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Effect of timber removal on the total nutrient fluxes from a freshwater-supplying forested watershed

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Abstract

Effects of 18% thinning on nutrient fluxes were investigated in a broadleaf forest. Streamflow and suspended sediment were sampled during the calibration and treatment periods for the treatment and control watersheds to determine total nutrient fluxes through bedload sediment and runoff. Streamflow was measured, and water samples were collected from the streams of the watersheds. The volume of the bedload deposited in both weirs' pools was measured, and sediment deposits were sampled at the ends of the calibration and treatment periods. Water and sediment samples were analyzed for calcium (Ca^{2+}), magnesium (Mg^{2+}), Kjeldahl nitrogen (KN), sodium (Na^{+}), potassium (K^{+}), iron (Fe^{3+}), and sulfur (S^{2-}). Results showed that there was only a significant increase in KN loss from 0.01 kg/ha to 0.10 kg/ha and from 0.04 kg/ha to 2.41 kg/ha in the second and the third post-treatment years, respectively ($P < 0.05$). Thinning was not intensive to change nutrient outflow in the study site.

Practitioner Points

- The 18% thinning was not intensive enough to increase the total nutrient flux, deteriorate water chemical quality, and hence threaten aquatic life in the stream water.
- Significant increases were found only in KN outflow after timber removal.
- If there is no information about the effect of timber harvest on nutrient loss in a specific watershed, the application of evenly distributed low-intensity timber harvest may be a good option to protect stream water quality in forested watersheds.
- Further investigations are needed about the effects of various timber harvest intensities on physical water quality (odor, color, turbidity, taste, temperature, etc.) and biological characteristics (population and biodiversity of aquatic organisms) of the stream water for making better water management plans.

KEYWORDS

forest harvesting, management option, nutrient flux, thinning

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INTRODUCTION

Increased nutrient fluxes because of timber harvest from forested watersheds are major environmental concerns with significant adverse impacts on the health of the forest and other ecosystems (Dahlgren, 1998; Siemion et al., 2011; Swank et al., 2001). Although several studies were carried out about the effect of timber removal on the nutrient outflow from forested watersheds, less information is available about the magnitude of the total nutrient fluxes caused by timber harvesting (thinning) in the oak-beech natural forest ecosystems in the region and across the world. Several studies also highlighted detecting or monitoring nutrient output in stream water (Bäumler & Zech, 1999; Fukushima et al., 2015; Hughes & Quinn, 2019; Yurtseven et al., 2017), but it is important to determine the nutrient output in the sediment as well as in the stream water together to find out the entire nutrient output in a watershed. Vegetation removal can lead to excessive nutrient outflow in the forested watersheds and finally lower forest productivity. Blanco et al. (2006) reported that whole-tree removal has a strong negative effect on the nutrient reserves in the thinned sites. Forested watersheds are generally regarded as important contributors of nutrient flux to soil and freshwater ecosystems, yet there is increasing evidence that total fluxes and direction of the net fluxes are highly dependent on biogeochemical processes in the forested ecosystems. In return, soil nutrients can strongly control the productivity of forests. Cleveland et al. (2011) found a positive correlation between net primary productivity and soil phosphorus (P) and nitrogen (N) contents in the forests. Therefore, the status of the vegetation (density, quality, etc.) affects the chemical content of the forest soil and its productivity. Previous studies have shown that forest ecosystems significantly influence soil and water nutrient dynamics through various mechanisms such as vegetation-induced export (Blanco et al., 2005; Liu et al., 2002).

The organic matter cycle plays a considerable role in the nutrient content of the forest soils and the nutrient cycle in forest ecosystems (Grigal & Vance, 2000; Osman, 2013). However, nutrient fluxes through forest ecosystems are generally studied without detailed knowledge of the decreased forest canopy cover that affects them. To understand the current interactions between forest ecosystems and nutrient fluxes, it is better to examine the large-scale effect of vegetation-induced dynamics on stream water by quantifying and qualifying nutrient fluxes from those forested areas with long-term paired watershed studies (Boggs et al., 2016; Zhao et al., 2021).

The forest ecosystems are managed to meet the public demands from the forestlands and establish healthier forest communities with good quality timber. In Turkey, the main purpose of thinning treatments in managed forestlands is to improve the growth and timber quality of the remaining trees. From a hydrological perspective, forest harvesting can have a strong impact on forest hydrology and changes in the dynamics of water quality and quantity can be expected in response to the types and intensities of the forestry operations applied (Swank & Douglass, 1974). Changes in the canopy cover because of forest harvesting can significantly cause changes in the quantity and quality of stream water, amount of litter on the forest floor and its decomposition, and hence soil properties of the forest ecosystems. Thinning is also practiced to increase soil moisture and water yield for public water supplies or sustainability of many ecosystem services of forest areas in water-limited environments (Bosch & Hewlett, 1982). Changes in the amount of forest litter due to harvesting of canopy cover as a source of the forest floor can release less or more decomposition products for the forest soil. Foster and Bhatti (2006) stated that the natural (e.g., fire, erosion, and leaching) and anthropogenic-induced (harvesting, fertilization) ecosystem disturbances can lead to the addition of some nutrients into forest soils or stream water of the forest ecosystems. Early studies focused entirely on the change of nutrient fluxes under different forest harvesting operations (Hume et al., 2018; Jerabkova et al., 2011; McHale et al., 2007; Westbrook et al., 2006). For instance, Feller (2005) stated that the stream chemistry is controlled by major factors such as climate (atmospheric deposition, precipitation chemistry), geological weathering, physical, chemical, and biological processes in the soil and the streams and emphasized that forest harvesting substantially have a significant influence on those controlling factors. Loss of NO_3-N and other anions due to leaching also may lead to Ca^{2+}, Mg^{2+}, and K^{+} exports after timber harvesting (Jewett et al., 1995). The initial deforestation experiment showed that concentrations of nutrients in stream water increased up to about 50% (Likens et al., 1978). Many studies using paired watershed approach reported and discussed nutrient outflow in the runoff (Campbell et al., 2016; Hopkins et al., 2017; Stottlemyer & Troendle, 1999; Wang et al., 2006; Yurtseven et al., 2018). These studies gained importance with the emerging harvesting treatments that can modify soil nutrient status, stream chemical composition, nutrient uptake of remaining trees, structure and amount of debris materials to the forest floor, litter structure, and understory and overstory vegetation composition (Serengil et al., 2007). Since the nutrient fluxes generally change after intensive timber harvest such as clearcutting, timber removal can deteriorate water quality (Merino et al., 2005). Some researchers stated that the

erosion or leaching that occurs with the reduction of forest cover also can affect the nutrient fluxes in the watersheds (Wang et al., 2006). The leaching of nutrients over a long-term period consequently drastically lowers the nutrient content of the forest soils under intense forestry operations. A great number of studies evaluated nutrient export mostly in the runoff (Finér et al., 2021; Kakaei Lafdani et al., 2020; Wilson et al., 2019).

Thinning is one of the most commonly used forest harvesting techniques in the forestlands. The effect of thinning on watershed hydrology varies depending on its intensity. Several studies examined the effect of thinning on nutrient fluxes (Blanco et al., 2005; Knust et al., 2016). Previous studies showed that nutrient fluxes were affected by the thinning intensity in experimental forest ecosystems, highlighting that intense thinning is expected to have more effects on soil quality through changes in vegetation and soil dynamics compared to moderate and light intensity (Lado-Monserrat et al., 2016; Nilsen & Strand, 2008). Testing of a detectable change in nutrient fluxes in an experimental watershed is a mainly important issue for productivity and hydrochemistry dynamics of forest ecosystems in the watersheds. Since there is a positive correlation between water discharge and nutrient outflow in the forested watersheds (Gökbulak et al., 2008), the determination of a threshold value in the thinning treatments is necessary for stable nutrient fluxes after forest harvest. Otherwise, unconscious forest harvesting activities can lead to productivity loss in the forest soils and deterioration in the physicochemical characteristics of the stream water. Bosch and Hewlett (1982) reviewed the studies dealing with the effect of timber harvest on water yield and concluded that at least 20% of the forest cover should be harvested to find a significantly detectable change in the streamflow of the forested watersheds. Thinning practices, which are the most commonly used forest management tools in Turkey, provide multiple benefits including timber harvesting and additional income with maintaining timber quality. On the other hand, if a thinning practice is applied above a certain threshold level, then it can cause a massive loss of nutrients from the watersheds. Therefore, the optimum thinning threshold level that can provide sustainable timber production can be ensured without causing nutrient loss from the watersheds.

This study examined the total fluxes of some selected important ions in the bedload sediment and stream water together and determined whether 18% of thinning would be effective enough to significantly alter these outputs from a deciduous forest ecosystem. The present study was initiated to provide more detailed information on the effects of slight forest harvesting on total nutrient fluxes, which are evaluated as the sum of nutrients in the stream water and bedload sediment using the paired watershed methodology. The paired watershed approach is an acceptable methodology to test the effect of timber harvest on the water yield and streamflow chemistry while eliminating extraneous effects resulting from variabilities in the biotic and abiotic factors in the treatment sites. The paired watershed method works on two or more watersheds located adjacent to or near each other with similar characteristics in terms of size, slope, aspect, soil, topography, climate, and vegetation (land cover) (Clausen & Spooner, 1993; Gökbulak et al., 2016). The great advantage of the paired watershed approach is to measure the effects of forestry activities on watershed hydrology on small scales and interpolate its results to large scales. In addition, changes in the nutrient fluxes in paired watershed approach can be attributed to selected management options (e.g., clear-cut, thinning, and shelterwood cutting) and their intensity with eliminating climatic and hydrologic differences between control and treatment watersheds using calibration equations that are developed between the watersheds during the calibration period in advance to treatment application.

The effect of 18% timber removal on streamflow chemistry, water yield, and physical water quality characteristics in the same experimental watersheds was studied, and results were published previously by Yurtseven et al. (2017), Gökbulak et al. (2016), and Erdoğan et al. (2018), respectively. More information about the effect of the timber harvest on water yield, nutrient flux, and physical water quality characteristics can be found in these publications.

However, none of these studies investigated total nutrient loss through streamflow and sediment. Similarly, as can be seen in the references cited in this paper, although some studies were carried out around the world to investigate the effect of timber removal on nutrient flux in the watersheds these studies did not examine total nutrient loss through stream water and sediment discharges. On the other hand, nutrient fluxes not only take place through the stream flow but also through the sediment carried by the streamflow after timber harvest. In this study, contrary to the results of previous cited in this paper, the outflow of some nutrients in the runoff and bedload sediment was evaluated together as the total nutrient outflow from the treatment watershed.

Measuring total nutrient losses through runoff and sediment discharges in the watersheds is important because increased nutrient concentration can affect the water quality, and therefore the aquatic life and the productivity in the soils of forest ecosystems in the long term. Therefore, the main purpose of this study was to outline the nutrient outflow from two experimental watersheds located in a mixed oak-beech forest

ecosystem, describe the initial impacts of slight thinning on nutrient outputs through the streamflow and bedload sediment depositions, and determine total nutrient losses through streamflow and sediment discharges together.

MATERIAL AND METHODS

Study site and sampling techniques

The study was conducted at the Ortadere Experimental Watersheds in Belgrad Forest, Istanbul, Turkey (41°N, 28°E) (Figure 1). Two watersheds as a control and treatment were used for this study. Both watersheds were monitored for streamflow and bedload depositions during the calibration and treatment periods. The calibration period was 3 years from January 2009 to September 2011, and the treatment period was also 3 years from January 2012 to December 2014. One watershed with a size of 77.5 ha was used as a treatment watershed (W-IV) while the other one with a size of 71.9 ha was kept untreated as a control watershed (W-I). Elevation ranges from 104 and 97 m at the control and treatment watershed outlets, respectively. The slope of the experimental watersheds changes between 10% and 14%. Long-term meteorological data indicate that the study site has a

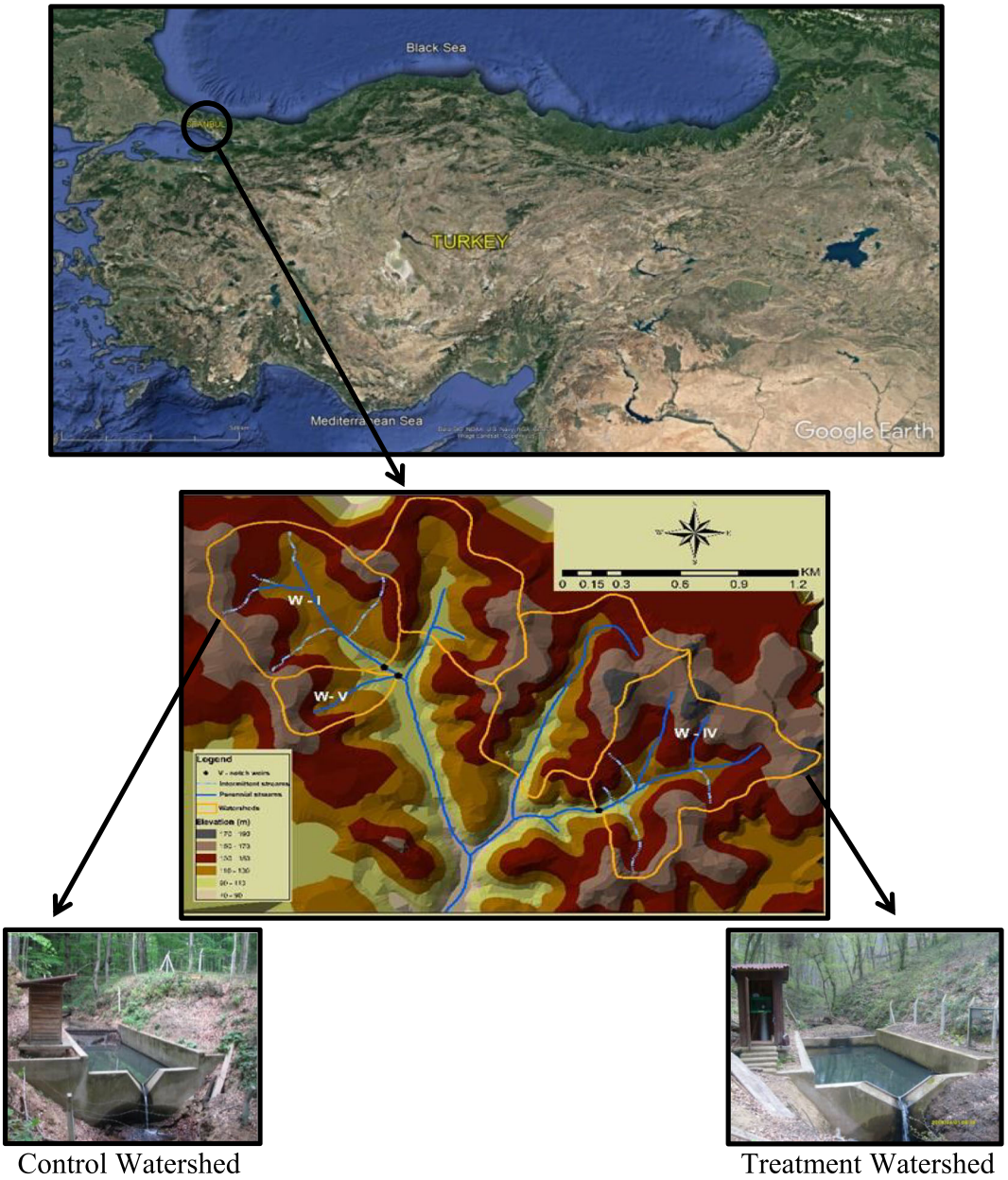


FIGURE 1 Location of the paired watersheds

mean annual precipitation of 1091 mm, a temperature of 12.8°C, and potential evapotranspiration of 698 mm Most of the precipitation falls between October and March (Balcı et al., 1986). Both watersheds have second-order streams that flow into a dam supplying a very little portion of drinking water for Istanbul City (Yurtseven et al., 2017) and drainage densities are 3.80 km/km^2 for the treatment and 3.60 km/km^2 for the control watersheds.

The dominant vegetation in both watersheds is composed of oak-beech mixed forests (*Quercus frainetto* Ten., *Quercus cerris* L., and *Fagus orientalis* L.) with an age of around 60–70 years old. Other plant species present in the mixture with small portions include some woody species such as *Populus tremula* L., *Alnus glutinosa* L., *Carpinus betulus* L., *Acer trautvetteri* Med., *Castanea sativa* Mill., *Acer campestre* L., *Ulmus campestris* L., and shrubs like *Sorbus torminalis* Crantz. Standing timber volumes were 311.18 m^3/ha with an annual average increment of 3.40 m^3/ha in the control watershed (W-I) and 334.44 m^3/ha with an annual average increment of 4.21 m^3/ha in the treatment watershed (W-IV). The soil type in the study watersheds is Vertic Xerochrept developed from carboniferous clay schists, Neogene loamy, and gravelly deposits.

The bedload depositions in the weir pools were completely removed in July 2008 and sediment depositions were monitored until the last observation date for this publication. Water levels were monitored with 10-min intervals by using an automatic water-level recording system installed in stilling wells of 90° and 120° concrete sharp-crested V-notch weirs at the outlet of the experimental watersheds (Figure 1). Water grab samples were taken from the streamflow in the watersheds on weekly basis during the calibration and treatment periods. At the ends of the calibration and treatment periods, the volume of the bedload depositions in both weirs was measured and sediment loads were sampled as both undisturbed core and disturbed polyethylene bag samples and a total of 20 bedload sediment samples were collected from each weir. Sediment samples were oven-dried at 105°C for 24 h, and their bulk density values were estimated from the core samples. In order to estimate mean monthly sediments for each watershed, the total oven-dried weight of sediment depositions in the weirs was distributed over months in proportion to mean monthly suspended sediment losses for the calibration and treatment periods separately.

Weekly stream water grab samples were collected at the outlet of the watershed and their suspended sediment concentrations were determined with the evaporation method. Then, the values were converted to monthly loads as kilogram. The water grab samples from the streamflow and the sediment samples from the bedload depositions in the weir ponds of control and treatment watersheds were analyzed to determine the concentrations of calcium (Ca^{2+}), magnesium (Mg^{2+}), Kjeldahl nitrogen (KN), sodium (Na^{+}), potassium (K^{+}), iron (Fe^{3+}), and sulfur (S^{2-}). The sediment samples were analyzed for KN according to the Kjeldahl method, S^{2-} with the turbidimetric method by using UV visible spectrophotometer, K^{+}, Ca^{2+}, Mg^{2+}, and Na^{+} were determined in the extract formed with ammonium acetate solution and Fe^{3+} in the extract obtained with a double acid solution (HNO_3 and HCI) by using atomic absorption spectrophotometer in the Laboratory of the Poplar and Fast Growing Forest Trees Research Institute, Izmit according to the standard methods of American Public Health Association, American Water Works Association, and Water Environment Federation (APHA;AWWA;WEF, 1998). The concentrations of the chemical parameters in sediment samples were measured as grams per kilogram, and these values were converted to mean monthly nutrient losses as kilograms per month by multiplying them with monthly bedload deposition (kg) in the weir pools. Concentrations of Fe^{3+} and S^{2-} in the stream water were measured by using UV visible spectrophotometer; KN, Ca^{2+}, and Mg^{2+} were determined with titration method; and K^{+} and Na^{+} were measured with ion-selective electrode method in the Department of Watershed Management Hydrology Laboratory at the Istanbul University-Cerrahpasa (APHA;AWWA;WEF, 1998). All parameters were measured in milligrams per liter except for Fe^{3+} (μg/L), and then these weekly values were converted to monthly values to estimate water nutrient outflows as kilograms per month. Then the total nutrient losses from both watersheds were estimated as the sum of the nutrient outflows through the streamflow and bedload sediment depositions together in this study, and hereafter, these values were taken into account in the statistical analyses.

Eighteen percent of the standing timber volume was removed from the treatment watershed (W-IV) between October and December months in 2011. Some trees in the treatment watershed were selected properly and harvested with a standard selective cutting technique, whereas forest cover in the W-I was preserved as a control site. Regression equations were developed between control and treatment watersheds for each of the selected water chemical characteristics in the calibration period, and these equations were used to estimate the predicted values of the same chemical parameters if the treatment would not be applied in the treatment watershed. Finally, the effect of 18% thinning on the monthly outflow of selected chemical parameters in the treatment watershed was examined by comparing measured values with those

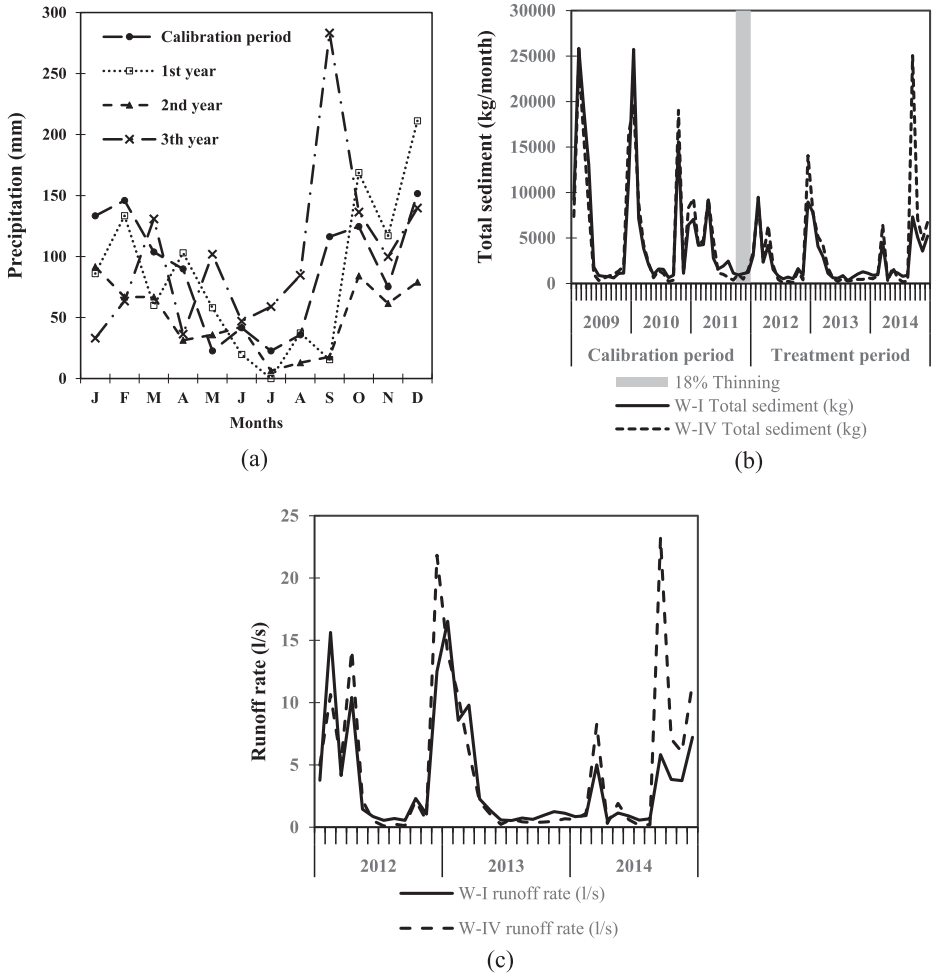


FIGURE 2 Variations in the precipitation (a) and total sediment losses (b) during the calibration and the treatment periods and runoff (c) during the treatment period for the treatment (W-IV) and control (W-I) watersheds

estimated with the calibration equation for the post-treatment period using a two-tailed paired-sample *t* test at an alpha level of 0.05 (Zar, 1996).

RESULTS AND DISCUSSION

Results showed that the amount of the precipitation differed markedly among years (Figure 2a). During the calibration period (January 2009–September 2011), the study area received 6% less precipitation than the long-term average. Similarly, annual precipitation in the first and second post-treatment years (2012 and 2013) was 7.4% and 45.3%, respectively, less than the long-term average. In contrast, annual precipitation in the third year of the treatment period was 11.3% greater than the long-term mean annual precipitation. When the whole treatment period was considered (3 years), annual precipitation averaged 940.4 mm, and it was 13.8% less than the long-term average. Mean monthly bedload depositions were 30% and 52% of the monthly suspended sediment outflows of the control and the treatment watersheds, respectively. As seen in Figure 2b, sediment depositions in the control and treatment watersheds showed a similar trend in both calibration and treatment periods. Mean monthly sediment depositions were 4466 kg for the control and 4485 kg for the treatment watersheds in the calibration period whereas they were 2258 kg for the control and 3089 kg for the treatment watersheds during the treatment period. Sediment losses from both watersheds decreased in the treatment period compared to the calibration period (Figure 2b). This situation can be attributed to differences in the precipitation amounts during both periods and between the years (Figure 2a). Increases in the sediment losses in both watersheds can be easily seen with the increase in the precipitation in the second and third years of the treatment period. There was an important decrease in sediment flux in the spring and summer months of 2013 (second year of the treatment period) in both watersheds due to severe drought observed during these months. During the treatment period, both treatment and control watersheds had similar sediment and runoff peaks but with different magnitudes in response to precipitation (Figure 2b,c). When sediment flux reached peak level in both watersheds, the amounts of sediment losses were two and threefold

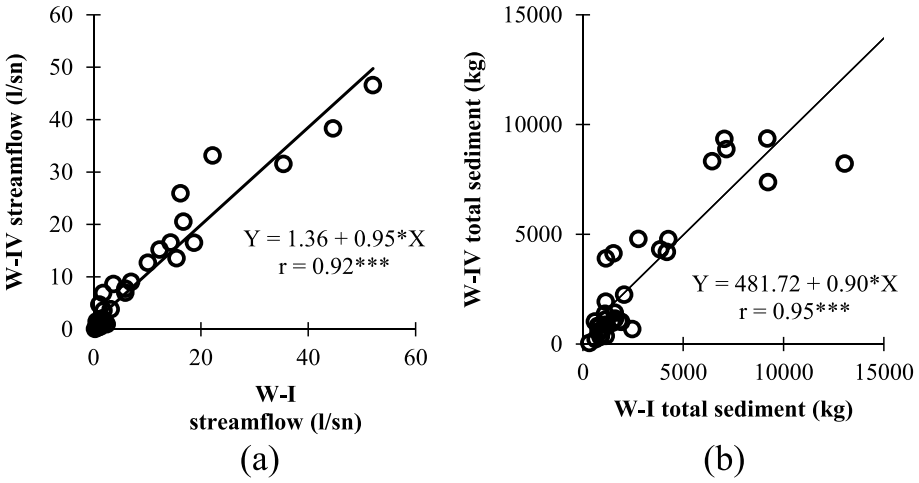


FIGURE 3 Scatter plots between control (W-I) and treatment (W-IV) watersheds for streamflow (a) and total sediment loss (b) for the calibration period (*** = $P < 0.001$)

greater than the average sediment losses in the control and treatment watersheds, respectively.

There was a significant relationship between the mean monthly runoff and sediment losses during the calibration period with high correlation coefficients between the control and treatment watersheds (Figure 3). Although the effect of the treatment on water yield and streamflow chemistry were examined and significant relationships were also reported between the same watersheds previously (Gökbulak et al., 2016; Yurtseven et al., 2017), the relationship between the watersheds was not determined for the total sediment flux (suspended sediment + bedload). Additionally, Erdoğan et al. (2018) studied the effect of 18% timber harvesting on physical water quality characteristics in the same experimental watersheds and reported a significant relationship between these watersheds only for suspended sediment, not the total sediment loss. In this study, the relationship between the watersheds for total sediment loss was determined for the first time (Figure 3b).

Results of the study revealed that there were significant relationships between control and treatment watersheds with significantly high correlation coefficients for Ca^{2+}, Mg^{2+}, KN, Na^{+}, K^{+}, Fe^{3+}, and S^{2-} outflows in the calibration period (Figure 4, Table 1). W-I had significantly greater monthly average Ca^{2+}, Mg^{2+}, KN, K^{+}, Na^{+}, and Fe^{3+} and lower S^{2-} discharges than W-IV during the pre-treatment period (Table 1). This could be due to slight differences in the watershed characteristics such as size, drainage density, slope length, road density, elevation range, litter depth, and crown closure (Gökbulak et al., 2016). Hydrograph response time and amount of runoff in the watersheds affected by topographical differences could lead to a change in the amount of nutrient outflow from both watersheds in the calibration period. Foster and Bhatti (2006) emphasized that climate, site, abiotic properties such as topography and parent material, and biotic communities can primarily control nutrient cycling in forest ecosystems. Therefore, differences in watershed characteristics could be responsible for the differences in the nutrient discharge during the calibration period.

We focused primarily on the possibility of exceeding values of nutrient fluxes due to the treatment and thus considered the upper 95% (one-tailed) confidence intervals (CI) for single observations from regression equations for the pre-treatment period. Figure 4 shows observed values of W-I and W-IV that exceeded the upper 95% confidence interval in the calibration period. We also determined observations of nutrient fluxes within the harvested and control watersheds during the calibration period with the 95% prediction interval (PI). Figure 4 also shows observed exceeded nutrient flux values above or below the 95% PI in the calibration period.

Mean monthly nutrient fluxes from the treatment watershed showed a similar trend except for KN, and they were generally greater in wet winter months than in dry summer months (Figure 5). Therefore, it can be said that nutrient losses were mostly influenced by the precipitation regime. Martínez-Mena et al. (2020) emphasized that nutrient mobilization was the highest during the most intense rainfall events. The measured monthly KN peak in the W-IV was significantly higher than the predicted value. It seemed that peak flows were not predicted correctly in KN despite the high correlation between watersheds in the calibration period (Table 1). As seen in Figure 5, the measured values of the peak events of other chemical parameters were considerably greater than the estimated values. Timber harvesting that reduces the forest canopy interception and transpiration and increases the proportion of precipitation reaching the soil surface leads to increase runoff and streamflow.

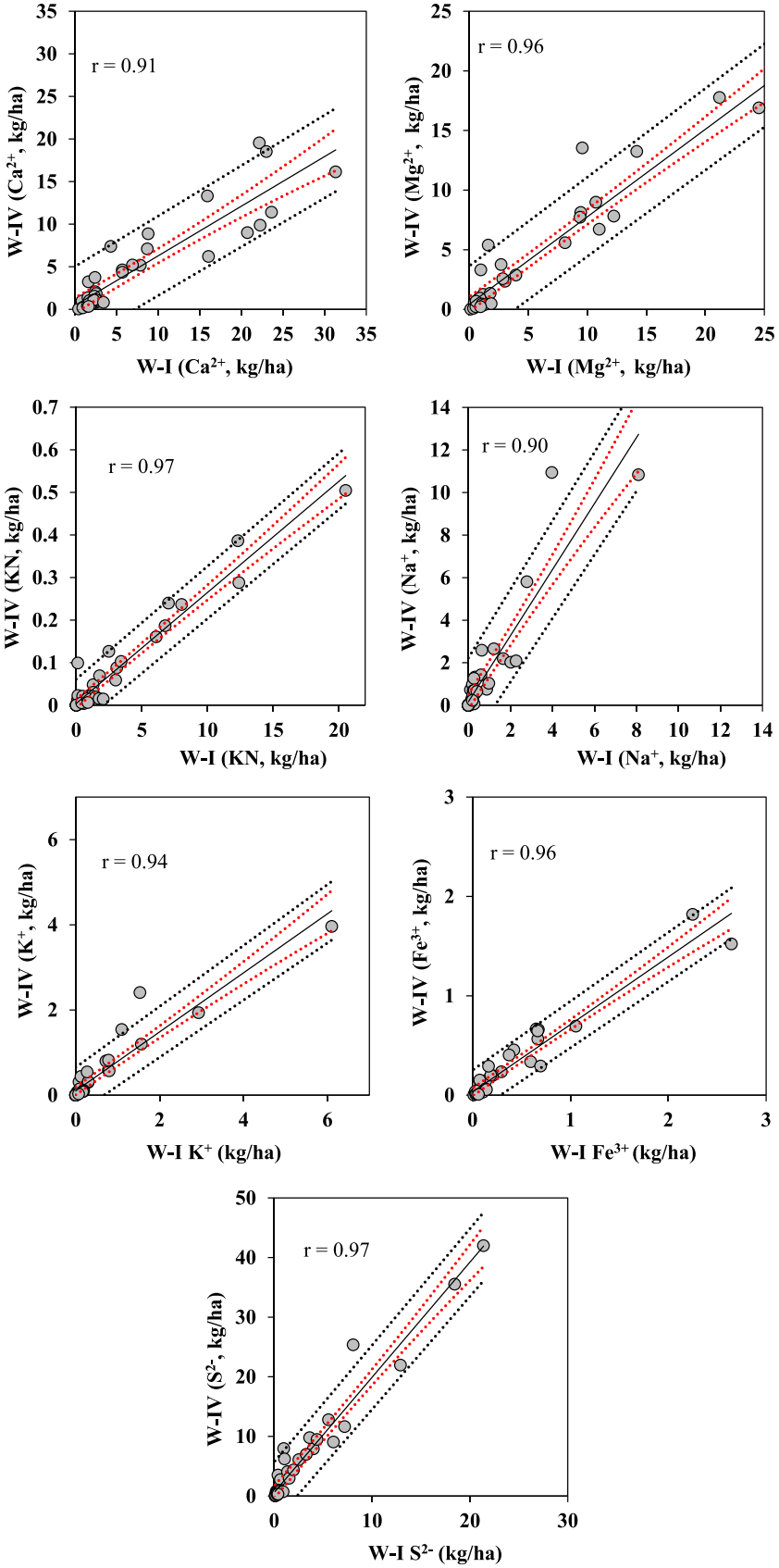


FIGURE 4 Regression lines between W-I and W-II watersheds for the pre-treatment periods for Ca^{2+}, Mg^{2+} KN, Na^{+}, K^{+}, Fe^{3+}, and S^{2-} outflows. Black dashed, red dashed, and solid lines represent predicted intervals, confidence intervals, and trend lines, respectively

The raindrops with high kinetic energy erode the upper zone of the forest soil in the areas where the forest floor was destroyed and the mineral soil surface exposes to the atmosphere due to harvest. The forest floor protects the

TABLE 1 Regression equations between control (W-I) and treatment (W-IV) watersheds for mean monthly selected nutrient fluxes during the pre-treatment period

Parameters	Regression equations	Mean monthly values (mean ± SER)		Significance of *r*
		W-I	W-IV	
Ca^{2+} (kg/ha)	$Y^1 = 0.4558 + 0.58*X^2$	6.99 ± 0.34	4.53 ± 0.22	$P < 0.05$
Mg^{2+} (kg/ha)	$Y = 0.4263 + 0.74*X$	5.13 ± 0.30	4.19 ± 0.23	$P < 0.05$
KN (kg/ha)	$Y = 0.004 + 0.03*X$	3.24 ± 0.19	0.13 ± 0.01	$P < 0.05$
Na^{+} (kg/ha)	$Y = 0.1666 + 1.55*X$	1.41 ± 0.09	1.73 ± 0.13	$P < 0.05$
K^{+} (kg/ha)	$Y = 0.0996 + 0.69*X$	0.66 ± 0.05	0.60 ± 0.04	$P < 0.05$
Fe^{3+} (g/ha)	$Y = 0.0302 + 0.68*X$	0.35 ± 0.02	0.27 ± 0.02	$P < 0.05$
S^{2-} (kg/ha)	$Y = 0.5814 + 1.93*X$	2.97 ± 0.20	6.32 ± 0.40	$P < 0.05$

Note: Numbers (1 and 2) represent W-IV and W-I, respectively.

soil surface against the erosive effects of raindrops because it has a good water retention capacity covers the mineral soil surface, and retards peak flows in the runoff (Sun et al., 2018). The decrease in the canopy cover with the forest harvesting can cause decreases in the amount of forest litter accumulated on the mineral soil surface. The forest litter is also the source of organic matter and hence nutrient pool for the forest soils. Therefore the potential magnitude of sediment nutrient fluxes can be affected by the rate of organic matter supply to the sediments (Jensen et al., 1990).

Erosion and leaching, which are controlled by rainfall intensity, after timber harvest, may also have had an important impact on the nutrient fluxes. Gökbulak et al. (2008) found that there was a significantly high correlation between streamflow nutrients and suspended sediment losses and these are important parameters in the hydrochemical dynamics of the forested watersheds.

After 18% timber removal, outflows of all cations except for sodium and potassium showed an increasing trend in the first year of the post-treatment period. KN had the highest (16.66%) whereas Fe^{3+} (0.01%) had the lowest mean monthly outflow increase (measured-estimated) in the first post-treatment year (Table 2). However, these increases were not great enough to be statistically significant. Significant decreases were found in the potassium losses in the first and second post-treatment years. Similar to potassium outflow, sodium also showed a decreasing trend in the first 2 years of the treatment period but a significant decrease was observed only in the second year of the treatment period (Table 2). The reasons for decreased Na^{+} and K^{+} outflows might be retention of Na^{+} and K^{+} in the soil due to changes in pH and physical properties of soils because of the timber removal. In the third post-treatment year, no selected chemical parameters from W-IV showed significant changes in their outflows except for KN. KN outflow showed a significant increase 3 years after the implementation of the treatment (Table 2, $P < 0.05$). Alongi and Brinkman (2011) reported that nitrogen cycling closely depends on rates of sediment accumulation. Sediment transportation cannot be observed immediately following the timber removal due to residues left on the site after harvest. For instance, Sakals and Sidle (2004) reported that the erosion rate increased 2- to 10-fold 3 to 15 years later from timber harvesting. Average monthly measured and estimated KN outflows were 0.06 kg/ha and 0.05 kg/ha, respectively, in the first treatment year whereas the averages significantly increased by 90% and 98% during the second and third post-treatment years, respectively. The largest losses of KN occurred in the third post-treatment year. In addition, the overall mean monthly KN outflow increased significantly from 0.03 kg/ha to 0.86 kg/ha after 18% timber harvesting. In contrast to KN, overall mean monthly outfluxes of other chemical parameters were not significantly altered by timber removal (Table 2, $P > 0.05$). Both watersheds received higher precipitation in the second and third post-treatment years than in the first post-treatment year and most of it fell between October and March. About 89% and 51% of mean annual precipitations fell between October and March during the calibration and treatment periods, respectively. As found in another study by Serengil et al. (2007), increases in the average monthly precipitation influenced nitrogen fluxes and caused increases in the runoff and sediment outflow in this study. Lehmann and Schroth (2003) reported that nutrient loss through leaching is generally affected by intensive precipitation that exceeds evapotranspiration. Besides increases in the precipitation during the second and third treatment years, changes in the nutrient fluxes can be attributed to increased nutrient concentration in the soil because of decreased tree density and decreased

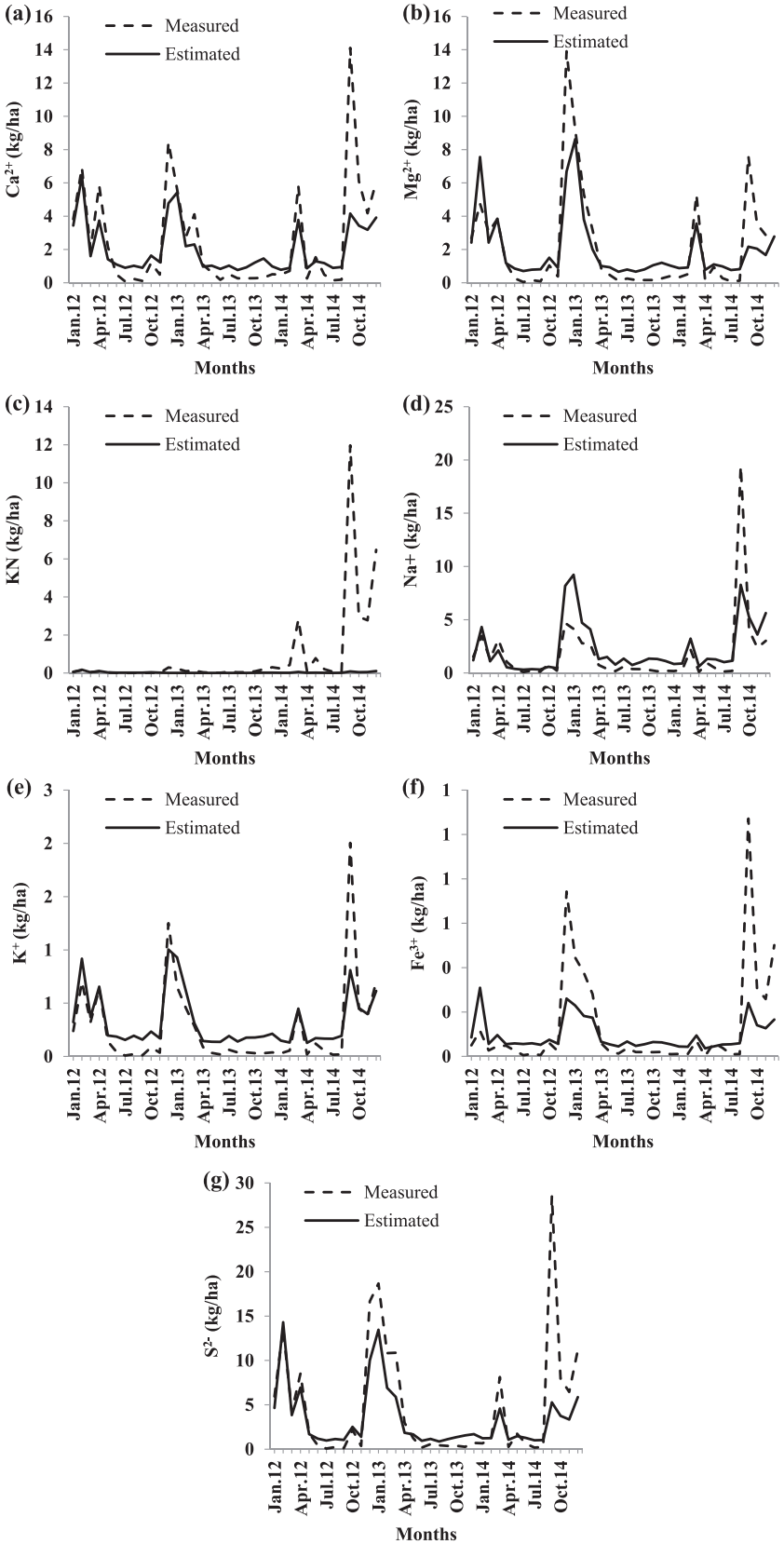


FIGURE 5 Trends of measured and estimated (a) Ca^{2+}, (b) Mg^{2+}, (c) KN, (d) Na^{+}, (e) K^{+}, (f) Fe^{3+}, and (g) S^{2-} outflows during the treatment period in the W-IV

nutrient uptake by trees left on the treatment watershed. In contrast, some previous studies have revealed that forest harvesting can result in reductions in soil nitrogen (N) stocks and it can continue for decades to centuries (Achat et al., 2015; Kellman et al., 2014; Mushinski et al., 2017; Prest et al., 2014).

TABLE 2 Mean monthly measured and estimated outflows (mean ± SER) of selected chemical parameters from the treatment watershed during the treatment period

Post-treatment years		Parameters (kg/ha)						
		Ca^{2+}	Mg^{2+}	KN	Na^{+}	K^{+}	Fe^{3+}	S^{2-}
1st year	Measured	2.65 ± 0.12	2.62 ± 0.16	0.06 ± 0.003	1.41 ± 0.06	0.29 ± 0.02	0.10 ± 0.01	4.51 ± 0.23
	Estimated	2.35 ± 0.07	2.47 ± 0.09	0.05 ± 0.002	1.65 ± 0.09	0.38 ± 0.01	0.10 ± 0.003	4.14 ± 0.17
	Significance	$P > 0.05$	$P > 0.05$	$P > 0.05$	$P > 0.05$	$P < 0.05$	$P > 0.05$	$P > 0.05$
	Differences (%)	11.32	5.72	16.66	−17.02	−31.03	0.01	8.2
2nd year	Measured	1.37 ± 0.07	1.71 ± 0.11	0.10 ± 0.004	1.08 ± 0.05	0.15 ± 0.01	0.11 ± 0.01	3.96 ± 0.24
	Estimated	1.59 ± 0.05	1.88 ± 0.09	0.01 ± 0.001	2.37 ± 0.10	0.28 ± 0.01	0.09 ± 0.003	3.21 ± 0.15
	Significance	$P > 0.05$	$P > 0.05$	$P < 0.05$	$P < 0.05$	$P < 0.001$	$P > 0.05$	$P > 0.05$
	Differences (%)	−16.06	−9.94	90	−119	−86.66	18.18	18.94
3rd year	Measured	3.34 ± 0.17	2.05 ± 0.10	2.41 ± 0.14	2.77 ± 0.22	0.36 ± 0.02	0.20 ± 0.01	5.60 ± 0.33
	Estimated	2.11 ± 0.06	1.54 ± 0.04	0.04 ± 0.001	2.75 ± 0.10	0.32 ± 0.009	0.09 ± 0.003	2.60 ± 0.07
	Significance	$P > 0.05$	$P > 0.05$	$P < 0.05$	$P > 0.05$	$P > 0.05$	$P > 0.05$	$P > 0.05$
	Differences (%)	36.82	24.88	98.34	0.72	11.11	55	53.57
Overall	Measured	2.46 ± 0.03	2.13 ± 0.03	0.86 ± 0.02	1.75 ± 0.03	0.27 ± 0.004	0.13 ± 0.002	4.69 ± 0.07
	Estimated	2.02 ± 0.02	1.96 ± 0.02	0.03 ± 0.001	2.26 ± 0.02	0.33 ± 0.003	0.10 ± 0.001	3.32 ± 0.04
	Significance	$P > 0.05$	$P > 0.05$	$P < 0.05$	$P > 0.05$	$P > 0.05$	$P > 0.05$	$P > 0.05$
	Differences (%)	17.88	7.98	96.51	−29.14	−22.22	23.07	29.11

Treatments resulted in 11.32%, −16.06%, and 36.82% changes in Ca^{2+} losses during the first, second, and third post-treatment years in W-IV, respectively. The differences between observed and estimated losses were 5.72% in the first, −9.94% in the second, and 24.88% in the third post-treatment year for Mg^{2+}, respectively. However, these changes between measured and estimated values were not statistically significant neither for Ca^{2+} nor for Mg^{2+} ($P > 0.05$). In contrast to Ca^{2+} and Mg^{2+}, K^{+} fluxes showed significant decreases in the first and second post-treatment years but not in the third post-treatment year (Table 2). This situation could be explained by the combined effect of two conditions. The first one is the low stream water discharge and erosion that caused decreases in the outflow of these chemicals from the watershed due to less amount of precipitation during the second post-treatment year compared with other treatment years. The second one is the replenishment of understory vegetation that could effectively slow down surface runoff and hence decrease soil erosion and transport and increase nutrient uptake by growing understory vegetation. Therefore, precipitation, streamflow, erosion, vegetation growth, thinning intensity, and interaction among these factors could be considered as driving forces for these temporal changes of nutrient outfluxes in the treatment watershed after timber harvesting. Leys et al. (2016) reported that vegetation growth had an important role in the decreased Ca^{2+} availability in the soil and acid rain led to mobilizing significant amounts of Ca^{2+} from watershed soils in the post-harvest period. In the same study, the clear-cut practice resulted in losing roughly 88% more Ca^{2+} and 75% more Mg^{2+} from the treatment area than the control during the 5 years after the harvest. Bäumler and Zech (1999) found that 40% thinning caused higher Ca^{2+}, Mg^{2+}, and K^{+} fluxes in the treatment watershed compared with the control watershed. Serengil et al. (2007) investigated the effect of 11% thinning on Ca^{2+} concentration in the stream water of the same experimental watersheds and found a 31% increase in the Ca^{2+} outflow after the thinning treatment. In this study, the comparison of measured and estimated total Ca^{2+} fluxes indicated that an 18% thinning resulted in an increase of 36.82% in the Ca^{2+} discharge in the treatment watershed for the third post-treatment year but the magnitude of Ca^{2+} increase was not great enough to be statistically significant (Table 2, $P > 0.05$). When the entire post-treatment period was considered together, results showed that the concentration of all selected chemical parameters except for KN did not show any significant changes due to the treatment (Table 2). In contrast, the overall mean monthly KN outflow averaging over 3 years treatment period significantly increased from 0.03 kg/ha to 0.86 kg/ha (Table 2).

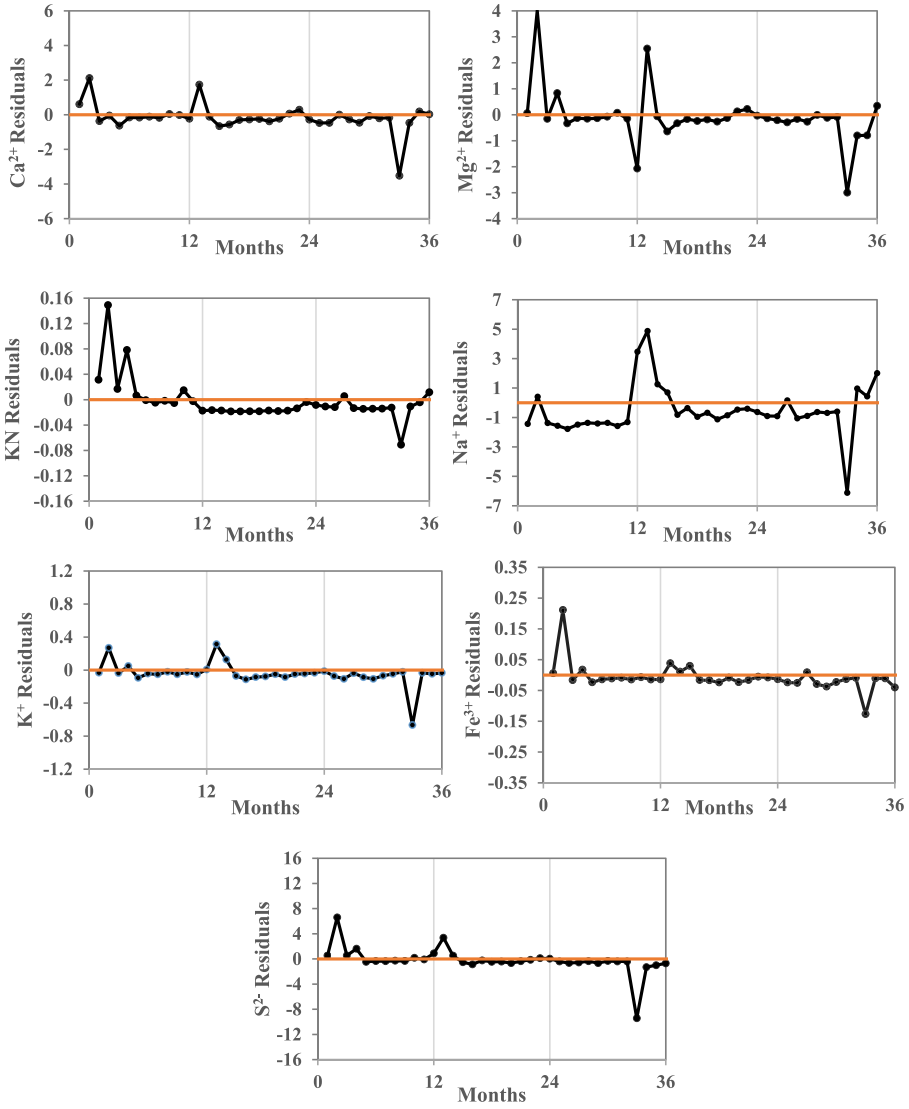


FIGURE 6 Residual plots for the treatment watershed (W-IV) during the treatment period indicating the deviations from the measured and the estimated values of nutrient fluxes

Figure 6 shows residual plots of chemical parameters indicating the deviation from the measured and the estimated values. Variance heterogeneity (unequal variance) and auto-correlated error were also detected by residual plots which used log-transformed data. Therefore, Figure 6 explains normality and heteroscedasticity between control and treatment watersheds. The residual peaks, which indicated the maximum deviation of estimated values and measured values, were probably due to the peak flows formed during the treatment period. Maximum peak nutrient fluxes occurred in the September of third post-treatment year. Residual peaks in the third post-treatment year can be explained by the effect of thinning. The difference between the measured and the estimated values was caused by the different responses of both watersheds to excessive rainfall. Compared with estimated fluxes based on calibrations, KN fluxes were reduced in the first year, but increases in the nutrient fluxes occurred at the beginning of the second post-treatment year. The amount and density of understory vegetation increased as a result of changes in the amount of sunlight reaching the ground due to reductions in the standing timber volume and overstory canopy cover may cause a decrease in the concentration of the parameters in the first treatment year (Figure 6). As can be seen in KN residual graph, the decrease in the amount of KN flux from the treatment watershed in the first post-treatment year can be explained by the growth rate of understory vegetation or the high rate of mineralization after following timber harvesting. It is known that the decomposition of organic matter under increased soil moisture and temperature conditions increases after harvesting. Decomposition may not have taken place at a high rate in the first year because of insufficient humidity and temperature conditions in the soil. In addition, it is known that the roots of harvested trees continue to take nutrients from the soil by maintaining their vitality in the first years. Fraterrigo et al. (2011) emphasized that forest nutrient

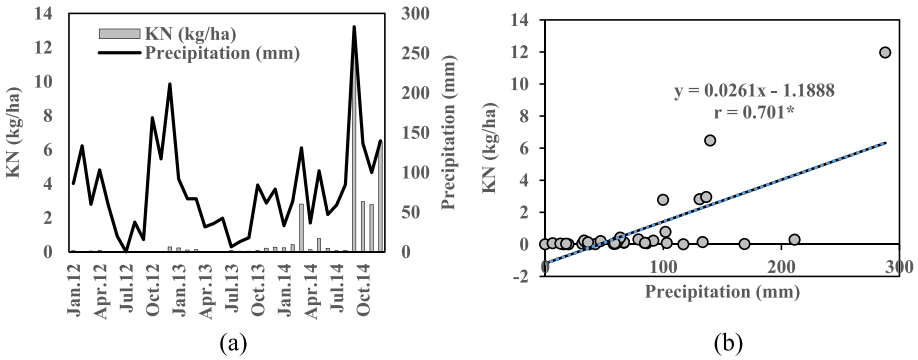


FIGURE 7 Trends of precipitation and KN (a) and the relationship between them (b) for the treatment watershed (W-IV) during the treatment period

dynamics have mainly been affected by understory plant communities. Therefore, understory species with high growth rates and especially nitrogen and other nutrient uptake rates may reduce leaching or fluxes. Lowrance et al. (1984) stated that plant nutrient uptake by plants during the growing season was the single most important process of N removal in the study area. Besides, low leaf area after treatment leads to lower interception of atmospheric N and therefore lower N deposition and N leaching rates (Davis, 2014).

Total KN fluxes would typically be closely related to precipitation if the high leaching rate is dominated by intensive precipitation. The nitrate leaching losses from forest systems are generally closely related to forest harvesting. Serengil et al. (2007) stated that nitrogen outflux was positively correlated with monthly water yield and suspended sediment load. It is already known that sediment is a major mechanism of nutrient transportation in forested watersheds and its magnitude is highly correlated with precipitation intensity (Pi-Chih et al., 2011). The study area received 11.3% more precipitation than the long-term average during the third year of the calibration period. This case may have been contributing as a major factor to the large nitrogen outflow (Figure 7a,b). Significantly highest KN losses took place in the second and third post-treatment years based on calibration equation estimates (Table 2). The result of other studies showed that a few high precipitation events could be responsible for most of the annual nitrogen losses (Edwards & Owens, 1991; Elliot et al., 2018). Contrary to findings of other studies, the second-highest precipitation event was measured in the first year of treatment but it did not have a significant effect on the nutrient fluxes in the first post-treatment year. This is an especially important finding showing that rapid vegetation growth was a more dominant factor in KN loss than precipitation in the first post-treatment year. While additional information is needed to determine if KN losses resulting from the effects of large precipitation events and vegetation dynamics can be effectively decreased by thinning procedure. Fahey and Jackson (1997) indicated that nitrogen leaching from a logged catchment remained three to five times higher than control (unlogged) catchment for 4 years after logging and the nitrogen level of logged watershed did not reach the control level by 6 years after the harvest. The role of nitrate in the soil solution below the crop rooting zone affects as a factor controlling Ca^{2+} and Mg^{2+} leaching. Federer et al. (1989) showed that Ca^{2+} was removed from the system faster than Na^{+}, K^{+}, N, and P, and this result was related to the effect of acid precipitation and intensive timber harvesting. In this study, although timber harvesting did not affect nutrient outflow significantly in the treatment watershed, the magnitude of the chemical outflows was numerically different among the parameters and they were in descending order of $KN > S^{2-} > Fe^{3+} > Ca^{2+} > Mg^{2+} > K^{+} > Na^{+}$ (Table 2). Therefore, treatment can lead to nutrient removals from the watershed and interrupt nutrient cycling temporarily. The recovery of the nutrient dynamics of the forested watershed from timber harvesting is dependent principally on the dominance of competing vegetation, especially understory, the ability of re-establishment speed of trees, the intensity of precipitation, and erosion in this period. In addition, physicochemical characteristics of soil could influence forest productivity and determine the regulation capacity of nutrient cycling processes. In this case, if the soil cannot provide enough nutrients as the growth rate of the previous forest, additional measures such as fertilization may be required for the sustainability of watershed productivity.

CONCLUSION

This study examined the impact of 18% thinning on the total nutrient loss through both stream water and sediment using the paired watershed approach in a broadleaf mixed forest ecosystem. The results showed that 18% timber harvesting significantly affected the overall mean monthly KN outflow and caused a 96% increase in the KN loss for the entire treatment period

($P < 0.05$). Timber harvesting did not have a significant effect on all nutrient outflows except for K^+ in the first year of the treatment period. The significant decreases were observed only in the K^+ outflows for the first two post-treatment years. Except for the KN export, overall mean monthly outflows of all nutrients did not show any significant changes for the entire treatment period. Timber removal had a significant effect on KN losses except for the first post-treatment year. Nitrogen availability or loss was strongly influenced by vegetation-specific controls over resource use efficiency in the first year of the treatment. The increase in the KN outflow could be caused by several factors such as disturbance of forest floor during the harvest practices and decomposition of organic matter under increased soil moisture and temperature conditions during the second and third years of the treatment period. Bosch and Hewlett (1982) claimed that a statistically detectable change in the water quantity and quality is not generally expected if a thinning treatment removes less than 20% of the standing timber volume. Based on this view, it can be concluded that timber harvest intensity smaller than 20% could cause a change only in the Kjeldahl nitrogen concentration. This situation will inevitably cause changes in the productivity of the forest soils and the physicochemical properties of the water. If a higher thinning intensity was implemented in the treatment watershed, its effect on other chemical parameters would be expected. In conclusion, the results of this study also showed that further studies are needed under different precipitation regimes, harvesting intensities and methods, vegetation types, and tree species to see a clear picture of the relationship between forest cover harvesting and total nutrient export from the forested watersheds through both runoff and sediment transport.

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CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

AUTHOR CONTRIBUTIONS

İbrahim Yurtseven took part in data collection in the field and writing manuscript. Ferhat Gökbulak was responsible for data collection from the field, statistical analysis, and manuscript preparation. Yusuf Serengil was in charge of experimental design and preparing a research proposal. Betül Uygur Erdoğan was responsible for the operation of measurement equipment in the field, data collection, and literature review. Reyhan Demir was responsible for the preparation of the manuscript according to journal format, data entrance from the data logger to the desktop, and manuscript preparation.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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