5-yr posttreatment period k , c_{i1} = treated/

control relationship on day i , years j in the pretreatment period. The mean of (log-transformed) daily flow at the control basin on day i for period k was:

$$e_{ik} = \sum_{j \in k} \ln(a_{ij}) / n_k$$

where n_k = number of years in period k . The absolute change in streamflow (back-transformed to units of mm/day) in the treated basin relative to the control basin on day i of 5-yr posttreatment period k was:

$$f_{ik} = d_{ik} \cdot \exp(e_{ik})$$

The detection of change in paired-based experiments depends fundamentally upon ratios, whose interpretation can be problematic when the denominator (flow at the control basin) is a small number. Several measures were taken in the analysis and presentation of results to protect

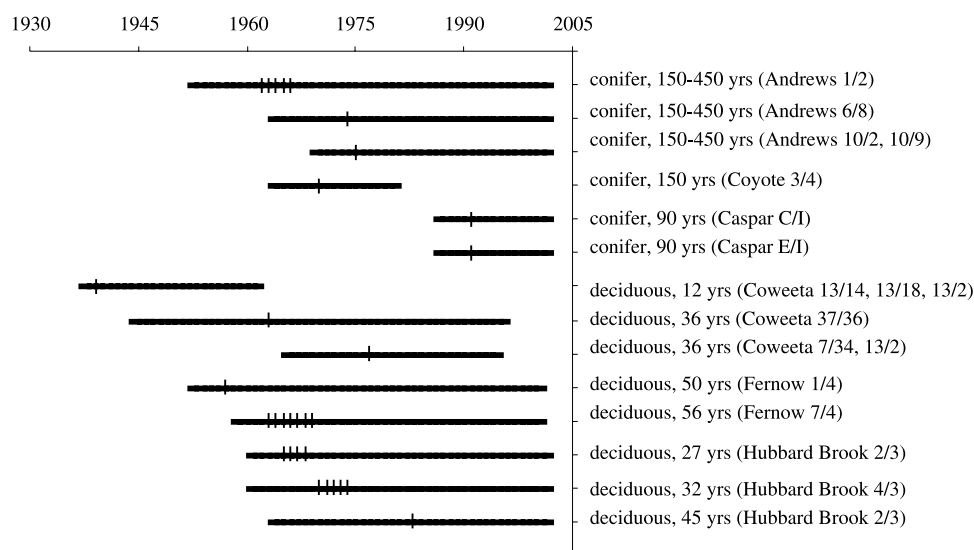


Figure 2. Periods of record of the fourteen small paired-watershed experiments examined in this study. Vertical lines indicate dates of forest harvest and herbicide treatments (where relevant). Experiments are arranged by forest type (conifer, deciduous) in the treated/control pair and age (time since most recent forest disturbance) of the treated watershed. Vertical lines indicate the date of forest removal. Some treatments lasted for multiple years: forests were harvested over 5 yrs at Andrews 1, Fernow 7 and Hubbard Brook 4; herbicide was applied for 3 years at Hubbard Brook 2 and Fernow 7. Some treated watersheds (Andrews 10, Coweeta 7, Coweeta 13) were compared to more than one control watershed.

against misleading interpretations from ratios. Streamflow data were filtered before analysis to remove very low flows. Days with streamflow less than 0.01 mm were treated as missing values, and streamflow changes were calculated only for days with less than two missing values in any five-year posttreatment period. Both absolute and relative changes were calculated to identify instances where very large relative changes were small in absolute terms. Relative changes (d_{ik}) and absolute changes (f_{ik}) were smoothed with a 15-day window to reduce the effect of large changes on any given day, and figure axes were restricted to exclude the occasional values that are improbably large.

Statistical analyses were either non-parametric tests based on counts of days exceeding some threshold of d_{ik} and f_{ik} , or regressions of average percent changes by season rather than daily values.

4.3. Hypothesis Tests

[19] Hypotheses involving seasons were tested using chi-squared tests of independence of streamflow changes by season [Ramsay and Schaefer, 1996]. Days with absolute streamflow changes were tested for independence to (1) moist periods when temperatures are conducive to evapotranspiration, and (2) snowmelt periods. Days with

Table 2. Eighteen Treated/Control Basin Pairs Examined in This Study

Treated/Control Basin Pair	Basin Size, ha		Streamflow Record, Years		
	Treated	Control	Total	Pretreatment	Posttreatment
Andrews 1/2 ^a	96	60	1953–2002	9	41
Andrews 6/8 ^a	15	22	1964–2002	10	28
Andrews 10/2 ^a	10	60	1969–2002	6	27
Andrews 10/9	10	9	1969–2002	6	27
Caspar C/I ^a	26	21	1986–2002	6	11
Caspar E/I ^a	27	21	1986–2002	6	11
Coyote 3/4 ^a	49	50	1964–81	6	11
Coweeta 7/2	59	13	1965–96	12	20
Coweeta 7/34 ^a	59	33	1965–96	12	20
Coweeta 13/2	16	12	1937–62	2	23
Coweeta 13/14 ^a	16	61	1937–62	2	23
Coweeta 13/18	16	13	1937–62	2	23
Coweeta 37/36 ^a	44	49	1944–96	20	43
Fernow 1/4 ^a	30	39	1951–2001	6	44
Fernow 7/4 ^a	29	39	1957–2001	6	38
Hubbard Brook 2/3 ^a	16	42	1958–96	7	31
Hubbard Brook 4/3 ^a	36	42	1958–96	12	26
Hubbard Brook 5/3 ^a	22	42	1958–96	25	13

^aResults from fourteen basin pairs are examined in detail.

Table 3. Seasons, Defined by Dates, Discharge, Runoff Ratio, Minimum and Maximum Temperatures From Control Basins^a

Control Basin	Moist			Dry or Moist Warm	Water Year
	Cool	Snow Accumulation	Snowmelt		
Andrews 2					
Dates	10/1–12/7	12/8–2/8	2/9–6/12	6/13–9/30	10/1–9/30
Discharge, mm	230	525	546	44	1344
Runoff ratio, %	36	74	72	28	59
Min temperature, °C	3	–1	3	10	4
Max temperature, °C	9	4	13	25	14
Andrews 8					
Dates	9/11–12/6	12/7–2/10	2/11–6/24	6/25–9/10	10/1–9/30
Discharge, mm	178	434	524	23	1160
Runoff ratio, %	28	67	70	24	53
Min temperature, °C	4	–1	4	11	5
Max temperature, °C	12	5	14	26	14
Andrews 9					
Dates	9/12–12/2	12/3–3/2	3/3–3/27	3/28–9/11	10/1–9/30
Discharge, mm	190	690	128	213	1222
Runoff ratio, %	31	70	66	45	54
Min temperature, °C	4	–1	–1	8	4
Max temperature, °C	11	4	6	21	14
Coyote 4					
Dates	11/5–12/25	12/26–2/4	2/5–5/20	5/21–11/4	10/1–9/30
Discharge, mm	124	162	201	24	511
Runoff ratio, %	51	115	57	10	52
Min temperature, °C	1	0	3	9	5
Max temperature, °C	7	6	12	22	15
Caspar I					
Dates	11/23–4/24	–	–	4/25–11/22	10/1–9/30
Discharge, mm	32	–	–	415	447
Runoff ratio, %	12	–	–	46	38
Min temperature, °C	10	–	–	6	8
Max temperature, °C	19	–	–	12	16
Hubbard Brook 3					
Dates	–	10/1–3/16	3/17–5/15	5/16–9/30	10/1–9/30
Discharge, mm	–	346	348	144	837
Runoff ratio, %	–	58	171	28	63
Min temperature, °C	–	–7	0	11	–3
Max temperature, °C	–	2	10	21	6
Fernow 4					
Dates	10/11–4/30	–	–	5/1–10/10	10/1–9/30
Discharge, mm	486	–	–	156	642
Runoff ratio, %	63	–	–	23	44
Min temperature, °C	–2	–	–	11	4
Max temperature, °C	8	–	–	23	15
Coweeta 14					
Dates	10/17–4/17	–	–	4/18–10/16	10/1–9/30
Discharge, mm	578	–	–	385	962
Runoff ratio, %	57	–	–	49	54
Min temperature, °C	0	–	–	12	6
Max temperature, °C	14	–	–	26	20
Coweeta 34					
Dates	10/17–4/17	–	–	4/18–10/16	10/1–9/30
Discharge, mm	658	–	–	509	1167
Runoff ratio, %	59	–	–	58	59
Min temperature, °C	0	–	–	12	6
Max temperature, °C	14	–	–	26	20
Coweeta 36					
Dates	10/17–4/17	–	–	4/18–10/16	10/1–9/30
Discharge, mm	1100	–	–	587	1687
Runoff ratio, %	89	–	–	61	77
Min temperature, °C	0	–	–	12	6
Max temperature, °C	14	–	–	26	20

Table 4. Numbers of Treated/Control Basin Pairs by Basin Type^a

	>100 Year-Old Conifer Forest, Dry Summer	<95 Year-Old Deciduous Forest, Wet Summer	Number of Pairs
Seasonal snowpack	Andrews 1/2 Andrews 6/8	Hubbard Brook 2/3 Hubbard Brook 4/3 Hubbard Brook 5/3	5
Transient snow or no snow	Andrews 10/2 Coyote 3/4 Caspar C/I Caspar E/I	Fernow 1/4 Fernow 7/4 Coweeta 7/34 Coweeta 13/14 Coweeta 37/36	9
Number of pairs	6	8	14

^aTypes are conifer, no seasonal snow; conifer, seasonal snow; deciduous, no seasonal snow; deciduous, seasonal snow. Basin types are based on vegetation type and forest age in control basin as of 2002 (time since most recent forest disturbance), summer precipitation, and presence/absence of a seasonal snowpack. A seasonal snowpack persists throughout the winter, whereas a transient snowpack may persist for only a few days to a few weeks [Harr, 1981]. Snow seasonality is based on long-term records (snow data at Hubbard Brook) and modeling [Perkins, 1997].

relative streamflow changes were tested for independence to warm periods. For each period k , absolute streamflow changes were defined as all days i for which the 15-day smoothed values of

$$f_{ik} > s[\ln(a_{ij})]$$

where $s[\ln(a_{ij})]$ was the back-transformed, smoothed standard deviation of a_{ij} for all years j in the period of record. Thus $n_{abs,k}$ is the count of days i in the water year for which f_{ik} , the absolute change in the treated/control relationship days in period k , exceeds the variation in the entire record of streamflow on that day at the control watershed. Relative streamflow changes were defined as all days i for which the 15-day smoothed values of

$$d_{ik} > 25$$

Thus $n_{rel,k}$ is a count of days i in the water year on which the treated/control relationship in streamflow in period k changed by more than 25%.

[20] Counts of days with absolute and relative changes ($n_{abs,k}$, $n_{rel,k}$) were subdivided by season. Every day of the water year at each control basin was classified into one of four seasons based on soil moisture, temperature, and snowmelt (Table 3). Two seasons occurred at basins lacking snowpacks: (1) warm (and dry at conifer basins, moist at deciduous basins), and (2) moist, cool. Basins with snowpacks had two additional seasons: (3) moist, snow accumulation and (4) moist, snowmelt. Seasons were defined based on mean values over the entire period of record at each control basin for each day i of minimum and maximum temperatures ($T_{min,i}$, $T_{max,i}$), precipitation (P_i), streamflow (Q_i), and snow water equivalent (S_i). Warm, moist periods were defined as all days i for which $T_{min,i} > T^*_{min}$, $P_i > P^*$, and $Q_i > Q^*$, where T^*_{min} is a temperature threshold of 5°C for deciduous forests and 0.1°C for conifer forests, and P^*

and Q^* are moisture thresholds of 2 mm and 0.5 mm, respectively. Warm periods were defined as all days i for which $T_{min,i} > T^*_{min}$, and (for warm, dry periods at conifer basins) $P_i < P^*$ and $Q_i < Q^*$. Periods in which snowpacks were present were divided into days for which $S_i > S_{i-1}$ (accumulation) or $S_i < S_{i-1}$ (melt).

[21] Hypotheses involving succession were tested by linear regression [Ramsay and Schaefer, 1996]. Response variables were the sum of daily streamflow changes f_{ik} by season and for the whole water year, and these sums as percents of seasonal or annual streamflow (Table 3). The independent variable was the difference in age between the control and treated basin (Table 1). Data points in regressions were coded by basin types: (1) conifer, seasonal snow; (2) conifer, transient or no snow; (3) deciduous, seasonal snow; (4) deciduous, transient or no snow (Table 4).

5. Results

5.1. Summer Precipitation and Snowmelt Effects on Daily Streamflow

[22] Daily streamflow responds to summer precipitation and snowpack characteristics of the basins. The Pacific Northwest (conifer forest) has dry summers, whereas the east (deciduous forest) has wet summers (Tables 3 and 4, Figure 3). In conifer forest basins with transient or no snow (Andrews 9, Coyote 4, Caspar I), smoothed daily streamflow peaks in January or February and declines rapidly starting in March, as precipitation declines and minimum temperatures rise above 0°C. In deciduous forest basins with transient or no snow (Fernow, Coweeta), streamflow peaks in March, just before leafout, and declines rapidly, despite constant precipitation, after minimum temperatures rise above 5°C. In conifer basins with seasonal snow (Andrews 2, Andrews 8), streamflow remains elevated after snowmelt in March, April, and May (Figure 3). In the deciduous forest basin with a seasonal snowpack (Hubbard Brook), streamflow declines after December as the snowpack forms, rises to a maximum in mid-April during snowmelt, begins to decline in late April, and continues to decline rapidly after minimum temperatures rise above 5°C in May (Figure 3).

5.2. Seasonal Effects

[23] Large streamflow changes, in both absolute and relative terms, were associated with vegetation change, but they occurred during different seasons and time periods in various basin pairs. Absolute changes in daily streamflow after 100% forest removal were strongly seasonal, and ranged from slight decreases of up to -2 mm/day, to no change at all, to increases of as much as 8 mm/day (Figure 4). In conifer forest basins, daily streamflow increased by as much as 6 to 8 mm during the fall, and 2 to 6 mm in the winter and spring, in the 1 to 5-yr period after forest removal. Some increases persisted for up to 35 years. In deciduous forest basins, streamflow changes were both positive and negative, and occurred during summer, snowmelt, and other periods. Except in one herbicided basin where initial increases were larger

Note to Table 3

^aDates are given in month/day. Seasons are defined in the text. Runoff ratio is streamflow/precipitation \times 100. The warm season is moist in eastern forests, and dry in Pacific Northwest forests.

Table 5. Absolute Streamflow Changes in Warm, Moist Seasons After Forest Removal and During Forest Regrowth at Fourteen Pairs of Small Experimental Basins in Pacific Northwest Conifer and Eastern Deciduous Forests, USA^a

Hypothesis/Season	Years After Forest Removal									
	Treatment	1 to 5	6 to 10	11 to 15	16 to 20	21 to 25	26 to 30	31 to 35	36 to 40	41 to 45
<i>Conifer Forests</i>										
Andrews 1/2										
Change (mm)	318	414	293	229	246	238	197	152		
Odds ratio	5 ^b	203 ^d	8 ^d	7 ^d	13 ^d	6 ^d	6 ^d	4 ^c		
Andrews 6/8										
Change (mm)		421	237	240	268	205	104			
Odds ratio		1	2	43 ^d	2 ^b	2	7 ^b			
Andrews 10/2										
Change (mm)		108	95	91	−16	−30	−31			
Odds ratio		4 ^c	7 ^d	10 ^d	3 ^b	4 ^b	2			
Coyote 3/4										
Change (mm)		265	284							
Odds ratio		5 ^d	8 ^d							
Caspar C/I										
Change (mm)		196	274							
Odds ratio		—	—							
Caspar E/I										
Change (mm)		124	520							
Odds ratio		—	—							
<i>Deciduous Forests</i>										
Hubbard Brook 2/3										
Change (mm)	661	262	51	−17	−21	−25	−59	4		
Odds ratio	7 ^d	3 ^b	0.4	0.4	0.1	0.2	0.2	0.2		
Hubbard Brook 4/3										
Change (mm)		101	79	37	−36	−61	−61	−51		
Odds ratio		0.1	0.1	—	0.1	0.1	0.3	0.2		
Hubbard Brook 5/3										
Change (mm)		131	87	0	−27					
Odds ratio		0.4	0.3	0.2	0.3					
Fernow 1/4										
Change (mm)		156	16	16	27	34	52	2	−8	
Odds ratio		48 ^d	0.1	—	0.1	4	1.6	0.1	—	
Fernow 7/4										
Change (mm)	66	149	60	9	−16	−5	8	−38		
Odds ratio	—	—	—	—	—	—	—	—		
Coweeta 7/34										
Change (mm)		105	1	−57	86					
Odds ratio		0.2 ^c	0.1 ^b	4 ^b	3 ^b					
Coweeta 13/14										
Change (mm)		17	14	−28	−39	−63				
Odds ratio		0.8	0.5	0.2 ^d	0.6	4 ^c				
Coweeta 37/36										
Change (mm)		164	61	55	—	−28	−46	−47		
Odds ratio		13 ^d	2	3 ^b	—	0.1 ^b	0.5	0.3 ^b		

^aChange and odds ratios are shown for each basin pair and postharvest time period. Blanks indicate no data for that time period. Dashes indicate that no chi-squared test could be conducted, because one or more cells of the 2 × 2 table contained no observations. An odds ratio >1 means that days with an absolute streamflow response were more likely to occur during the warm, moist season, and an odds ratio <1 means that days with an absolute streamflow response were less likely to occur during the warm, moist season.

^bChi-squared tests of independence between absolute streamflow changes and the warm, moist season were significant at $p < 0.05$.

^cChi-squared tests of independence between absolute streamflow changes and the warm, moist season were significant at $p < 0.001$.

^dChi-squared tests of independence between absolute streamflow changes and the warm, moist season were significant at $p < 0.0001$.

(Figure 4g), daily streamflow in deciduous basins increased by no more than 2 to 3 mm in the 1 to 5-yr period after forest removal. After a decade of forest regrowth, streamflow surpluses became deficits in several deciduous basins.

[24] Relative changes in daily streamflow after 100% forest removal also were strongly seasonal, and ranged from initial increases of a few tens to hundreds of percent (Figure 5). In conifer forest basins, daily streamflow increased by several hundred percent during the late summer/early fall (and late spring, at Caspar Creek, but results are affected by missing data) in the 1 to 5-yr period after forest removal. By 25 to 35 years after forest removal, maximum

summer deficits ranged from −30 to −50% (Figure 5). In deciduous forest basins, daily streamflow increases ranged from more than several hundred percent (in herbicided basins), 200–300% (at Hubbard Brook and Fernow), to a few tens of percent (Coweeta), in late summer and early fall in the 1 to 5-yr period after forest removal. By 25 to 35 years after forest removal, maximum summer streamflow deficits ranged from −50% (Hubbard Brook and Fernow) to −30% (Coweeta) (Figure 5).

[25] Seasons were accurate predictors of when streamflow change occurred. Absolute streamflow change was significantly associated with warm moist periods in three of

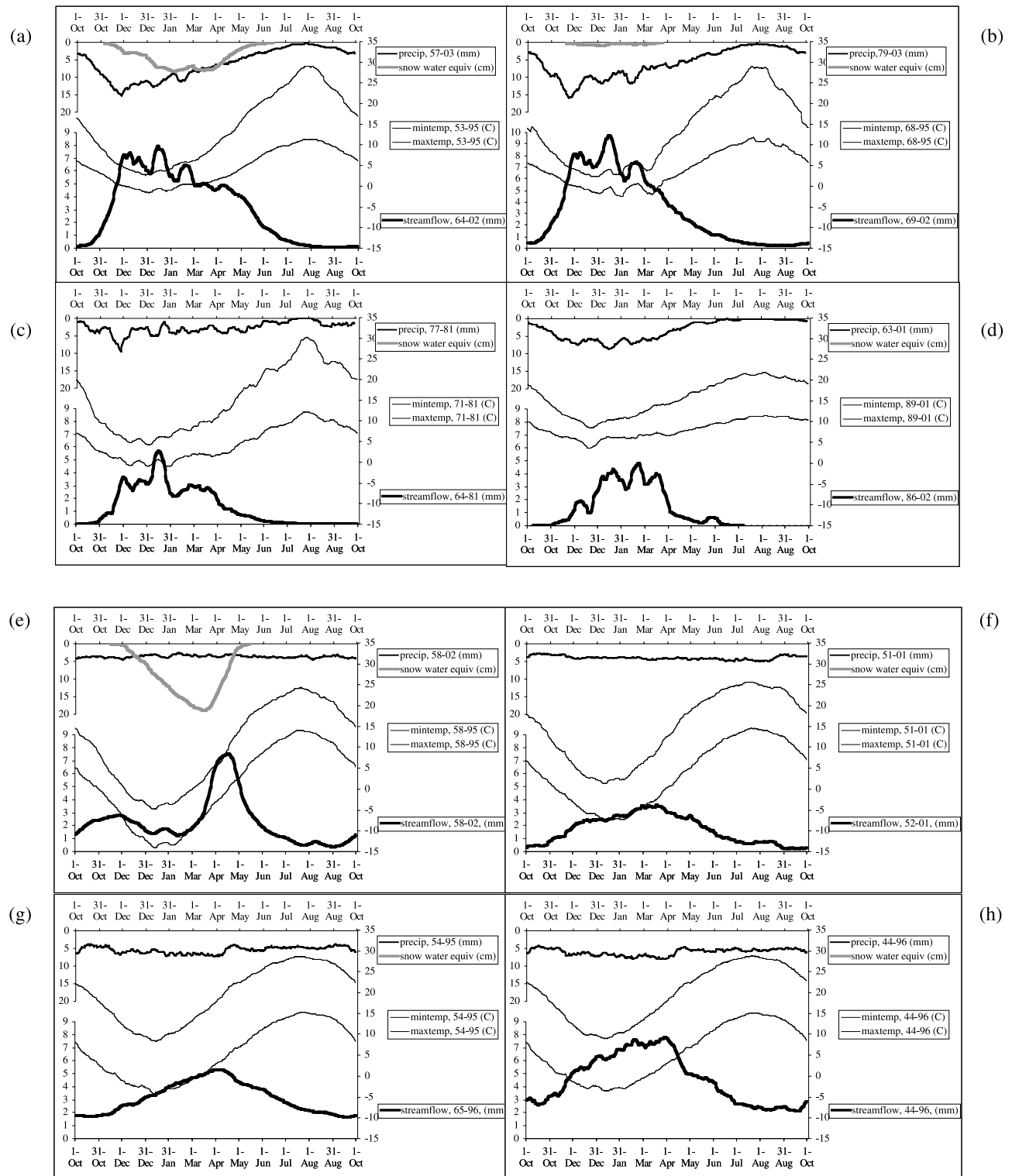


Figure 3. Mean daily precipitation (mm), snowpack (mm of snow water equivalent), streamflow (mm), maximum and minimum temperatures (°C) in ten control basins used in this study. Forest type (conifer versus deciduous), presence/absence of seasonal snowpack, and forest age in 2002 are noted. (a) Conifer, seasonal snow, 500 and 150 years (Andrews 2, Andrews 8); (b) conifer, transient/no snow, 150 years (Andrews 9); (c) conifer, transient/no snow, 150 years (Coyote 4); (d) conifer, no snow, 100 yrs (Caspar I); (e) deciduous, seasonal snow, 64 years (Hubbard Brook 3); (f) deciduous, transient snow, 95 years (Fernow 4); (g) deciduous, no snow, 75 years (Coweeta 2); (h) deciduous, no snow, 75 years (Coweeta 36).

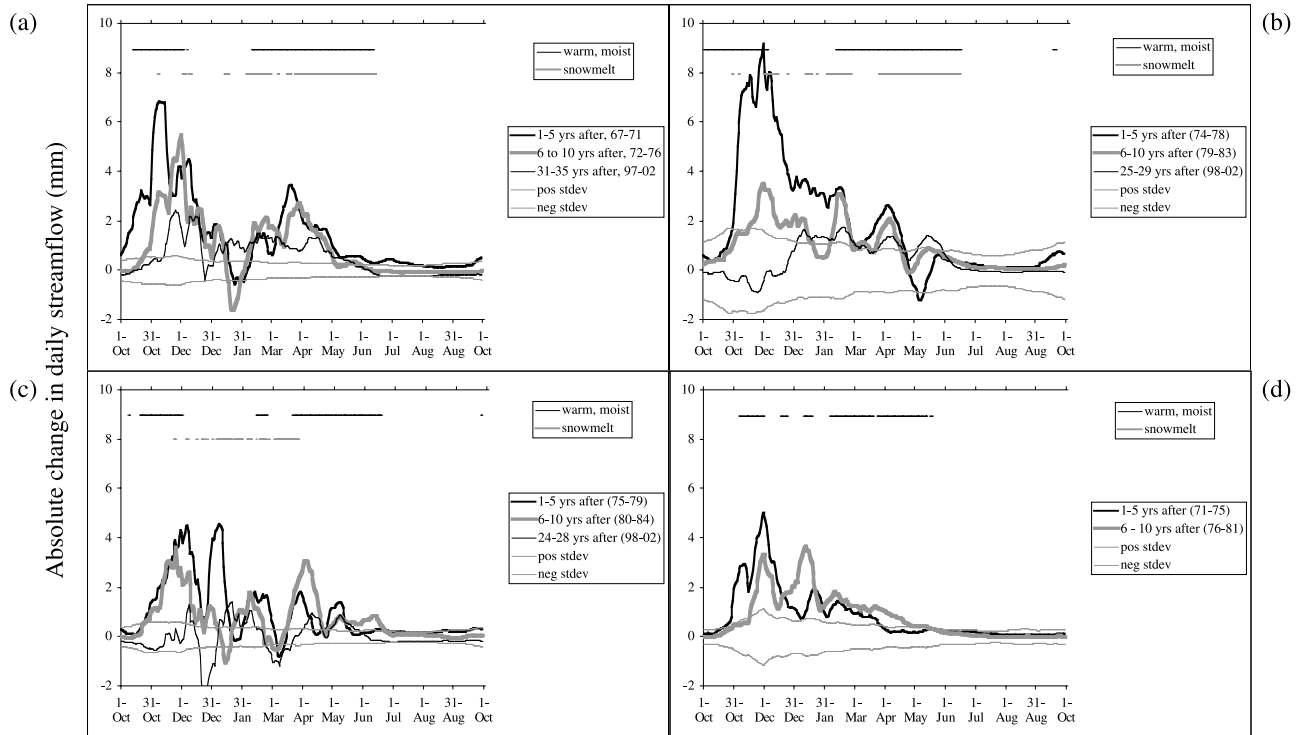


Figure 4. Absolute change in daily streamflow (mm) by day of water year (1 October - 30 September) for 5-year periods after forest removal at fourteen treated/control basin pairs. At the six conifer forest pairs, forest age (time since most recent forest disturbance) and snow conditions were (a) 462 year-old Douglas-fir/western hemlock forest, seasonal snow (Andrews 1/2); (b) 125-to 450-year old Douglas-fir/western hemlock forest, seasonal snow (Andrews 6/8); (c) 125 year old Douglas-fir/western hemlock forest, transient snow (Andrews 10/2); (d) 125-year old mixed-conifer forest, transient/no snow (Coyote 3/4); (e) 90-year old coast redwood/Douglas-fir forest, no snow (Caspar C/I); (f) 90-year old coast redwood/Douglas-fir forest, no snow (Caspar E/I). At the eight deciduous forest pairs, forest age (time since most recent forest disturbance) and snow conditions were (g) 27 year-old deciduous forest, seasonal snow (Hubbard Brook 2/3); (h) 32 year old deciduous forest, seasonal snow (Hubbard Brook 4/3); (i) 45 year old forest, seasonal snow (Hubbard Brook 5/3); (j) 50-year old red oak/sugar maple forest, transient/no snow (Fernow 1/4); (k) 56-year old red oak/sugar maple forest, transient/no snow (Fernow 7/4); (l) 50-year old deciduous forest, no snow (Coweeta 7/34); (m) 12-year old deciduous forest, no snow (Coweeta 13/14); (n) 36-year old deciduous forest, no snow (Coweeta 37/36).

four conifer basins, whereas absolute changes for the most part were independent of warm, moist seasons in the deciduous forest basins (Table 5). Days with absolute streamflow changes were three to many times more likely to occur during warm, moist periods than other periods in these six basin pairs, but they were no more, or slightly less likely to occur during warm moist periods in four deciduous forest basins. Net increases of 100 to 400 mm occurred in fall and spring in conifer forest basins, and net increases of 100 to 200 mm occurred in summer in deciduous forest basins (Table 5).

[26] Relative streamflow change was significantly associated with warm periods in all basins (Table 6). Relative streamflow changes in the 1 to 5-yr period after forest removal were significantly associated with periods of warm temperatures (summer), and amounted to net increases of 5 to 200% of summer flows (Table 6). However, in one case involving removal of 12-yr old forest (Coweeta 13/14), relative streamflow responses were not associated with season, and in another case (Coweeta 7/34), relative streamflow changes were significantly associated with cold peri-

ods. In conifer forest basins, summer streamflow changes disappeared by 5 to 10 years after forest removal. By 25 to 35 years after forest removal in conifer forest basins, a significantly higher than expected number of days had summer streamflow deficits exceeding -25% , but the net changes in summer streamflow ranged from $+6$ to -48% (Table 6). In contrast, streamflow changes were significantly more likely during the summer in all periods after forest removal in most of the deciduous forest basins, but the net changes in summer streamflow ranged from $+33\%$ (Fernow 1/4) to -42% (Hubbard Brook 2/3) (Table 6).

[27] In basins with snowpacks, absolute streamflow changes were significantly associated with periods of snowmelt in all 5-yr periods after forest removal (Table 7). In conifer forest basins with seasonal snowpacks (Andrews 1/2 and 6/8), these changes amounted to net increases of 100 to 200 mm during the snowmelt period (Table 7). In the conifer forest basin with a transient snowpack (Andrews 10), initial streamflow surpluses became streamflow deficits relative to the control, which has a seasonal snowpack (Andrews 2). In the deciduous forest basins, streamflow deficits occurred

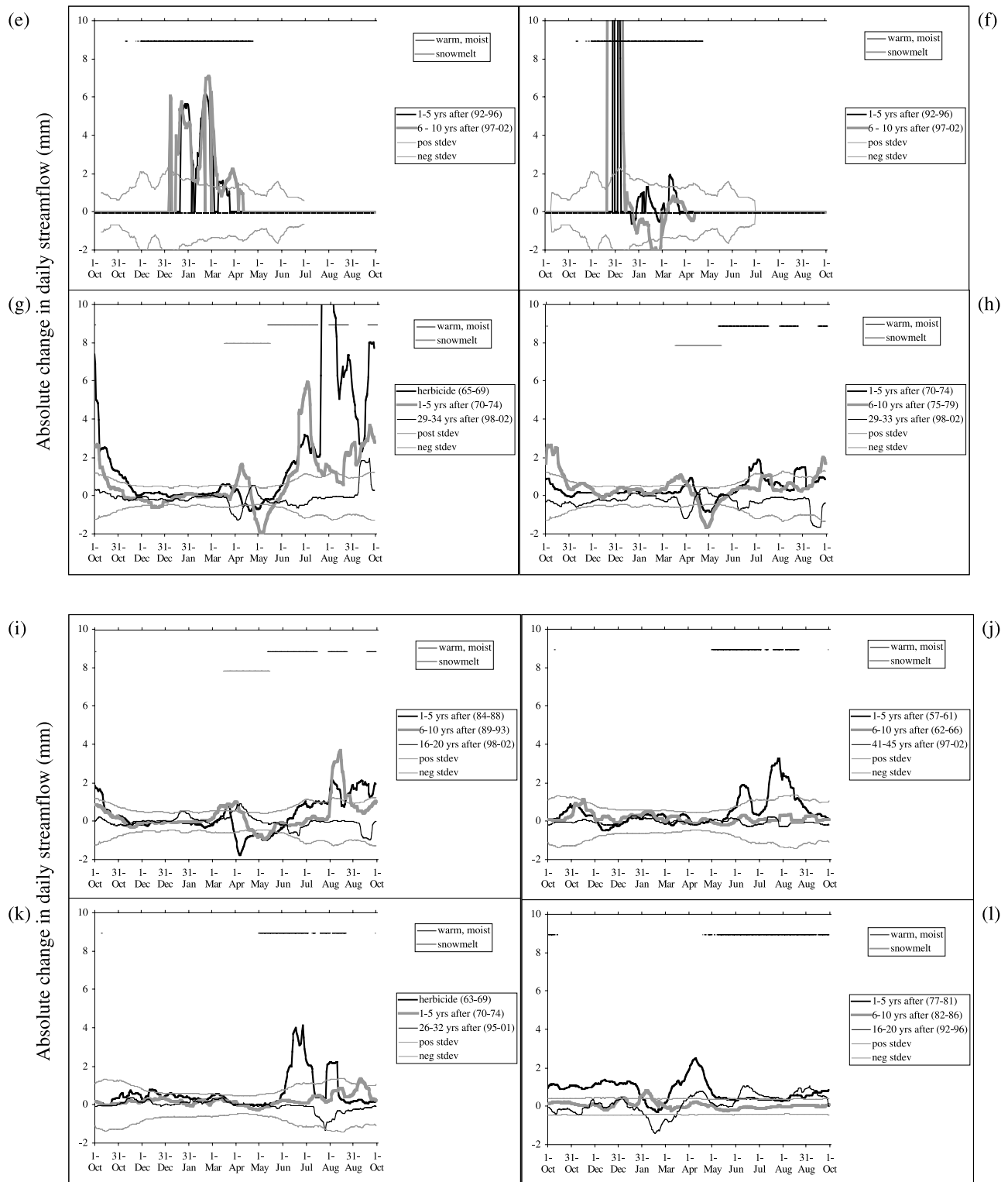


Figure 4. (continued)

during the snowmelt period; net changes ranged from +19 to -47 mm.

5.3. Successional Effects

[28] Streamflow responses to forest removal were related to two aspects of forest succession: (1) age of the regenerating forest (i.e., time since treatment, Figure 6), and (2) the difference in forest age between the treated and control

basins (Figure 7). Streamflow responses to forest removal declined over several decades of forest regrowth, but the rate of decline varied by season and forest type and age, and there is considerable between-site variability in response for any given posttreatment period (Figure 6). For the entire water year, streamflow surpluses were highest and most persistent after removal of 90 to 450-yr old conifer forests, and lowest and most ephemeral after removal of

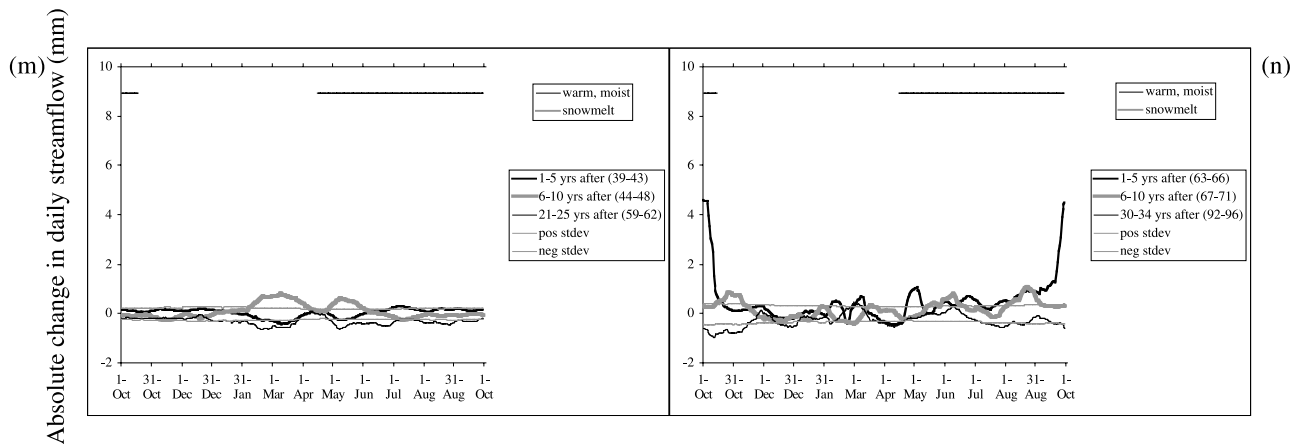


Figure 4. (continued)

12 to 56-yr old deciduous forests (Figure 6a). Conifer forests with transient snow or no snow had intermediate responses in annual streamflow. Surpluses during the snowmelt period persisted for up to four decades after removal of conifer forests from basins with a seasonal snowpack (Figure 6b). Streamflow surpluses in warm, moist seasons were higher and more persistent in conifer forest basins compared to deciduous forests (Figure 6c). By 20–25 years after forest removal (period 5), streamflow deficits had developed in August in all but one treated basin (Figure 6d). Although absolute changes were small, August streamflow 15 years after forest removal had declined by 60 to 80% relative to pretreatment August streamflow (Figure 6d).

[29] The age of forest at the time it was harvested (which is equivalent to the difference in age between the forest in the control and the treated basin) explains additional variability in streamflow response beyond that explained by season or time since treatment (Figure 7). Streamflow response in both absolute (Figure 7) and relative (data not shown) terms increased log-linearly, from treated basins with deciduous forests that were 12 to 56 years younger than their control basins, to treated basins with conifer forests 90 to 460 years younger than their control basins. Changes in annual streamflow, in streamflow during the warm, moist season, and in the snowmelt period were significantly positively related to forest age, in both the 1 to 5- and 15 to 25- yr periods after forest removal

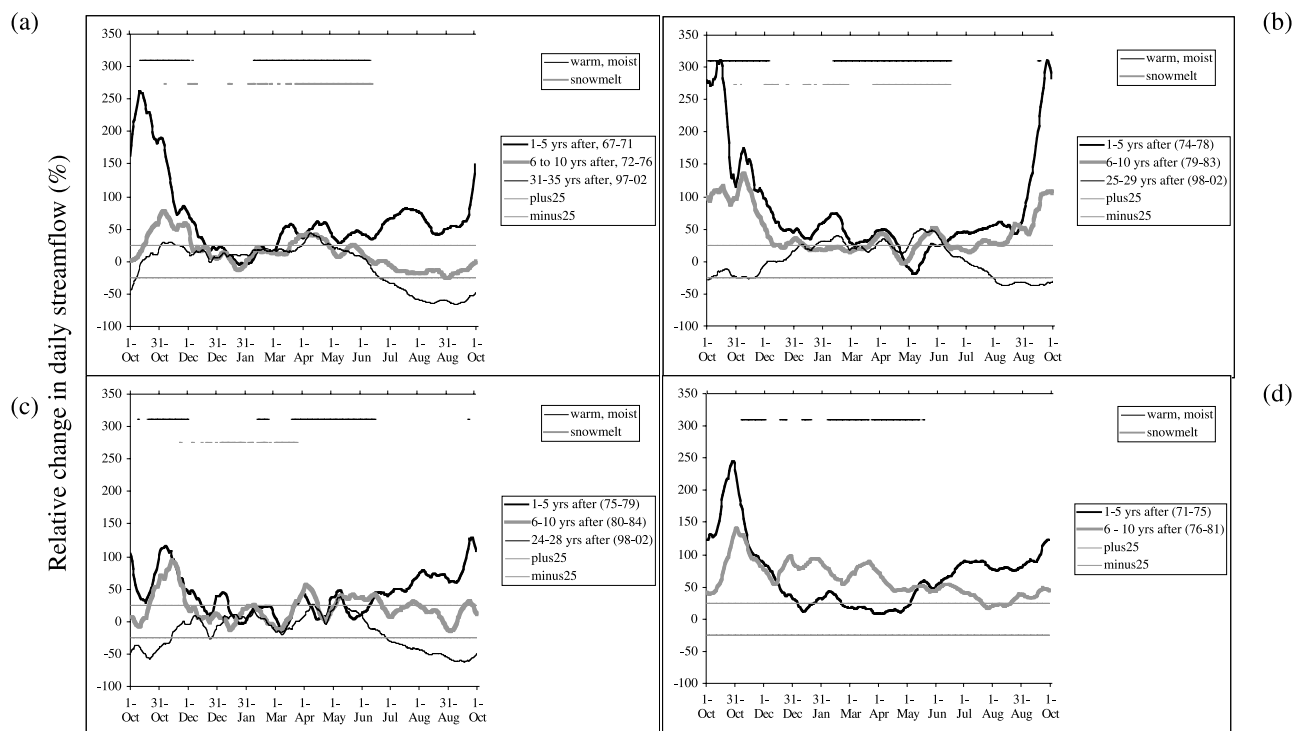


Figure 5. Relative (%) change in daily streamflow (mm) by day of water year (1 October–30 September) for 5-year periods after forest removal at fourteen treated/control basin pairs. See Figure 4 for basin names, forest types, and ages.

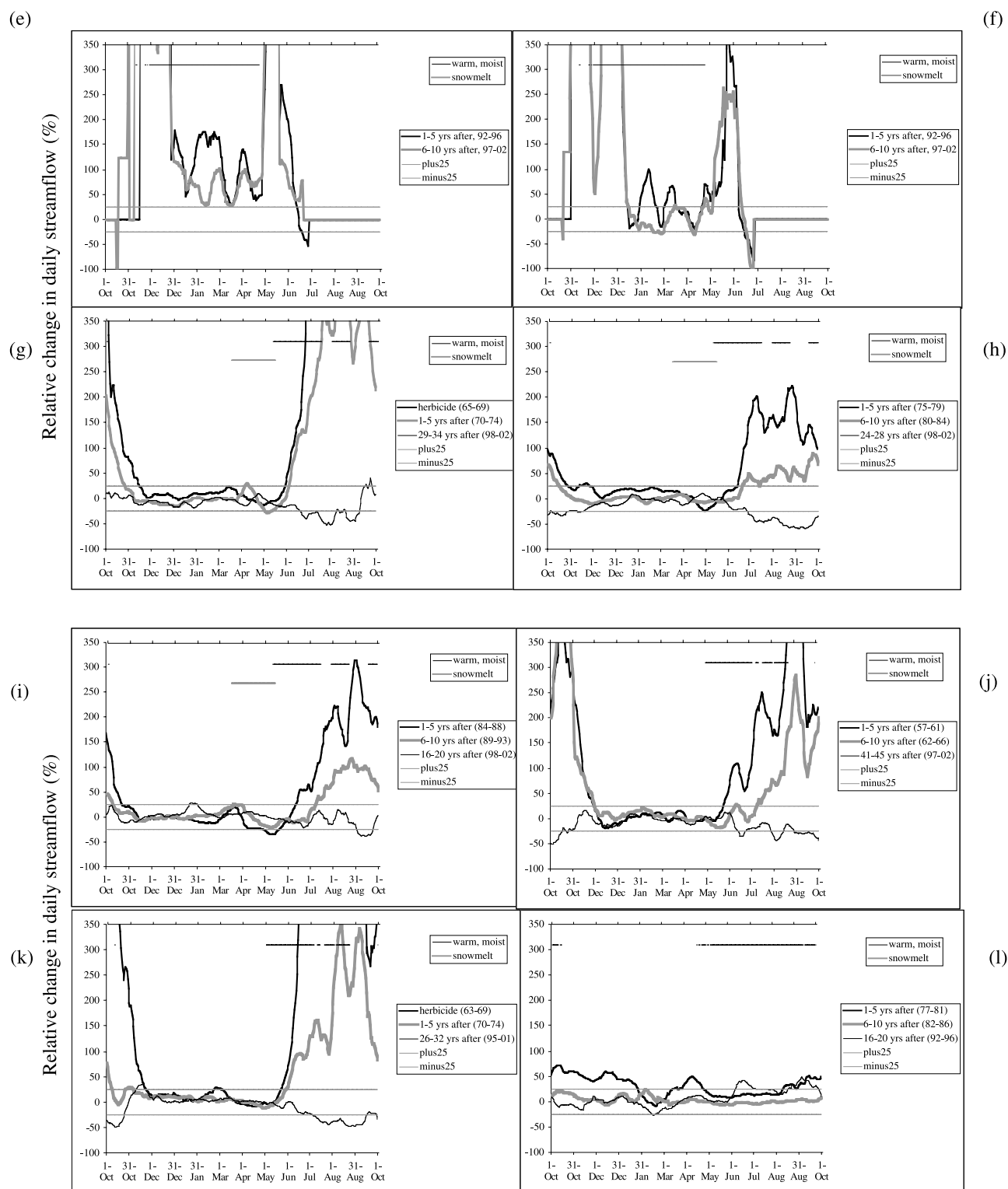


Figure 5. (continued)

(Figure 7). Fitted relationships explained from 45 to 92% of variation in absolute changes (Figure 7) and from 37 to 65% of variation in percent changes in streamflow (data not shown). Even when the “conifer-seasonal snow” points in Figure 7 were removed, six of eight regressions were still significant, with r^2 values ranging from 0.40 to 0.81. Change in streamflow during the cold season was not related to forest age in the 1 to 5-yr period, but was related

to forest age in the 15 to 25-yr period after forest removal (Figures 7g and 7h).

6. Discussion

[30] Streamflow response to experimental forest removal and regrowth in fourteen treated/control basin pairs in the Pacific Northwest and eastern United States indicates that

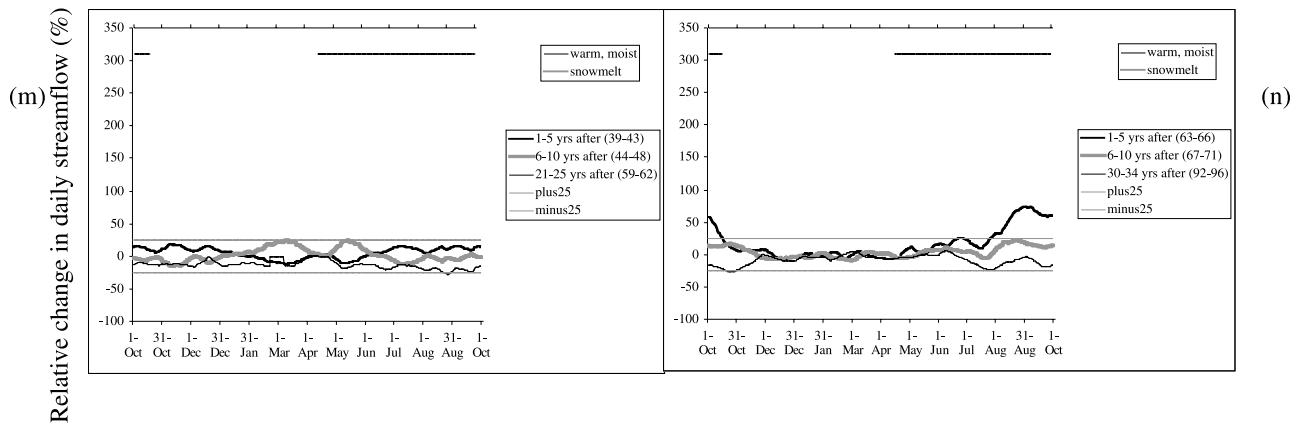


Figure 5. (continued)

Table 6. Relative Streamflow Changes in Warm Seasons After Forest Removal and During Forest Regrowth at Fourteen Pairs of Small Experimental Basins in Pacific Northwest Conifer and Eastern Deciduous Forests, USA^a

Forest Type/Basin Pair	Years After Forest Removal									
	Treatment	1 to 5	6 to 10	11 to 15	16 to 20	21 to 25	26 to 30	31 to 35	36 to 40	41 to 45
<i>Conifer Forests</i>										
Andrews 1/2										
Change (%)	110	60	-7	-22	-7	-5	-12	-48		
Odds ratio	61 ^d	53 ^d	0.1 ^d	1	2	0.3 ^b	1	23 ^d		
Andrews 6/8										
Change (%)		52	33	35	39	10	-13			
Odds ratio		22 ^b	2	1	1	0.1 ^c	2			
Andrews 10/2										
Change (%)		25	37	16	13	23	6			
Odds ratio		44 ^d	0.5	1.0	2 ^b	0.9	15 ^d			
Coyote 3/4										
Change (%)		145	67							
Odds ratio		145 ^d	0.02 ^b							
<i>Deciduous Forests</i>										
Hubbard Brook 2/3										
Change (%)	469	186	36	-12	15	-18	-42	3		
Odds ratio	404 ^d	18 ^d	9 ^d	3 ^b	7 ^d	20 ^d	22 ^d	18 ^d		
Hubbard Brook 4/3										
Change (%)		70	55	26	-25	-43	-42	-35		
Odds ratio		744 ^d	10 ^d	17 ^d	11 ^d	22 ^d	10 ^d	13 ^d		
Hubbard Brook 5/3										
Change (%)		91	61	0	-19					
Odds ratio		347 ^d	14 ^d	8 ^d	6 ^d					
Fernow 1/4										
Change (%)		100	10	11	17	22	33	22	1	-5
Odds ratio		334 ^d	4 ^c	4 ^c	10 ^d	5 ^b	7 ^d	7 ^d	6 ^d	6 ^d
Fernow 7/4										
Change (%)	95	38	6	-10	-3	5	-24			
Odds ratio	351 ^d	31 ^d	0.7	1.4	4 ^c	6 ^d	8 ^d			
Coweeta 7/34										
Change (%)		21	0	-11	17					
Odds ratio		0.2 ^d	0.2	0.6	8 ^d					
Coweeta 13/14										
Change (%)		4	4	-7	-10	-16				
Odds ratio		3	0.6	1	0.2	19 ^b				
Coweeta 37/36										
Change (%)		28	10	9	-	-5	-8	-8		
Odds ratio		173 ^d	3	16 ^b	-	11	-	0.1		

^aPercent change and odds ratios are shown for each basin pair and postharvest time period. Blanks, dashes, and odds ratios are defined in legend to Table 5.

^bChi-squared tests of independence between relative streamflow changes and the warm season were significant at $p < 0.05$.

^cChi-squared tests of independence between relative streamflow changes and the warm season were significant at $p < 0.001$.

^dChi-squared tests of independence between relative streamflow changes and the warm season were significant at $p < 0.0001$.

Table 7. Absolute Streamflow Changes in Snowmelt Periods After Forest Removal and During Forest Regrowth at Fourteen Pairs of Small Experimental Basins in Pacific Northwest Conifer and Eastern Deciduous Forests, USA^a

Forest Type/Basin Pair	Years After Forest Removal									
	Treatment	1 to 5	6 to 10	11 to 15	16 to 20	21 to 25	26 to 30	31 to 35	36 to 40	41 to 45
Conifer Forests										
Andrews 1/2										
Change (mm)	167	170	154	153	159	139	141	103		
Odds ratio	7 ^b	11 ^d	5 ^d	8 ^d	6 ^d	4 ^c	8 ^d	7 ^d		
Andrews 6/8										
Change (mm)		139	139	180	237	171	126			
Odds ratio		4 ^c	4 ^c	8 ^d	9 ^d	6 ^d	12 ^d			
Andrews 10/2										
Change (mm)		6	14	21	−17	−24	−14			
Odds ratio		4 ^c	11 ^d	4 ^c	5 ^d	9 ^d	6 ^d			
Deciduous Forests										
Hubbard Brook 2/3										
Change (mm)		−10	−8	−27	−17	−47	−19	−17	−18	
Odds ratio		0.7	12 ^d	160 ^d	91 ^d	185 ^d	60 ^d	100 ^d	75 ^d	
Hubbard Brook 4/3										
Change (mm)		−1	−12	−5	−25	1	−4	−13		
Odds ratio		172 ^d	227 ^d	−	118 ^d	73 ^d	40 ^d	60 ^d		
Hubbard Brook 5/3										
Change (mm)		−41	0	10	19					
Odds ratio		372 ^d	384 ^d	75 ^d	40 ^d					

^aChange and odds ratios are shown for each basin pair and postharvest time period. Blanks, dashes, and odds ratios are defined in legend to Table 5.

^bChi-squared tests of independence between absolute streamflow changes and the snowmelt season were significant at $p < 0.05$.

^cChi-squared tests of independence between absolute streamflow changes and the snowmelt season were significant at $p < 0.001$.

^dChi-squared tests of independence between absolute streamflow changes and the snowmelt season were significant at $p < 0.0001$.

forest effects on streamflow are strongly seasonal, and depend upon the age or successional stage of the forest. The analysis involved a complete re-analysis of primary data using a novel approach to paired-basin analysis, rather than relying upon reviews or meta-analyses of published studies as in *Bosch and Hewlett* [1982] or *Robinson et al.* [2003]. Our findings may differ slightly from published values for specific sites [*Rothacher*, 1970, 1975; *Douglass and Swank*, 1972; *Harr et al.*, 1979, 1982; *Swift and Swank*, 1981; *Hornbeck et al.*, 1993, 1997; *Martin et al.*, 2000; *Lewis et al.*, 2001; *Swank et al.*, 2001] because of differences in watershed pairing, use of daily average flows, and log-transformation of data. The results are relevant to eco-physiology, global change modeling, and stream ecology as well as hydrology, and they highlight the future potential for paired basin experiments.

[31] Atmospheric stresses (i.e., temperature, vapor pressure) and soil moisture stresses imposed on individual plants [e.g., *Eagleson*, 2002] scale up to influence streamflow at the small watershed scale, producing streamflow responses to forest removal and regrowth that were concentrated during seasons when moisture and temperature are conducive to evapotranspiration. Evapotranspiration depends upon (among other things) soil moisture, net interception, and evaporation from the canopy (Figure 1). Streamflow responses were larger in absolute terms after removal of conifer compared to deciduous forests, for basins with similar mean annual precipitation, confirming the site-specific work of *Swank and Douglass* [1974]. Conifers are adapted to use water throughout the year, as long as soil moisture and temperatures are not limiting, whereas transpiration in deciduous trees is limited to periods when leaves are present. Plant-level differences between conifer and deciduous forests were accentuated at the basin

scale in this study, because coniferous forests were older than deciduous forests, and evapotranspiration from deciduous understory and early successional components of the regenerating conifer stands was limited by dry summers typical of these western sites.

[32] Changes in forest canopy interactions with the snowpack over the course of succession provide a possible alternative mechanism for documented long-term changes in snowmelt runoff [*Hodgekins et al.*, 2003]. Seasonal snowpack volume, and hence the snow water equivalent available to melt in the spring, depends upon the balance of additions and losses to sublimation and melt (Figure 1). Removal of deciduous forest canopies increases the exposure of cold snowpacks to winter sunlight in climates of eastern forests, and characteristically dense regenerating stands (e.g., of pin cherry [*Marks*, 1974]) may intercept more snow, enhancing sublimation and reducing snowpack volume. Therefore in the first decade after removal of deciduous forest canopies, snowmelt occurred earlier and streamflow was reduced during the snowmelt period compared to 40 to 60 yr-old forests (Figures 4g–4i). This effect was reversed after two or three decades of forest regeneration, and snowmelt occurred later, but streamflow remained reduced during the snowmelt period compared to the control. In contrast, removal of conifer forest canopies decreases interception and increases the exposure of warm snowpacks to radiative heat losses, cooling mixed rain/snow to snow, in climates of Pacific Northwest forests [*Harr*, 1981]. Moreover, sparse regenerating stands [*Halpern*, 1989; *Acker et al.*, 2002] may intercept less snow. All these factors enhance snow accumulation and increase snowpack volume [*Marks et al.*, 1998; *Storck et al.*, 2002]. Therefore in the first decade after removal of conifer forest canopies, snowmelt occurred earlier and streamflow was

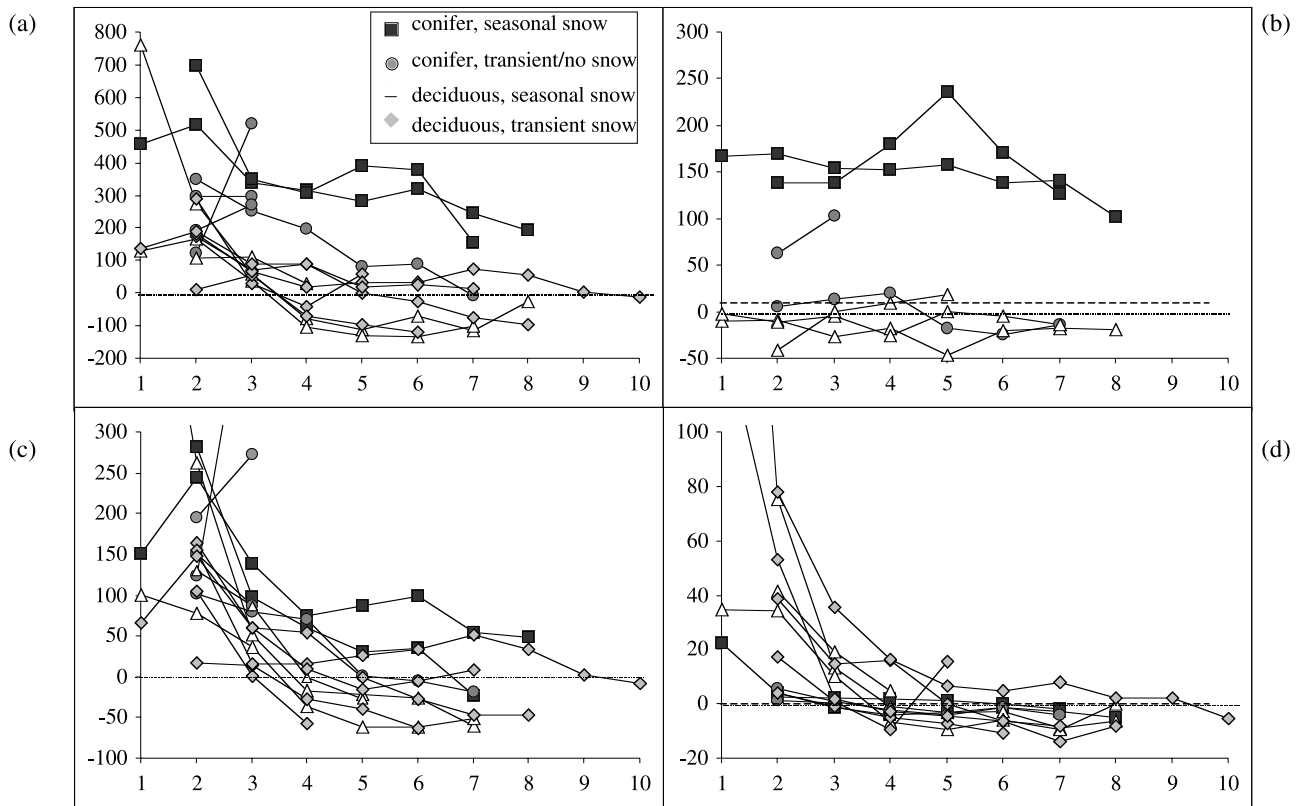


Figure 6. Effect of time since treatment (5-yr period after forest removal) on absolute changes in streamflow (mm) in fourteen treated/control basin pairs. (a) Entire water year, (b) snowmelt period, (c) warm, moist period without snow (summer for deciduous forest sites, fall for conifer forest sites), (d) August lowflow period. X axis values are 1 = treatment period, 2 = 1 to 5-years after forest removal, ..., 10 = 41 to 45 after forest removal.

increased during the snowmelt period compared to 125 to 500 year-old forests (Figures 4a and 4b). After two or three decades of forest regeneration, snowmelt occurred later, and streamflow during the snowmelt period remained elevated, compared to the control.

[33] Streamflow variability in winter may be coupled to forest vegetation through lagged effects transmitted by soil moisture reservoirs. Lagged effects were limited to circumstances when moisture was held at high tensions, such as when soil moisture content was low or soils were very fine-textured. Soil moisture at high tensions has low hydraulic conductivity, so a “pulse” of increased or decreased soil moisture could take months to travel from the rooting zone through a small basin to the gage. Thus in deciduous sites, maximum streamflow responses in summer appeared near the middle or end of the warm period (Figures 4g–4k, 4n). In two cases (Figures 4l and 4m) the maximum streamflow response appeared several months after the end of the summer, an effect noted by earlier workers [Swank *et al.*, 1988].

[34] The strong relationships of streamflow change to two aspects of forest age (time since treatment and age of the forest at the time it was removed) support the notion that forest succession results in more efficient use of fixed moisture resources [Eagleson, 2002]. Forest age is a proxy for forest condition, which influences hydrologic processes. Specifically, time since treatment, and time since most recent severe disturbance are proxies for leaf area, sapwood

densities, species composition, and canopy structure, which in turn are proxies for interception, evaporation, and transpiration. Thus as noted by Hornbeck *et al.* [1993, 1997] and Swank *et al.* [2001], young (10 to 30-year old) forests regenerating from disturbance were higher water users per unit leaf area than older forests (12 to 450 years older). However, based on 14 basin pairs in both conifer and deciduous forests, young forests (10 to 30 yrs old) were higher water users than old forests (70 to 450 yrs old) only in relative terms during late summer periods (August). In fact, the converse was true: removal of old (90 to 450-year old) conifer forests had a larger absolute effect on streamflow than removal of young (13 to 56-year old) deciduous forests. As forest succession proceeds over 50, 100, or 500 years, many factors (the increasing age of individual trees, changes in water use by new species succeeding in the overstory and understory, altered interception capacity, or development of a canopy epiphyte community) may increase the ability of a forest community to capture and store water. Disturbance history can help predict the ranges of streamflow responses to forest removal, but further work [e.g., Link, 2001] is needed to elucidate the many hydrologic mechanisms that operate in aging forests.

[35] Streamflow responses to forest removal observed in this study indicate that forest vegetation effects on streamflow variability may have consequences for stream ecology [e.g., Poff *et al.*, 1997]. In basins draining northwestern conifer forests, persistent absolute streamflow increases

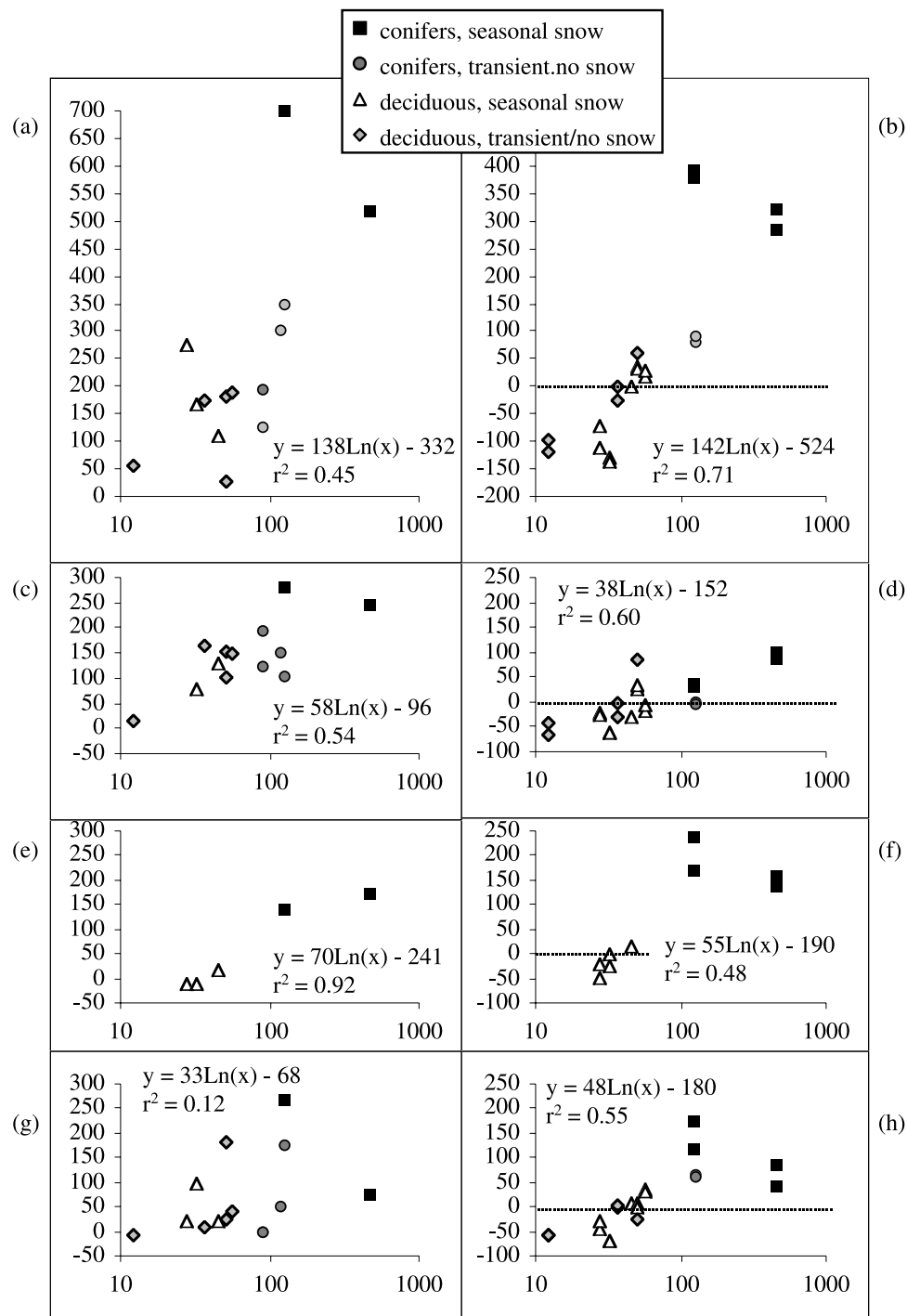


Figure 7. Effect of forest age at the time of harvest (time since most recent forest disturbance) on absolute change in water yield for various seasons and stages of succession. Entire water year: (a) 1 to 5 year and (b) 15 to 25 year periods after forest removal. Warm, moist season, fall for conifers, summer for deciduous forest: (c) 1 to 5 year and (d) 15 to 25 year periods after forest removal. Snowmelt season: (e) 1 to 5 year and (f) 15 to 25 year periods after forest removal. Cold season (winter): (g) 1 to 5 year and (h) 15 to 25 year periods after forest removal. Herbicided basin (Hubbard Brook 2) was excluded from regression for the warm, moist season, 1 to 5 year period after forest removal. Least-squares fitted log-linear models and r^2 values are shown.

during spring, combined with persistent relative summer deficits, imply that stream organisms are subjected to bigger ranges of streamflow variability in young compared to old-growth forest stands. Basins draining young eastern forests

also may experience higher streamflow variability compared to older forests as a result of the combined effects of forest canopy on streamflow through changes in snow accumulation and melt, and summer water use.

[36] The methods used in this study represent a departure from prior work, and indicate the potential for continued analyses of paired-basin experiments.

[37] 1. The treated/control relationship in paired-basin experiments, rather than a black and white one, can be viewed as a function of continuous, and continuously changing, differences between basins in vegetation structure, composition, and climate. Thus multiple basins may be used as controls for a given treated basin, and the responses may be compared.

[38] 2. Paired-basin records provide the opportunity to quantify and compare streamflow responses at multiple temporal scales, including storm events, seasons, successional periods, and decadal climate change. Work is needed to examine how streamflow responses at seasonal and successional timescales, addressed in this study, interact with streamflow responses at the storm event scale [e.g., Jones, 2000; Lewis *et al.*, 2001], and at the scale of decadal climate change [e.g., Greenland *et al.*, 2003].

[39] 3. Small paired-basin experiments permit comparison of streamflow responses across vegetation types and treatments, climates, and basin scales. This analysis, which was restricted to <100-ha, mountainous, temperate deciduous and conifer forest basins, could be extended with additional replicates of these basin types, or records from other climates, other treatments (e.g., fire), or other vegetation types. The very high streamflow variability at basins of <20 ha may obscure some important streamflow changes, so records from larger basin scales should be included in analyses. Relevant data are available through Hydro-DB [Baker *et al.*, 2000].

[40] Prediction of streamflow from ungaged basins is a major ongoing challenge for hydrologists (see e.g., the PUB initiative, <http://iahs.info>). This study indicates that to some extent streamflow can be predicted from climate, forest type, and disturbance history effects on hydrologic processes. The approaches presented in this paper provide useful advances for understanding and prediction of hydrologic response.

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