Chapter 33
The Effects of Forest Harvesting on Forest Hydrology and Biogeochemistry

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33.1 Introduction

The hydrological consequences of forest harvesting are arguably the longest-studied aspect of interactions between hydrology and land cover or land use. Chang (2003) notes that increased understanding of interactions between forest management and hydrology led to enactment of forest protection laws in China as early as 300 BC, while the Swiss initiated the establishment of forested watershed reserves in Europe in 1342 (Kittredge 1948). The earliest documented basin-scale comparison of streamflow and erosion from forested and agricultural lands (1902) also comes from Switzerland (Whitehead and Robinson 1993). Numerous studies of forest harvesting effects on various aspects of the hydrological cycle (particularly streamflow) followed, complemented in the past several decades by research on the biogeochemical impacts of forest harvesting. Aspects of this work (particularly related to harvesting effects on streamflow) were summarized in classic reviews by Hibbert (1967), Bosch and Hewlett (1982), and Sahin and Hall (1996). Recent summaries of the hydrologic and biogeochemical impacts of forest harvesting have focused on individual countries (e.g., USA – Stednick 1996, National Research Council 2008; Canada – Buttle et al. 2005, 2009), specific regions (e.g., Pacific Northwest – Moore and Wondzell 2005; Feller 2005), or particular environments (e.g., tropical forests – Bruijnzeel 2004). Rather than restate these reviews, this chapter attempts to synthesize the results of studies of the hydrologic and biogeochemical effects of forest harvesting from a more global perspective. In particular, it focuses on areas of consensus that have arisen from this work, caveats to that consensus that arise from specific environmental conditions or forest management practices, and areas of controversy, both in terms of the results of this research and the methods employed to obtain them. The latter is an important but often overlooked issue in attempts to assess the consequences of forest harvesting, and some of the ongoing debates regarding these outcomes can be linked to the experimental and analytical approaches used in various studies. This assessment of consensus, caveats, and controversies begins with a review of the effects of forest harvesting on hydrological processes and water partitioning, links these effects to harvesting impacts on various aspects of streamflow at the basin scale, and then turns to the biogeochemical

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consequences of forest harvesting. The chapter concludes with an outline of major research issues that should be addressed in future work.

33.2 Effects of Forest Harvesting on Hydrologic Processes and Water Partitioning

33.2.1 Precipitation

The question of whether deforestation affects the amount of precipitation at that location is a long-standing one, and some have characterized views on the issue as based on folklore rather than science (Hamilton 1985). Early research (e.g., Pereira 1973) showed little or no relationship between an area's precipitation and whether it was forested or not. However, the topic has received increased interest, partly as a result of concerns regarding the contributions of modifications of Earth's vegetative cover to anthropogenic climate change (Marland et al. 2003). This has been spurred in part by research on precipitation recycling (Vanclay 2009), such as isotopic studies (e.g., Salati et al. 1979) that show that large forest regions, such as Amazonia, can regenerate their own rainfall via evapotranspiration. da Silva and Avissar (2006) note that the effects of forest removal on precipitation may differ depending on the scale of deforestation. Massive deforestation may decrease rainfall due to reduced transpiration and surface roughness combined with increased albedo, as supported by work in Central America (Lawton et al. 2001). However, current levels of deforestation in Amazonia and other tropical regions may enhance convection and promote a transient increase in precipitation (Henderson-Sellers and Pitman 2002; Avissar et al. 2002). Marland et al. (2003) suggest that the scale of deforestation needed to induce a significant change in precipitation patterns depends in part on where such land surface changes occur, with smaller extents of deforestation required in equatorial regions and presumably larger areas needed in other locations.

33.2.2 Interception

It is generally accepted that harvesting increases net precipitation reaching the forest floor as a result of reduced interception losses. The magnitude of this increase can be considerable, given that annual interception can range from 10 to 50% of annual precipitation (Roth et al. 2007). This increase differs depending on the type of forest harvested (e.g., conifers vs. deciduous) and extent of forest removal (clearcutting vs. selection harvesting), and also varies as function of storm size, weather conditions, and canopy characteristics (Van Dijk et al. 2009). The effect of harvesting on net precipitation will vary seasonally for forests that experience a dormant period and will be greatest at the time of maximum leaf area for deciduous forests. While the increase in net precipitation occurs for both rainfall and snowfall, it is important to note that the significance of forest harvesting for snow interception is strongly linked to regional climate. Thus, work by Pomeroy and colleagues (e.g., Pomeroy et al. 1998, 2002) has demonstrated that most intercepted snowfall in cold, dry boreal forests of central Canada is sublimated back to the atmosphere, such that harvesting can result in a substantial increase in snow accumulation. This increase would be less pronounced in warmer and moisture forest landscapes where sublimation losses of intercepted snow would be reduced. A further caveat is that forest harvesting in some environments can result in a decrease in net precipitation reaching the soil surface. This is attributed to the forest's role in collecting occult precipitation and contributing this water to the soil as fog drip, and has been observed in high-relief coastal forests of the western USA (Harr 1982) as well as maritime forests in eastern Canada (Jewett et al. 1995).

33.2.3 Evaporation/Evapotranspiration

Removal of forest cover produces a dramatic reduction in evaporation and transpiration from the harvested area. This reduction is due to the partial or complete (depending on harvesting intensity) elimination of interception and its subsequent evaporation combined with the cessation of transpiration by the harvested trees (Bosch and Hewlett 1982). Soils in harvested areas generally experience increased solar radiation inputs, turbulent atmospheric fluxes, and soil temperature, which will enhance direct evaporation from the soil surface (Sun et al. 2001). However, this increase only partly counterbalances reduced water loss due to the elimination of transpiration from harvested trees. The reduction in evapotranspiration fluxes is most obvious in clear-cut areas, since the transpiration reduction following partial cuts can be partly compensated for by increased transpiration by the remaining individual trees (Hubbart et al. 2007).

33.2.4 Snow Accumulation and Snowmelt

Harvesting in forested landscapes with seasonal snowcover generally leads to significantly greater snow water equivalents (SWE) in open areas relative to undisturbed forest (e.g., Troendle and Meiman 1984; Gary and Watkins 1985; Stottlemyer and Troendle 1999). This may be partly offset by enhanced sublimation losses as a result of greater wind speeds over the snowpack, as suggested by Stednick (1996) for the Rocky Mountain region and inland intermountain region of Oregon in the USA. Snowmelt rates can increase in harvested areas as a result of increased snowpack exposure to incoming shortwave radiation and turbulent fluxes (Murray and Buttle 2003), and the combination of greater SWE and faster melt rates means that soils in harvested areas receive larger and more intense water inputs during spring snowmelt.

33.2.5 *Infiltration*

The term "infiltration opportunities" (coined by Bruijnzeel 1988) is a valuable means of conceptualizing the key issues associated with harvesting effects on a soil's ability to infiltrate water. The infiltration capacity of forest soils is generally large and infiltration-excess overland flow is limited, such that most infiltrating water recharges soil water and groundwater stores during wet periods (Bonell 2005). Tree removal by itself does not generally produce significant reductions in infiltration rates unless the harvesting method results in significant soil compaction and reductions in soil hydraulic conductivity and infiltration rate (e.g., Whitson et al. 2003). Nevertheless, if these areas of significant compaction are spatially discontinuous, then any resulting overland flow will likely move laterally to unimpacted sites and have the "opportunity" to infiltrate. Instead, it is specific areas (roads, skidder and tractor tracks, landings) that are associated with a significant reduction in overall basin infiltration rates (Sidle et al. 2004; Waterloo et al. 2007), by virtue of the small infiltration rates for these highly compacted surfaces combined with their spatial connectivity.

33.2.6 *Soil Water Storage*

The combination of increased net precipitation reaching the soil surface and reduced evapotranspiration losses leads to a general increase in soil water storage in harvested areas (Best et al. 2007; National Research Council 2008). However, increases in soil water content following vegetation removal in the case of partial cuts or canopy thinning may be less than expected due to increased use of available moisture by retained vegetation and vegetation in adjacent uncut areas (Hubbart et al. 2007).

33.2.7 *Groundwater Recharge and Discharge*

Groundwater recharge generally increases following harvesting (e.g., Cook et al. 1989; Bent 2001), and often results in rising water tables (e.g., Peck and Williamson 1987; Díaz et al. 2007). Implications of increased recharge for groundwater discharge to surface waters will be determined mainly by the travel time of groundwater from the harvested area, such that travel times greatly in excess of the persistence of increased recharge following harvesting likely mean that no significant change in groundwater discharge will be observed immediately after harvesting (Smerdon et al. 2009). This reinforces the need to consider the hydrogeologic setting of a particular forest landscape when considering the hydrologic response to forest harvesting, since harvesting impacts on groundwater discharge are more likely to manifest themselves for local groundwater flow systems than for larger-scale regional systems (Devito et al. 2000). Nevertheless, the increases in water yields and dry-season low flows that often accompany forest harvesting (see Sect. 33.3.4) indicate that the increased water availability following interception and evapotranspiration reductions due to harvesting is translated into greater groundwater fluxes to surface water bodies.

33.2.8 Changes in Streamflow Generation Processes Following Harvesting

In addition to changes in water flux and partitioning between various hydrologic stores, forest harvesting can lead to significant shifts in the contribution of various runoff-generating mechanisms to streamflow in a drainage basin. As noted previously, infiltration-excess overland flow is rare in undisturbed forest basins, and any overland flow that is observed is generally saturation overland flow (Dunne 1978). Subsurface stormflow is a dominant runoff mechanism in such basins, as saturated layers develop within the soil profile above less-permeable horizons (e.g., Bonell and Gilmour 1978) or at the base of the soil horizon above shallow bedrock (e.g., Peters et al. 1995). Some of this subsurface stormflow may appear as return flow at the soil surface at particular locations (e.g., slope concavities, downslope areas with thinner soil cover). Greater water inputs to the soil surface following harvesting often simply increase subsurface flow discharge to stream channels (Stottlemyer and Troendle 1999), particularly if there has been no significant reduction in infiltration rates. However, overland flow can increase as a result of soil disturbance during forest operations (Waterloo et al. 2007), particularly on roads, skidder trails, and landings. In addition to generating overland flow, roads cut into hillslopes may intercept subsurface water, rerouting it as surface flow along the road and adjacent ditches (Wemple et al. 1996; Hubbart et al. 2007). This interception is maximized when subsurface flow occurs above a hydrologic impeding layer that is exposed at the road cut (Sidle et al. 2006). The potential for such overland flow to contribute to basin streamflow (rather than reinfiltrate into downslope soils) is mediated by the role of hydrologic connectivity within the basin (Stieglitz et al. 2003; Van Miegroet and Johnson 2009), such that water delivery from impacted areas to stream channels depends on the former's position relative to the stream network, downslope vegetative buffers and/or features (e.g., gullies, diversions) that allow surface flow to bypass potential buffers (Sidle et al. 2006). Increased partitioning of water fluxes to overland pathways generated by disturbed areas and the enhanced drainage efficiency provided by roadside ditches and cross drains may be supplemented by more saturation overland flow in harvested basins, since greater soil wetness likely will expand saturated areas within the basin (Waterloo et al. 2007). In addition, groundwater fluxes to streams will generally increase (see Sect. 33.2.7).

33.3 Effects of Forest Harvesting on Streamflow

33.3.1 Approaches Used to Assess Harvesting Impacts on Streamflow

Mallik and Teichert (2009) identified four basin-scale approaches to examine the hydrologic effects of forest harvesting: paired-basin studies (Best et al. 2007); single-basin studies (termed time-trend studies by Bosch and Hewlett 1982); retrospective studies (after-the-fact pairing of harvested and undisturbed basins for which some preharvesting data exist – e.g., Buttle and Metcalfe 2000); and nested basin studies (e.g., Hubbart et al. 2007). Of these approaches, data from paired-basin studies provide the greatest potential to identify any changes in streamflow behavior as a result of forest harvesting, given their greater statistical power (Loftis et al. 2001) when used with multivariate approaches such as analysis of covariance that employ the dummy variable method (e.g., harvested/nonharvested – Scott 1997; Waterloo et al. 2007) to assess harvesting impacts. Nevertheless, the strength of the results of such analyses hinges on the degree to which control and treatment basins are truly similar in terms of geology, soils, topography, and vegetation (Moore and Wondzell 2005), and a sound grasp of the basins' hydrology is needed to distinguish harvesting-related streamflow changes from those due to other factors (Fuller et al. 1988).

33.3.2 Water Yield

Regardless of which experimental or analytical approach is employed, the general finding of studies conducted around the globe indicates that reduced forest cover results in increased water yield (National Research Council 2008). Figure 33.1 shows data from Stednick's (1996) synthesis of paired-basin experiments in the USA, which mirrors findings from studies including results from other countries (e.g., Bosch and Hewlett 1982; Sahin and Hall 1996). Figure 33.1 highlights points that have been raised in previous reviews:

1. Water yield response to harvesting is highly variable. This reflects variations in such factors as climate [e.g., amount and seasonal distribution of precipitation, such that water yield increases tend to be greater in areas of high precipitation (Bosch and Hewlett 1982) and in wetter years (Hubbart et al. 2007)], vegetation type [e.g., greater water yield increases following harvesting of coniferous vs. deciduous forests (Sahin and Hall 1996)] and health prior to harvesting (Waterloo et al. 2007), soils, and geology.
2. Harvesting has to exceed ~20% of basin area in order to produce a demonstrable increase in water yield.
3. The increase in water yield is inversely related to basin size. This relationship is not apparent when the Stednick basins are standardized according to harvesting

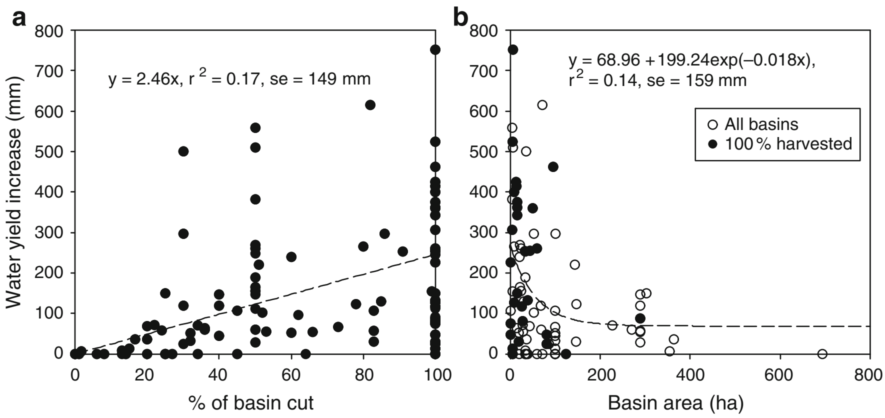

Fig. 33.1 (**a**) Annual water yield increase versus % of basin harvested, based on experimental studies in the USA (data from Stednick 1996); (**b**) annual water increase versus basin area for all basins and basins with 100% of their area harvested (data from Stednick 1996). Lines of best fit are significant at $p = 0.05$; best-fit line in (**b**) is for all basins

magnitude (e.g., 100% harvested), which reflects the greater range of land uses and land covers in large drainage basins (Bruijnzeel 2004).

Best et al. (2007) note that generalizations about annual increases in water yield such as Fig. 33.1 are often based on the maximum change in water yield in the first five years after treatment or first year increases in yield. Permanent land use change experiments indicate that it may take more than five years for the maximum change in water yield to be observed and for a new hydrologic equilibrium to be established, such that summaries such as Fig. 33.1 may underestimate the potential increase in water yield for a given amount of forest removal. Some of the scatter in Fig. 33.1 also reflects variations in experimental design and execution (Adams and Fowler 2006), such as the length of the calibration period, whether regrowth was allowed after harvesting, and the accuracy of the data collected.

33.3.3 Peak Flows

Changes in the relative importance of overland flow pathways to streamflow generation outlined earlier suggest that peak streamflows will increase following harvesting. However, the debate about whether forest harvesting leads to increased peak flows and flooding is one of the most contentious in hydrology (Van Dijk et al. 2009), as illustrated by the controversy regarding whether harvesting changes both frequent as well as infrequent peak flows in a basin. For example, Jones and Grant's (1996) finding that forest operations (forest removal as well as forest roads) in basins in the Pacific Northwest of the USA increased peak flows for both small and large storms provoked Thomas and Megahan's (1998) reanalysis of the same data and their conclusion that the impact of forest harvesting on peak flows decreases for larger storms. This issue has subsequently been taken up by hydrologists working in other forest landscapes around the world. To some extent, this debate reflects differing opinions regarding the most appropriate statistical approach to use to examine the question (e.g., analysis of variance vs. analysis of covariance). Nevertheless, there appears to be consensus from a process-based perspective that forest harvesting should have a greater proportional effect on small flows compared to larger ones. Thus, Waterloo et al. (2007) found that the largest relative changes in peak discharge and stormflow volume occurred during smaller rainfall events, which was attributed to a shift in the relative importance of runoff-generating mechanisms with storm size. Infiltration-excess overland flow from disturbed surfaces may make a significant contribution to changes in the stormflow hydrograph following harvesting during small storms; however, the effect of harvesting on relative changes in stormflow diminishes with increasing rainfall because runoff contributions from saturated areas and return flow become increasingly more dominant in stormflow generation. Similarly, Van Dijk et al. (2009) contended that the impacts of forest removal on net precipitation delivery to the soil surface and water storage in the soil profile would be minimized for large storm events responsible for generating major peak flows, such that forest harvesting would more likely affect smaller localized floods than extreme, large-scale events.

In order to minimize complications introduced by the influence of storm size on peak flow generation, it is useful to examine harvesting effects on a standardized measure of peak flow, as in Guillemette et al.'s (2005) review of changes in bankfull peak flow from 50 paired-basin studies (Fig. 33.2). Linkage of bankfull flow to stream morphological changes and modifications of aquatic habitat make it a particularly valuable metric to examine in the context of forest disturbance. Figure 33.2 indicates that relative increases in bankfull peak flow increase with the proportion of the basin harvested; however, as with water yield there is substantial variability in response to harvesting, due to such factors as variations in climate, topography, soil characteristics, and species harvested (Guillemette et al. 2005). Several studies show no change in peak flows with harvesting while others show decreases, reinforcing Thomas and Megahan's (1998) observation that previous research provides mixed messages about peak flow response to forest harvesting. Figure 33.2 reveals a tendency for increases in bankfull discharge to decrease with basin size, although unlike the water yield data in Figure 33.1 this trend was not statistically significant. Complete harvesting of basins did not necessarily produce larger percentage increases in bankfull peak flows relative to basins experiencing partial cuts. The data suggest that the smallest proportional increases in bankfull peak flows are in relatively wet landscapes (mean annual precipitation $>$1,200 mm), likely because such regions experience larger preharvest bankfull flows. Similar to the harvesting threshold noted for water yield increases, Guillemette et al. (2005)

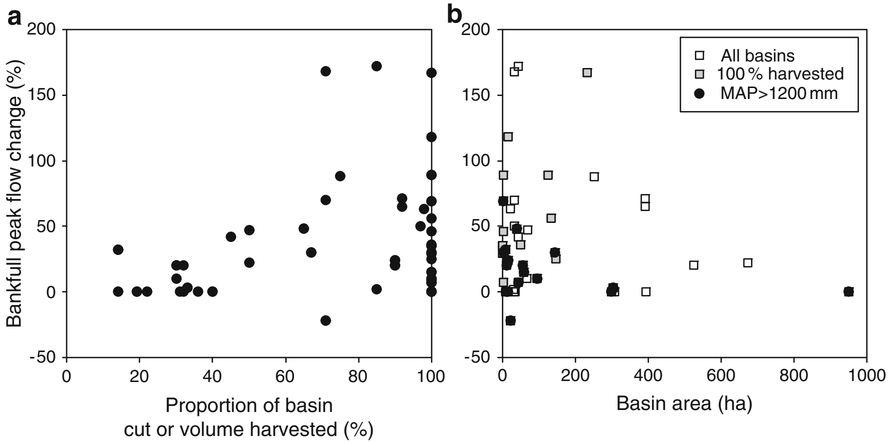

Fig. 33.2 (**a**) % change in bankfull peak flows versus % of basin cut or volume of standing timber harvested, based on experimental studies from around the world (data from Guillemette et al. 2005); (**b**) % change in bankfull peak flows versus basin area for all basins, basins with 100% of their area cut or volume of standing timber cut, and basins where mean annual precipitation (MAP) exceeds 1,200 mm (data from Guillemette et al. 2005)

suggest that harvesting should not exceed 50% of basin area in order to restrict increases in bankfull peak flows to <50% of preharvest values.

33.3.4 Low Flows

There is a general consensus that low flows increase following harvesting, with increased soil and groundwater recharge following forest removal leading to increase in groundwater discharge to streams (Best et al. 2007). Given that increased overland flow contributions to streamflow depend on the degree of compaction within the basin as well as sufficient hydrologic connectivity to allow such runoff to reach stream channels, the general increases in water yield that accompany forest harvesting have been largely been attributed to enhanced low flows (e.g., Hornbeck et al. 1993, 1997). However, Bruijnzeel (2004) sounds a cautionary note that variations in the degree of harvesting impact on soil infiltration properties mean that low flows may not necessarily increase in tropical and semitropical landscapes (particularly in regions with pronounced wet-dry seasonality in precipitation). Impeded infiltration will reduce recharge during the wet season, which in turn may lead to diminished low flows during the dry season relative to an unharvested condition.

The variability in the response of water yield, peak, and low flows (as well as other streamflow metrics not discussed here) to forest harvesting supports the National Research Council's (2008) conclusion: that while forest hydrologists have great confidence in their statements of the general hydrological response to forest harvesting, they cannot predict precisely how harvesting will affect hydrologic processes in areas that have not received intensive study.

33.4 Biogeochemical Aspects of Forest Harvesting

Forest harvesting can affect biogeochemical cycles in a variety of ways, such as through alterations of stream water temperatures, nutrient sinks and sources, soil temperature and humidity, changes in soil structure, and transport of nutrients and dissolved organic carbon (DOC) from organic soil surfaces to receiving waters (Carginan and Steedman 2000). The focus here will be on selected aspects of the water quality of streamflow draining harvested basins, which involves such parameters as temperature, concentrations of suspended sediment, major ions, nutrients such as N and P, cyanobacterial toxins, DOC, and dissolved O_2 (Mallik and Teichert 2009). Attempts to understand the effects of forest harvesting on these parameters must acknowledge their interconnected behavior. For example, water temperatures influence the chemical, biological, and ecological integrity of streams, such as through their control on streamwater dissolved O_2 (Bourque and Pomeroy 2001). These dissolved O_2 levels in turn influence the processing and form of nutrients such as N. It is also important to preface our examination of the biogeochemical aspects of forest harvesting by recognizing that the geologic, geomorphic, pedologic, vegetative, topographic, and management factors that exert a fundamental influence on interbasin differences in water movement will also control the response of a given basin to forest harvesting (Chanasyk et al. 2003; Gravelle et al. 2009).

33.4.1 Water Temperature

Stream water temperatures are influenced by such factors as stream aspect, water surface area, microclimatic conditions at the water surface, surface turbulence, channel morphology, source water temperature, stream water travel time, and upstream land use conditions (Mallik and Teichert 2009). Forest harvesting can impact several of these factors. For example, removal of riparian forest cover can increase solar radiation receipt at the water surface as well as wind speed and exposure to advected energy from nearby harvested areas, thus increasing stream temperatures, particularly in summer (Moore et al. 2005). Harvesting may also impact stream temperatures through increased discharge of groundwater into streams, although the exact nature of this effect depends on such factors as the influence of harvesting on the potential warming of shallow groundwater, and hyporheic exchanges of surface and subsurface waters.

33.4.2 Nutrients and Contaminants

Feller (2005) provides a valuable review of the solution chemistry (nutrients and contaminants) of forested streams (primarily in western North America) that summarizes the major factors controlling this chemistry that likely operate in all forest landscapes: geological weathering, atmospheric deposition and climate; precipitation acidity; terrestrial biological processes; physical/chemical reactions in the soil; and physical, chemical and biological processes within streams. Table 33.1 summarizes the anticipated change in concentrations of a subset of inorganic solutes examined by Feller (2005) resulting from forest harvesting impacts on these controlling factors. For example, the dominant controls on H^+ concentrations in streamflow are precipitation chemistry and physical–chemical reactions in the soil. Forest harvesting will likely lead to an increase in the H^+ concentration in net precipitation due to the reduction or elimination of H^+ exchange with cations on vegetated surfaces, while soil physical–chemical reactions will act to reduce H^+ concentrations after harvesting. As Table 33.1 highlights, the controls on nutrient and contaminant concentrations as well as the influence of harvesting on those controls and the direction of concentration response to harvesting differ between water quality parameters. There is often no consensus regarding how the concentration of a particular nutrient or contaminant will respond to the influence of forest harvesting on a given controlling factor (e.g., the effect of harvesting on the hydrologic factors controlling Al^{3+} concentrations), which partly reflects the variable nature of the controlling factors noted earlier. This also reinforces the need to consider preharvest site conditions when interpreting the biogeochemical response to harvesting (Dise and Gundersen 2004). Thus, McHale et al. (2007) found the response of Al concentrations to harvesting exceeded those reported previously, which they attributed to preceding decades of acid deposition that depleted exchangeable base cations and caused long-term soil acidification.

There is considerable evidence to suggest that there may be a lag between forest harvesting and the biogeochemical response of a particular water quality parameter. Figure 33.3 is adapted from Feller (2005), based on Vitousek and Reiners (1975). Assuming other factors remained the same, chemical fluxes through soils into streams would show an inverse pattern: a decrease after loss of vegetation from an initial value to a minimum (as a result of uptake by forest regrowth) followed by an increase to a dynamic equilibrium in old-growth forests. The magnitude of the minimum concentration attained would depend on whether the chemical was a nonessential, essential, or limiting nutrient. However, the partial picture provided by this ecologically based model of nutrient concentration response to forest harvesting would benefit from consideration of accompanying hydrochemical changes. This is illustrated by the fate of Cl^- following harvesting, which is not a limiting nutrient and whose concentrations in streamflow should not change significantly according to Figure 33.3. However, Oda et al. (2009) found that harvesting reduced Cl^- input to a maritime basin in Japan due to reduced dry deposition of Cl^- to vegetation. The resulting step shift in Cl^- inputs led to a

Table 33.1 Major factors governing stream chemistry in forest landscapes and suggested concentration response of selected nutrients and contaminants to harvesting effects on these governing factors (adapted from Feller 2005)

Factor	Al^{3+}	C (CO_3^{2-}, HCO_3^-)	Ca^{2+}	Cl^-	H^+	K^+	N (NO_3^-, NH_4^+)	P (PO_4^{3-}, HPO_4^{2-}, $H_2PO_4^-$)	Trace metals
1. Geological weathering	↑	**↑**	**↑**	–	↓	**↑**	↑–	↑	↑
2. Atmospheric precipitation/climate									
(a) Precipitation chemistry	**↑–**	↓–	↑–	–	**↑–**	↑–	**↑–**	↑–	↑–
(b) Hydrologic influences	**↑↓**	**↑↓**	↑↓	–	↑↓	↑↓	–	↑↓	**↑↓**
(c) Temperature	**↑**	**↑**	**↑**	↑–	↑↓	**↑**	**↑**	↑	↑–
3. Terrestrial biological processes									
(a) Chemical uptake	–	–	↑	↑	↑	↑	**↑**	**↑**	–
(b) Chemical transformations	–	↑↓	–	–	↑↓	–	**↑↓**	–	–
(c) Production of soluble chemicals	–	↑–	↑–	↑	↑–	↑–	↑–	↑–	↑–
4. Physical/chemical reactions in the soil	**–**	↓	–	↓–	**↓–**	–	↓–	↓–	–
5. Processes within aquatic ecosystems		–							
(a) Ion exchange reactions	↑↓	–	↑↓	↑↓	↑↓	↑↓	↑↓	↑↓	**↑↓**
(b) Chemical redox reactions	↑↓	–	–	–	–	–	↑↓	–	↑↓
(c) Evaporation-crystallization									
(d) pH-induced transformations	**↑–**								
(e) Uptake by primary producers	↓	–	↓–	–	–	↓–	**↓–**	**↓–**	↓–
(f) Microbial transformations	–	–	–	–	–	–	**↑↓**	–	–

↑ harvesting effects on factor lead to an increase in concentration; ↓ harvesting effects on factor lead to a decrease in concentration; – harvesting effects on factor have little to no impact on concentration; bolded symbols indicate that the related factors are the primary and dominant control on concentration

decrease in Cl^- concentrations in streamflow. McHale et al. (2007) stress the importance of considering differences in water residence times for various hydrologic compartments when assessing biogeochemical response to harvesting. Thus, relatively long groundwater residence times mean that the chemical response

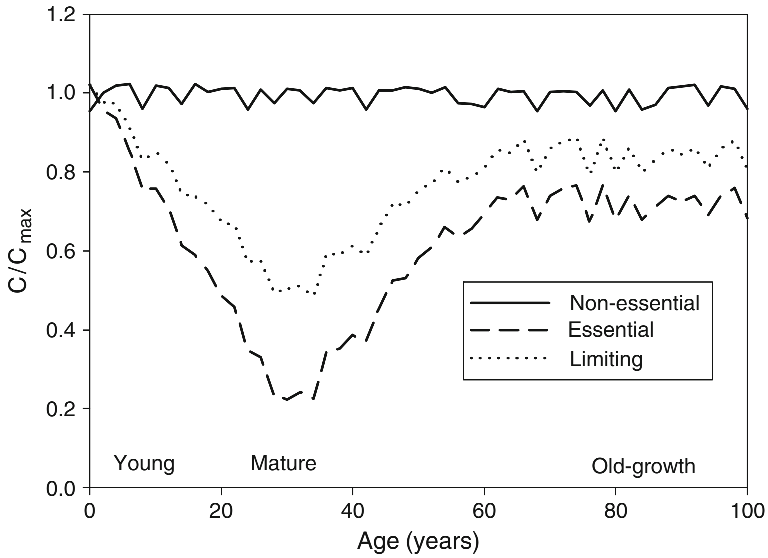

Fig. 33.3 Hypothesized changes in streamflow concentration (*C*) relative to maximum concentration (C_{max}) for nonessential, essential, and limiting chemicals after forest harvesting and throughout forest regrowth (adapted from Feller 2005)

can lag harvesting by several years while at the same time delaying system recovery, since streams may continue to receive contributions of nutrient-rich groundwater recharged immediately after harvesting while forest regrowth is returning soil water nutrient concentrations to preharvest conditions.

Two water quality parameters that deserve particular attention are N and Hg; N by virtue of its important role as a nutrient and Hg for its potential for accumulation in fish and the resulting implications for human health. Harvesting decreases N uptake by trees and can increase mineralization and nitrification rates, as has been noted elsewhere (e.g., Likens et al. 1969; Reuss et al. 1997). Loss of NO_3-N and other anions by leaching also leads to export of Ca, Mg, and K (Jewett et al. 1995) as well as Al from the basin after the harvest (McHale et al. 2007). However, others have found limited or no effects of harvesting on soil N transformations and litter decomposition (Brais et al. 2002; Westbrook et al. 2006) and have noted that harvesting may lead to reduced NO_3-N leaching (Van Miegroet and Johnson 2009). Conflicting results may be due to differences in such site factors as climate, vegetation, time since harvesting disturbance, type of machinery used for logging, and land use history (Pérez et al. 2009). Thus, Parfitt et al. (2002) found that nitrate-N leaching losses decreased after harvesting, which they attributed to increased weed growth and soil microbial biomass after harvesting that would have removed much of the N from soil solution in the upper soil layers. Microbial processes play a key role in mediating nutrient and element mobility from both harvested and undisturbed forest landscapes (Lindo and Visser 2003), and the effects of harvesting on the soil microbial biomass are often a key element in understanding how harvesting affects nutrient and contaminant fluxes to streams. This is illustrated by the fate of Hg in harvested basins. Povari et al. (2003) found that clearcutting increased total Hg and methyl Hg (MeHg), partly in response to an increased flux of total organic carbon (TOC) from harvested areas. Hg accumulates in forest soils as a result of atmospheric deposition and Hg methylation may be stimulated by saturation of forest soils due to increased water availability following harvesting. Garcia and Carignan (2000) suggest that harvesting may enhance the transport of toxic MeHg to receiving waters, where it may accumulate in game fish and thus pose a threat to human health.

33.4.3 Sediments

Harvesting impacts on sediment transport to receiving waters must be considered from a biogeochemical as well as a geomorphological perspective, since sediment can be a stressor in its own right (e.g., in terms of its impacts on drinking water quality and its ability to impact fish spawning habitat in streams) and a vector for some contaminants (e.g., metals – Feller 2005) and nutrients (e.g., phosphorus – Gravelle et al. 2009). Sediments can be supplied to streams by surface erosion, mass movements, and bank erosion. It is generally acknowledged that harvesting alone does not substantially contribute to increased sediment fluxes unless severe and widespread disturbance occurs (Sidle et al. 2006). Instead, the primary sediment sources consist of logging roads, road crossings, and skidder trails (Sidle et al. 2004), augmented by such management activities as prescribed burning, scarification (Hetherington 1987), and ditching of forested wetlands for drainage (Prevost et al. 1999).

Sediment yields from harvested basins generally peak shortly after harvesting and decline as forest regrowth proceeds. However, as with nutrient and contaminant fluxes from harvested areas to streams, there may be a lag between harvesting and the period of maximum sediment supply to streams (Bruijnzeel 2004). This is particularly the case if mass movements represent a major vector of sediment transport in a forest landscape. Sidle et al. (2006) cite several studies noting increased landslide erosion roughly 3–15 years after harvesting, which appears to relate to the time required to allow root systems of harvested trees to decay and thus reduce root strength and slope resistance to mass movement. Thus, short-term monitoring of sediment transport after disturbance may give a distorted picture of forest management influences on sediment (Sidle et al. 2006).

33.5 Issues for Future Research

The intention here is not to provide an exhaustive list of issues to be considered in future research dealing with the hydrologic and biogeochemical aspects of forest harvesting, since many research issues raised in previous work are specific to particular forest landscapes or forest management practices (e.g., the role, dimensions, and function of riparian management practices such as forest buffer zones – Neary et al. 2009). Instead, the goal is to identify common research needs that apply across regional and national scales. Such needs include:

1. Maintaining and expanding the monitoring networks of sites examining the long-term hydrologic and biogeochemical effects of forest harvesting (National Research Council 2008, Neary et al. 2009). Such networks will be of increasing scientific and societal value in the context of a changing climate and associated shifts in the intensity of other impacts on forests (e.g., fire, disease, insect infestations) (National Research Council 2008). A critical element of assessing the hydrologic and biogeochemical effects of harvesting in the context of climate change will require refinement of the "natural range of variability" of water quantity and quality in forest landscapes (Neary et al. 2009), which can be provided by the research results of these networks.
2. As part of (1), promoting mechanistic studies of the internal hydrologic and biogeochemical behavior of forest basins (Hubbart et al. 2007) in a wider range of forest landscapes than has been hitherto examined. The complex interactions between hydrology, chemistry, and ecology ensure that such studies are a vital component of basin studies (Mallik and Teichert 2009), while greater understanding of the role of such factors as climate, geology, and topography on hydrologic and biogeochemical behavior is key to interpreting results from paired-basin studies (Fuller et al. 1988). From a biogeochemical perspective, these mechanistic studies should be extended to include greater consideration of such factors as the effects of harvesting on the geological weathering release of chemicals, the behavior of trace metals, and in-stream processing of nutrients (Feller 2005).
3. Looking beyond harvesting effects on water yield to consider seasonal changes in streamflow and changes in the overall flow regime (Hubbart et al. 2007). Thus, Bruijnzeel (2004) identifies the "low flow problem" as the key research issue for studies of harvesting effects in tropical forests.
4. Assessing how the hydrologic and biogeochemical effects of harvesting change with scale. Sivapalan et al. (2003) note that the processes that dominate basin hydrologic behavior may change with changing scales, while Devito et al. (2005) emphasize that the scale at which dominant processes act to control a basin's hydrologic and biogeochemical behavior must be considered in order to determine the most suitable methodological and modeling strategies to apply to study harvesting impacts in a given region. For example, Sidle et al. (2006) outline the scale issue of sediment delivery from harvested areas: although increases in infiltration opportunities and storage generally lead to reductions in sediment yield with increasing basin size, this may be countered by a change in the dominant sediment delivery process with scale (e.g., gully development, mass wasting) that might produce an increase in yield with scale.
5. Determining the long-term cumulative effects of forest harvesting in the context of other land use/land cover changes. The National Research Council (2008) argues for a landscape-scale approach to relate downstream conditions to

upstream changes in forest conditions, which will require spatially explicit modeling that identifies, connects, and aggregates temporal changes in hydrologic and biogeochemical behavior due to forest disturbance and management at larger spatial scales.

6. Improving our ability to translate the results from experimental basins to other sites within the same forest landscape and between differing landscapes (Best et al. 2007, National Research Council 2008). This will involve an increased integration of stand and paired basin-scale mechanistic studies with modeling of basin hydrologic and biogeochemical response to forest harvesting (Bruijnzeel 2004).

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