

**RESEARCH AND OBSERVATORY CATCHMENTS:
THE LEGACY AND THE FUTURE**

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Forest operations, tree species composition and decline in rainfall explain runoff changes in the Nacimiento experimental catchments, south central Chile

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Abstract

Few long-term studies have explored how intensively managed short rotation forest plantations interact with climate variability. We examine how prolonged severe drought and forest operations affect runoff in 11 experimental catchments on private corporate forest land near Nacimiento in south central Chile over the period 2008–2019. The catchments (7.7–414 ha) contain forest plantations of exotic fast-growing species (*Pinus radiata*, *Eucalyptus spp.*) at various stages of growth in a Mediterranean climate (mean long-term annual rainfall = 1381 mm). Since 2010, a drought, unprecedented in recent history, has reduced rainfall at Nacimiento by 20%, relative to the long-term mean. Pre-drought runoff ratios were <0.2 under 8-year-old *Eucalyptus*; >0.4 under 21-year-old *Radiata* pine and >0.8 where herbicide treatments had controlled vegetation for 2 years in 38% of the catchment area. Early in the study period, clearcutting of *Radiata* pine (85%–95% of catchment area) increased streamflow by 150 mm as compared with the year before harvest, while clearcutting and partial cuts of *Eucalyptus* did not increase streamflow. During 2008–2019, the combination of emerging drought and forestry treatments (replanting with *Eucalyptus* after clearcutting of *Radiata* pine and *Eucalyptus*) reduced streamflow by 400–500 mm, and regeneration of previously herbicide-treated vegetation combined with growth of *Eucalyptus* plantations reduced streamflow by 1125 mm (87% of mean annual precipitation 2010–2019). These results from one of the most comprehensive forest catchment studies in the world on private industrial forest land indicate that multiple decades of forest management have reduced deep soil moisture reservoirs. This effect has been exacerbated by drought and conversion from *Radiata* pine to *Eucalyptus*, apparently largely eliminating subsurface supply to streamflow. The findings reveal tradeoffs between wood production and water supply, provide lessons for adapting forest management to the projected future drier climate in Chile, and underscore the need for continued experimental work in managed forest plantations.

KEYWORDS

annual runoff, Chile, drought, experimental catchments, forest management, global change, pine to eucalyptus replacement, water supply

1 | INTRODUCTION

A major issue in forest hydrology is how forest management interacts with climate variability to affect water yield and its timing. Intensively managed plantation forests have significantly expanded in several countries in the developed and developing world, and now cover about 131 million hectares (FAO, 2020). Although Chile is one of the few countries in Latin America where persistent losses in tree cover have been reversed, reforestation has been largely driven by the expansion of forest plantations using non-native tree species (primarily *Eucalyptus spp.* and *Pinus radiata*; Heilmayr et al., 2016). Plantation forestry using non-native tree species has also expanded rapidly in South America in the past few decades, with many implications for water yield (Jones et al., 2017). Many studies show that the establishment of intensively managed forest plantations leads to reductions in streamflow relative to the yield under native vegetation. Forest plantations may intercept and evapotranspire almost all incoming precipitation (Almeida et al., 2007), especially in dry years or dry climates (Scott, 2005). Although in water-limited regions the potential reduction of water resources caused by forest plantations is smaller, in absolute terms, than in wetter regions, the impact can be socially and environmentally more damaging, owing to the already scarce water availability (Farley et al., 2005).

Afforestation with fast-growing tree species has been associated with reduced streamflow in large river basins globally (Farley et al., 2005; Jackson et al., 2005) as well as in South America (Iroumé & Palacios, 2013; Lara et al., 2009; Little et al., 2009; Salas et al., 2016; Silveira & Alonso, 2009). In small catchments draining forest plantations, water yield is related to plantation species and age (Iroumé et al., 2006), and to the amount of native forest retained in the riparian zone (Lara et al., 2009; Little et al., 2015). Nevertheless, few studies have examined forest hydrology in intensively managed forest plantations.

Model projections indicate that a warming global climate has increased atmospheric moisture demand and altered atmospheric circulation patterns, enhancing the potential for sustained drought (Dai, 2011). In the past two decades, some regions of Earth have been affected by drought that is unprecedented in the past few millennia (Diffenbaugh et al., 2015; Garreaud et al., 2020). Recent studies have examined how drought may influence forest health (Bouchard et al., 2019; Saatchi et al., 2013; Stovall et al., 2019). However, little is known about how persistent drought affects short-rotation forest plantations of exotic tree species managed by large private forest corporations.

Many studies have shown that timber harvests can increase water yield, but the magnitude and duration of this effect varies among sites (Andréassian, 2004; Best et al., 2003; Bosch & Hewlett, 1982; Brown et al., 2005, 2013). Increases in water yield after forest harvests are less likely when potential evapotranspiration is high, such as in dry seasons or arid climates (NAS, 2008; Jones et al., 2009). As forests regenerate, streamflow deficits can develop, especially during periods of seasonal drought (Gronsdahl et al., 2019; Perry & Jones, 2017;

Segura et al., 2020). Yet little is known about how intensive forest management interacts with major, multi-year droughts.

We address these knowledge gaps. In response to scientific evidence and public discussion of the effects of plantation forestry on streamflow, starting in 2007 a large private forestry company, FORESTAL MININCO (Spa) undertook a long-term study in a number of catchments in south central Chile, where forest plantations of *Eucalyptus* and *Radiata* pine had been established in the 1960s. Within a year or two after this study began, central Chile was affected by a protracted and unprecedented drought (Garreaud et al., 2020). We analysed long-term streamflow, precipitation, and forestry treatment data from 11 catchments in this study to determine how the history of plantation establishment and subsequent forestry treatments in plantations of *Eucalyptus spp.* and *Pinus radiata*, combined with the drought, influenced annual water yield over the period 2008–2019. The catchments contain intensively managed, short-rotation forestry plantations of non-native species on private corporate forest land and form one of the most comprehensive and detailed forest catchment studies in the world. We ask:

1. How did plantation establishment in the preceding 60-years and subsequent forestry treatments (thinning, clearcutting, and replanting) influence streamflow in intensively managed forests over the period 2008–2019 in south central Chile?
2. How did a severe, multi-year drought interact with the history of plantation management and ongoing forestry treatments to influence streamflow?
3. How did effects of forestry treatments vary based on the amount of riparian forest retained in the catchment?

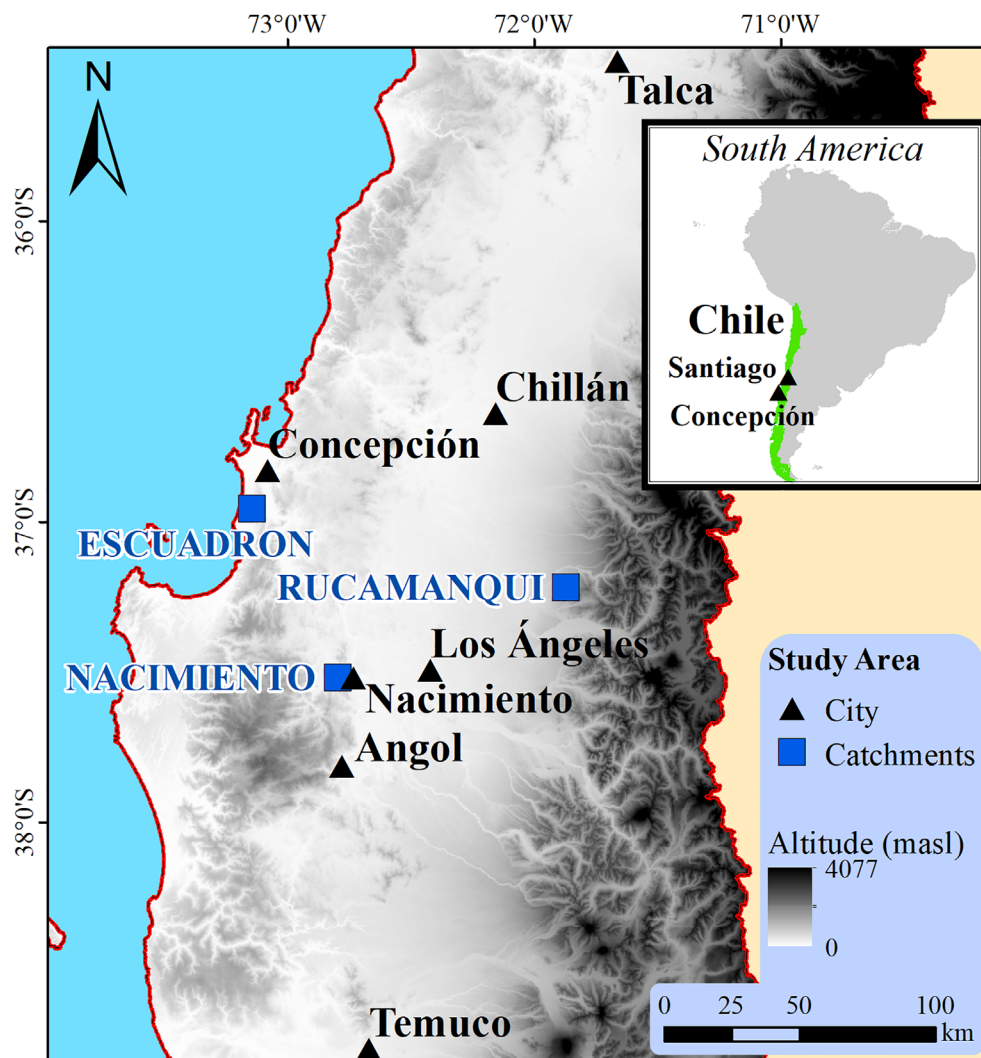
In addition to contributing to the understanding of the complex relationships between forests and water, our results are also intended to provide forest companies with information relevant to forest management in water-limited areas.

2 | STUDY SITE

The study catchments are located on land belonging to FORESTAL MININCO Spa, the second largest forest company in Chile, part of the CMPC holding company (www.cmpc.com/en/).

They are part of a research program maintained by FORESTAL MININCO since 2007 to monitor hydrology and meteorology to understand links among land use, forest operations, and water quality and quantity. As of 2020, 18 experimental catchments are monitored in three sites (Nacimiento, Rucamanqui and Escuadrón) with varying forest, climate, and edaphic characteristics (Figure 1). FORESTAL MININCO uses these data for multiple purposes including: (1) to determine compliance with environmental monitoring guidelines for sustainable forestry certification; (2) to manage plantations of *Pinus radiata* and *Eucalyptus spp.* to prevent and mitigate undesired downstream effects; (3) to help develop indicators and standards to ensure sustainable forest and ecosystem management; (4) to promote

FIGURE 1 Location of the Nacimiento study site in south central Chile



collaborative research on ecosystem science, natural resource management, ecosystem services, and society; and (5) to provide outreach to the scientific community, natural resource managers, policy makers, and the general public.

The study was conducted in 11 of the 18 experimental catchments monitored by FORESTAL MININCO. They are located on the eastern slope of the Cordillera de la Costa, about 3 km west of the city of Nacimiento in south central Chile (37°28'S, 72°42'W; Huber et al., 2010; Mohr et al., 2012; Figure 2). The study site is in the principal forest plantation zone of Chile, which extends from 34.5° to 41°S (Salas et al., 2016). Total planted area of forest plantations in Chile as of December 2018 was 2.3 million hectares (INFOR, 2020). This area refers to established plantations and excludes plantations destroyed by wildfire in 2016 and 2017 as well as areas recently harvested but not yet reforested. Of these 2.3 million hectares, 55.8% is *Pinus radiata*, managed in rotations of 22–24 years, 25.3% is *Eucalyptus globulus* and 11.9% is *E. nitens*, managed in rotations of 12–14 years (Salas et al., 2016).

The climate of the site is warm-summer Mediterranean (Csb in the Köppen-Geiger climate classification), characterized by dry and

warm summers (Peel et al., 2007). Mean annual precipitation (1980–2018) is 1084 mm at Los Angeles (139 m asl), and 1381 mm at the Nacimiento catchments (250–400 m asl; Figure 3). At Nacimiento, 85% of precipitation occurs between May and October during frequent and prolonged low- to moderate-intensity frontal storms. Mean annual temperature is 13°C, mean monthly temperature ranges from 7°C in winter (July) to 19°C in summer (January), and hourly air temperature ranges from less than −3°C in winter to more than 40°C during the summer (Mohr et al., 2012). Potential evapotranspiration (PET, 1980–2018, estimated using the Hargreaves & Samani, 1982 equation) is 1164 mm. Precipitation records since 1980 indicate that starting in 2010, the region (and most of Chile) was affected by a severe drought, and P declined by >20%. As a result, although P exceeded PET by >250 mm at Nacimiento prior to 2010, PET was almost equal to P after 2010 (Figure 3).

The original vegetation of the study site was temperate evergreen forest dominated by *Nothofagus obliqua* (Roble), *Aextoxicon punctatum* (Olivillo), *Laurelia sempervirens* (Laurel), and *Persea lingue* (Lingue; Millán & Carrasco, 1993). Most of these forests were logged and burned during the period of European colonization and subsequently

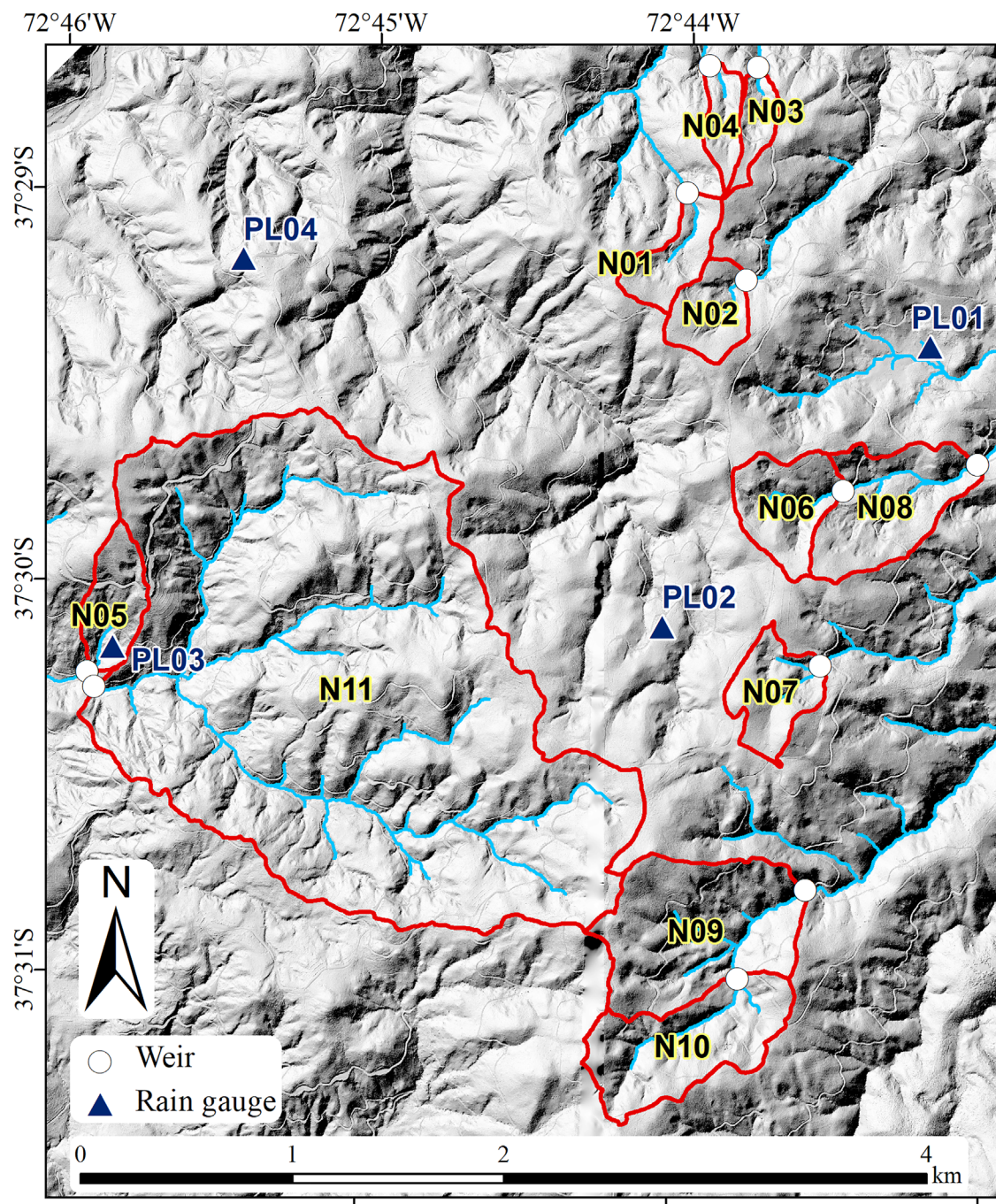


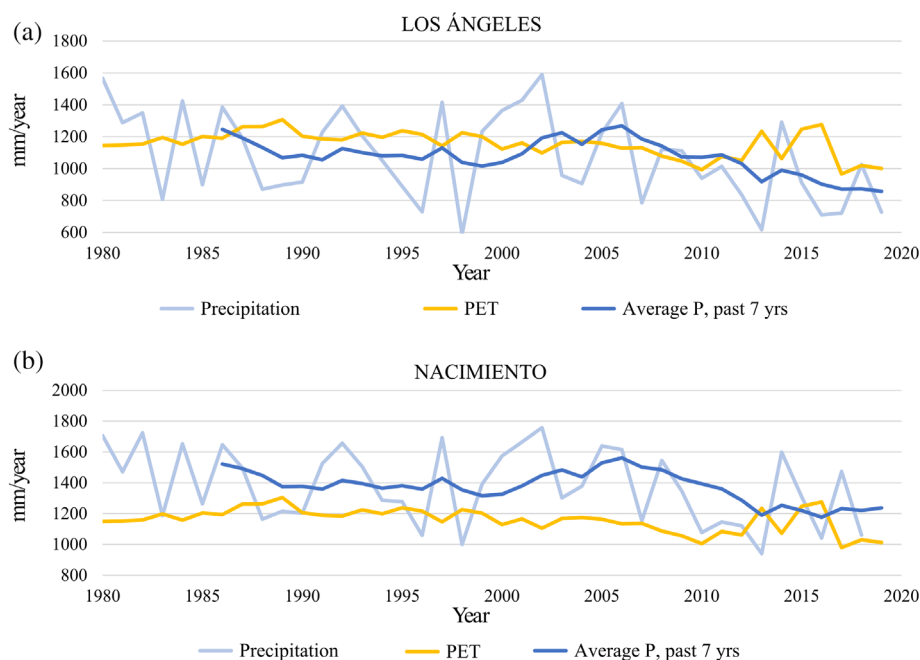
FIGURE 2 Shaded relief map showing Nacimiento study catchments (outlined in red), precipitation gages (triangles), and weirs (white circles). Major streams are shown with blue lines

converted to cultivation of wheat for export to California and Australia in the late 19th and early 20th centuries (Cisternas et al., 1999). Over time, the wheat-cultivation practices caused significant soil erosion and loss of topsoil, leaving a legacy of degraded land (FAO, 1974). Forest plantation establishment began in the area in the 1950s (Millán & Carrasco, 1993).

The 11 study catchments range in area from 7.7 to 414 ha (Table 1 and Figure 2). Elevation ranges from 127 to 475 m above sea level. Geology is dominated by metamorphic rocks (Hervé

et al., 2007; Melnick et al., 2009). Soil depth ranges from 0.5 to 3 m (Huber et al., 2010; Mohr et al., 2012). Soils are moderately well-drained, with surface textures ranging from loamy-sand to clay-silt and subsurface textures ranging from loam to clay (Schlatter et al., 2003). Saturated infiltration rates are low ($3\text{--}10\text{ mm h}^{-1}$). High soil rock content, plant roots, highly weathered saprolite, and underlying highly fractured bedrock promote preferential flow and deep wetting (Mohr et al., 2012; Ziegler et al., 2006). Soil water content in study catchments (N01 and

FIGURE 3 Long-term P and PET at Los Ángeles and Nacimiento (Dirección General de Aguas data base (www.dga.cl), accessed at <http://explorador.cr2.cl>). At Los Ángeles, the running mean P for the preceding 7 years was less than annual PET in the 1980s and 1990s, exceeded PET in the 2000s, and fell below PET starting in 2012. In 2012 the running mean P for the preceding 7 years fell below 1000 mm at Los Ángeles, and remained lower than at any time since the mid-1980s. At Nacimiento, the running mean P for the preceding 7 years exceeded annual PET until 2012. In 2013 the running mean P for the preceding 7 years fell below 1300 mm at Nacimiento and remained lower than at any time since the mid-1980s



N07) was near the maximum water holding capacity of these soils (i.e., 40%, Huber et al., 2010) below 2 m depth during the winters prior to the drought, indicating that excess precipitation recharges deep soil moisture reservoirs. However, soil water content in the upper 20 cm decreases during summers even to below the permanent wilting point.

Detailed information on the history of afforestation and plantation management in the study catchments enables interpretation of the cumulative effects of afforestation and forestry treatments since the 1960s, and their interaction with drought in the past decade. The study catchments were afforested in 1960–1961 (N05 and N11) and in 1964–1966 (N01, N02, N03, N04, N06, N07, N08, N09 and N10) with *Pinus radiata*, and after two successive rotations (45–47 years), the plantations are being converted to *Eucalyptus globulus* (Table 1). In N06, *P. radiata* was converted to *E. globulus* in 1987. In addition, forest fires during 1999–2000 affected stands of *P. radiata* established in 1987–1989 in N07, N08, N09 and N10, and these areas were reforested with *E. globulus* in 2000. Understory vegetation in the plantations includes grasses and forbs, shrubs, and occasional native trees (Huber et al., 2010; Mohr et al., 2012). Riparian forests provide a canopy cover of 50%–70% and consist of communities of native shrub and tree species, as well as *P. radiata* trees that have invaded the riparian zone during prior rotations (Huber et al., 2010; Mohr et al., 2012; Ulloa et al., 2011). In contrast, the riparian forest at N09 and N10 is a remnant of the original temperate evergreen forest of the area. All forestry treatments in the study involve clearcutting and replanting, except for thinning of *Radiata* pine in N02 and coppicing of the *E. globulus* plantation in N06 after harvest in 2000. The Nacimiento experiment is unique considering the range of forestry interventions, stages of plantation cycle and tree covers represented by its multiple catchments, as well as the

detailed records of afforestation and forestry treatments in each catchment.

3 | METHODS

3.1 | Experimental design and study questions

Detailed information on the history of forest management in the study catchments provides opportunities to examine the effects of forestry practices that are typical of intensive forest management in Chile (Table 1). First, the study catchments provide the opportunity to examine effects of clearcutting, replanting, thinning and partial harvest, as well as replacement of *Pinus radiata* with *Eucalyptus spp.*, consistent with general trends in Chilean forestry (Table 1). Second, both Chilean law (McGinley et al., 2012) and international forest certification processes (Tricallotis et al., 2018) specify the maintenance of native forest in riparian buffer zones in managed forests. In the Nacimiento catchments, riparian protected areas have been in place since the establishment of the plantations in the early 1960s. The varying sizes of the riparian zones (3%–13% of the area in seven catchments and 22%–46% of the area in four catchments, Table 1) therefore provide the additional opportunity to examine how riparian forests influence hydrology in catchments with ongoing forestry operations. Third, the study provides the opportunity to examine the interactive effects on streamflow of varying forestry treatments and a protracted and severe drought. Because all catchments were managed during the study period, there were no reference catchments. Also, the onset of drought coincided with the initiation of the study, so there are no pre-drought streamflow data. These limitations required special analysis approaches, described below.

TABLE 1 Vegetation cover and forestry treatments in study catchments N01–N11

	N01	N02	N03	N04	N05	N06	N07	N08	N09	N10	N11
Area (ha)	13	14	8	8	15	21	17	55	96	41	414
Roads											
Area (%)	0	1	3	3	1	2	4	3	3	3	5
Riparian forest											
Area (%)	7	4	13	8	19	14	5	15	42	50	11
<i>Pinus radiata</i>											
Area (%) 2008	93	95	71	87	–	–	–	26	25	17	7
Age (years) 2008	21	21	22	22	–	–	–	21	20	20	22
Date of harvest	–	2009	2009	2010	–	–	–	2010–2011	2009–2012	2010–2012	–
Type of harvest	–	T	C	C	–	–	–	C	C	C	–
% of area harvested	–	–	71	87	–	–	–	25	24	15	–
<i>Eucalyptus spp.</i>											
Area (%) 2008	–	–	13	3	42	84	84	56	30	30	69
Age (years) 2008	–	–	7	7	2	8	8	8	8	8	0–8
Date of harvest	–	–	2009	2010	2017–2018	–	2011	2011	2010–2012	2011	–
Type of harvest	–	–	C	C	C	–	C	C	C	C	C
% of area harvested	–	–	13	3	32	–	84	21	4	4	^a
Date of planting	–	–	2010	2010	2018	–	2012–2013	2011–2013	2010–2012	2011–2012	–
Area (%) planted	–	–	84	90	29	–	81	46	28	19	–
Acacia											
Area (%) 2008	–	–	–	–	–	–	8	–	–	–	–
Regeneration											
Area (%) 2008	–	–	–	–	38	–	–	–	–	–	–
Total % clearcut	–	–	84	90	32	–	84	46	28	19	0
Total % planted (2009–2013)	–	–	84	90	29	–	81	46	28	19	–
Sum (%)	100	100	100	100	100	100	100	99	100	100	100
Nested						In N08				In N09	

^aAt the beginning of 2008, total planted area was 312 ha, with 8.5% of planted area with Radiata, and 91.5% of planted area with Eucalyptus. Planted area remained the same until January 2015, but with a partial cut in 2010 of 25 ha of Radiata that was reforested the same year with Eucalyptus. During water years 2015–2016 to 2017–2018, planted area reduced to ~260 ha, after partial cuts of 44 ha during 2015, 14 ha during 2016 and 99 ha in 2017 (all Eucalyptus plantations). These areas were partially reforested the same years, but reforestation was completed during 2018. At the beginning of 2019, planted area was again 312 ha.

Abbreviations: C, clearcut; T, thinning.

3.2 | Data

Precipitation data were collected at four stations (Figure 2). Precipitation gages are Davis[®] (Rain Collector with Flat Base for Vantage Pro2, Davis Instruments Corporation, Hayward, CA) tipping-buckets with ± 0.24 mm resolution connected to Hobo[®] (Pendant Event Data Logger UA-003-64, Onset Computer Corporation, Bourne, MA) data loggers. A Davis[®] weather station operated from 2008 to June 2013 at the location of P04 (Figure 2), prior to the current precipitation gage. All gages were calibrated once a year. In our investigation, rainfall varies among rain gages, but it is not consistently related to elevation or orography, thus for runoff ratios and for double-mass curves, monthly precipitation data were spatially interpolated over the study area using kriging (Oliver & Webster, 1990) with the Spatial

Analyst Tools in ArcGIS[®]. Kriging is a geostatistical method that interpolates a raster surface from points. Kriging produces superior spatial predictions of rainfall compared to conventional and deterministic methods (Adhikary et al., 2015, 2017).

Analyses predicting mean daily streamflow at each study catchment from precipitation used the average daily precipitation from all four precipitation gages.

Uninterrupted data on streamflow recorded at 6-min intervals were obtained from the 11 catchments for the period April 2008 to March 2019 (Figure 2). Catchments N01–N10 are gaged with 60° sharp-crested weirs and N11 has a rectangular flume. Data at all stations were initially collected using float-operated sensors with a ± 2 mm accuracy designed and built at the Laboratory of Microprocessors, Universidad Austral de Chile. From 2011 to 2017, these

sensors were incrementally replaced by Trutrack® (WT-HR Water Height Data Logger, Tru Track Ltd., Christchurch, New Zealand) capacitive water height probes (± 1 mm accuracy), and some of the original instrumentation was preserved for backup. Data were stored at 6-min intervals. Rating curves ($R^2 > 0.99$) were developed using measurements over a wide range of discharges, based on the velocity–area method with flow meter measurements in most cases, and volumetric measurements during low flow periods. Missing values of mean daily streamflow in the first half of April 2008 for catchments N01, N02, N03, N04, N05, N08, N10 and N11 were estimated using a multiple linear regression model like $Q_i = C_1 + C_2 Q_{i-1} + C_3 P_i + C_4 P_{i-1}$, where Q_i and P_i are discharge and precipitation of day i , Q_{i-1} and P_{i-1} are discharge and precipitation of day $i - 1$, and C_i are constants. Missing values of mean daily streamflow for the first 3 months of the 2008–2009 water year at N06 and N07, and for the first 6 months at N09, were estimated based on regression models with neighbouring catchments. Estimated data represented $\sim 1.2\%$ of the total 11-year dataset for catchments N01, N02, N03, N04, N05, N08, N10 and N11, $\sim 2.9\%$ for catchments N06 and N07, and 5.6% for N09. Discharge and precipitation data were summarized by water year, that is, 1 April–31 March.

Soil water content was monitored at approximately 30-day intervals starting in 2008 using time domain reflectometry (TDR) equipment (TRIME-FM3, tube probe T3, Field Measurement Device Version P3 brand IMKO), at 10 cm intervals up to 2.5 m depth (Huber et al., 2010). Access tubes were installed directly into the soil at 10 locations evenly distributed throughout each of the study catchments. Several factors, including forest operations, animals, the 2010 earthquake, as well as instrument repairs, created gaps in the data, and measurements ceased when the TDR was stolen in early 2015. We illustrate soil moisture dynamics based on data from 6 February 2008 to 9 March 2010 and from 19 December 2013 to 31 December 2014 in catchments N01 (Radiata pine plantation) and N07 (Eucalyptus plantation, clearcut in 2011 and replanted with Eucalyptus).

3.3 | Data analysis and statistical methods

We calculated the running mean of precipitation for the past 3 and 7 years (Figure 3). Three approaches were used to examine streamflow responses to forestry treatments: runoff ratios, double-mass curves, and a method that we developed, using precipitation as the reference to predict streamflow. The annual runoff ratio is Q/P , where Q = streamflow (mm) and P = precipitation (mm). A double mass curve is a plot of cumulative Q versus cumulative P .

The third approach was a novel method developed to account for the fact that the study includes no reference catchment and no pre-treatment period. This approach is a simple modification of the well-known *Before-After-Control-Impact* (BACI) method (see Alila, Yuras, Schnorbus, & Hudson et al., 2009, for an example). Typically, a relationship is established between the flow regimes of two catchments in a pre-treatment period. Following treatment in one of the catchments (leaving the other as the reference), any change in the flow

relationship is considered to indicate an impact of the treatment. By involving a reference catchment, the BACI method eliminates the effect of any change in climate from the comparison. In the modification applied here, given the absence of a reference catchment and pre-treatment data, we used precipitation as the reference for estimating changes in streamflow. We generated a synthetic reference of expected streamflow based on the relationship of antecedent precipitation to streamflow in catchments which did not experience disturbance over the full period of the study (2008–2019), including the drought. The approach involves creating antecedent precipitation indices (Equation 1–6) and estimating the relationship of antecedent precipitation to streamflow at N01 and N06 (Equation 7) for several possible antecedent precipitation indices (Equation 8). Antecedent precipitation for each day was:

$$AP = P(t) + P(t-1)^{k1} + P(t-2)^{k2} + \dots + P(t-n)^{kn} \quad (1)$$

where $P(t)$ = precipitation on day t and $k1, k2, \dots, kn$ are decay constants. The relationship of antecedent precipitation to streamflow depends on precipitation patterns, which vary over time. To account for this variability, we created five indices of antecedent precipitation using various values of k :

$$AP_1 = P(t) + P(t-1)^{0.7} \quad (2)$$

$$AP_2 = P(t) + P(t-1)^{0.9} \quad (3)$$

$$AP_3 = P(t) + P(t-1)^{0.9} + P(t-2)^{0.7} \quad (4)$$

$$AP_4 = P(t) + P(t-1)^{0.7} + P(t-2)^{0.5} \quad (5)$$

$$AP_5 = P(t) + P(t-1)^{0.9} + P(t-2)^{0.7} + P(t-3)^{0.5} \quad (6)$$

We estimated the relationship of Q to $AP(t)$ for each AP model (Equation 2–6), for each day t for all years of the record for catchments N01 and N06:

$$Q_i(t) = \alpha + \beta AP_i(t) \quad (7)$$

where α and β are coefficients, and the index i refers to the model of antecedent precipitation used. We calculated the average and standard error of the five models:

$$Q(t) = [Q_1(t) + Q_2(t) + Q_3(t) + Q_4(t) + Q_5(t)]/5 \quad (8)$$

The standard error was very small (only 2.66 mm, or 0.5% of mean annual runoff), indicating that predicted streamflow was not sensitive to variations in antecedent precipitation. Therefore, we used the average model in Equation (8) to predict $Q(t)$ for each day t for all years for all catchments (N01–N11). Values of predicted and observed $Q(t)$ were summed by water year (April–March). The treatment effect was defined as the difference between observed and predicted annual

streamflow. Annual values of observed minus predicted Q were summed in consecutive years to obtain a time series of cumulative runoff change for each year (2008–2019) for each catchment.

We compared runoff ratios, double-mass curves, and observed vs. predicted streamflow for eight different subsets of catchments (Table 2). The eight groups display the effects of different forestry treatments on streamflow. The comparisons examined:

- How streamflow in small catchments responded to (a) aging of existing plantations (C1), (b) thinning of Radiata pine plantations (C2), (c) clearcutting of Radiata pine and replacement with Eucalyptus (C3), and (d) partial cuts of Radiata pine and replacement with Eucalyptus (C4).
- how streamflow responded to partial cuts in (a) small, nested catchments versus larger catchments with narrow riparian buffers (C5), (b) small, nested catchments versus larger catchments with wide buffers (C6), (c) large catchments with wide vs. narrow riparian buffers (C7), and (d) in small versus large catchments (C8) (Table 2).

We constructed a simple annual water balance model to reconstruct the long-term changes in streamflow over a hypothetical 40-year period of plantation establishment followed by drought, comparable to the history at Nacimiento from 1980 to 2020. We simulated precipitation (P), evapotranspiration (ET), shallow soil moisture (ΔS), and contributions to deep soil moisture (to G , or ΔG), based on $Q = P - ET - \Delta S - \Delta G$. We used these to estimate groundwater storage (G), streamflow (Q), the runoff ratio (Q/P), and cumulative runoff reduction, or deficit (D) over the 40-year simulation period. In Period 1 (years 1–10), P (precipitation) was set at 1400 mm, evapotranspiration (ET) was set at 700 mm (based on Figure 3), shallow soil recharge (ΔS) was 200 mm, and 100 mm of shallow soil recharge percolated to deep soil moisture (to G) when the sum of ET and soil moisture was <1000 mm. The groundwater reservoir (G) contributes to streamflow ('from G '). In Period 2 (years 11–20), ET was increased to 1000 mm to simulate establishment of a plantation, or a shift from Radiata pine to Eucalyptus. In Period 4 (years 31–40), precipitation was reduced from 1400 to 1200 mm to simulate the drought.

4 | RESULTS

Precipitation was relatively constant over three decades of plantation forestry in Nacimiento (1980–2010), prior to the initiation of streamflow measurements (in 2008). However, starting in 2010, the region (and most of Chile) was affected by a severe drought (a 'mega-drought'), and P declined by $>20\%$. As a result, although P exceeded PET by >250 mm at Nacimiento prior to 2010, PET was almost equal to P after 2010 (Figure 3).

In the first year of the study (2008), before the mega-drought, deep soil moisture (at 2.5 m depth) remained low (below 24%) from the beginning of February (austral summer) 2008 until the end of May in both the aging Radiata pine plantation (N01) and the Eucalyptus plantation (N07; Figure 4(a)). Soil moisture at 2.5 m rose above 24% and remained high ($>24\%$) throughout the austral winter, but it fell below 24% in early December 2008 in the Eucalyptus plantation (N07) and not until mid-February 2009 in the Radiata pine plantation (N01; Figure 4(a)). The 2009 dry period lasted for 7.5 months (from early December 2008 to mid-July 2009) in the Eucalyptus plantation (N07), but for only 4 months (from mid-February 2009 to 20 June 2009) in N01 (aging Radiata pine plantation). In the following austral winter and spring, soil moisture fell below 24% in December of 2009 in the Eucalyptus plantation (N07), but not in the aging Radiata pine plantation. Soil moisture patterns at 2.5 m depth are representative of the soil moisture patterns throughout the soil profiles. Throughout the 2014 water year, a relatively wet year during the mega-drought, soil moisture was 5–10 percentage points (e.g., 25% vs. 35% moisture) lower throughout soil profile under a 3-year-old Eucalyptus plantation (N07) compared to an aging Radiata pine plantation (N01; Figure 4(b)).

4.1 | Streamflow response to treatments in small catchments (8–21 ha)

4.1.1 | Aging plantations of Radiata pine (N01) and Eucalyptus (N06)

We contrasted streamflow trends in a Radiata pine plantation (N01, aged 21–33 years) and a Eucalyptus plantation (N06, aged

TABLE 2 Comparisons of groups of catchments in the Nacimiento study

Comparisons	N01	N02	N03	N04	N05	N06	N07	N08	N09	N10	N11
Clearcuts											
C1: aging plantations (pine, Euc)	x					x					
C2: thinning of aging pine	x	x									
C3: 100% clearcut of pine, Euc, replant			x	x			x				
C4: herbicide, regeneration, Euc growth					x	x					
Partial cuts											
C5: partial cut, pine to Euc versus aging Euc (nested)						x		x			
C6: partial cuts, pine to Euc, wide riparian buffers (nested)									x	x	
C7: partial cuts, wide versus narrow buffer								x		x	
C8: large versus small catchments	x		x			x					x

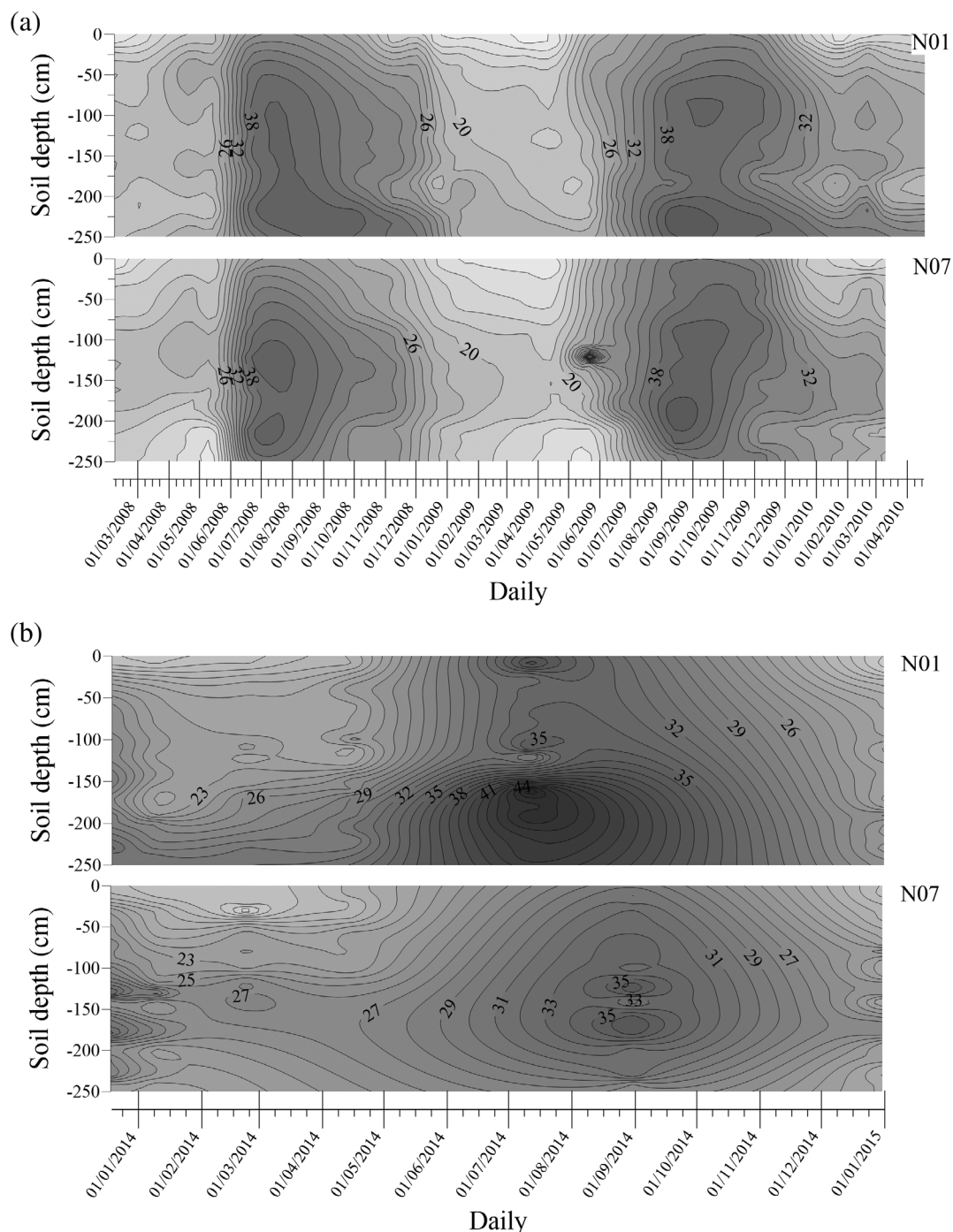


FIGURE 4 Spatio-temporal variation of soil water content of catchments forested with *Pinus radiata* (N01) and *Eucalyptus globulus* (N07). Isoleths are soil water moisture values (% Vol). Soil water content was measured at 10 cm intervals at 10 locations evenly distributed throughout each of the study catchments, and soil water content at each depth is the average of the measurements in the 10 locations. (a) Period 6 February 2008 to 17 April 2010 for N01 and 6 February 2008 to 9 March 2010 for N07; (b) period 19 December 2013 to 31 December 2014

9–20 years), which grew beyond their rotation age (Figure 5). Both catchments have a native vegetation riparian buffer zone representing 7% of catchment area in N01 and 14% in N06 (Table 1). The average runoff ratios of the two catchments (2008–2009 to 2018–2019) were similar: 0.17 (N01) and 0.18 (N06). Runoff ratios decreased in both catchments from 2010 to 2013 and increased in 2015–2017 following the 3-year running mean P (Figure 5(a),(c)). Catchment N01 (under an aging Radiata

pine plantation) initially had a higher runoff ratio (0.31–0.41, 2008–2009 to 2010–2011) but runoff declined dramatically in 2011–2012 producing a sharp reduction in the gradient of the double-mass curve (Figure 5(b)), and it remained below that of N06 (Eucalyptus plantation) for the remainder of the study period. In contrast, the runoff ratio in N06 varied less, between 0.24 and 0.13. By 2018–2019, these changes resulted in a smaller cumulative runoff decline in the aging Eucalyptus plantation

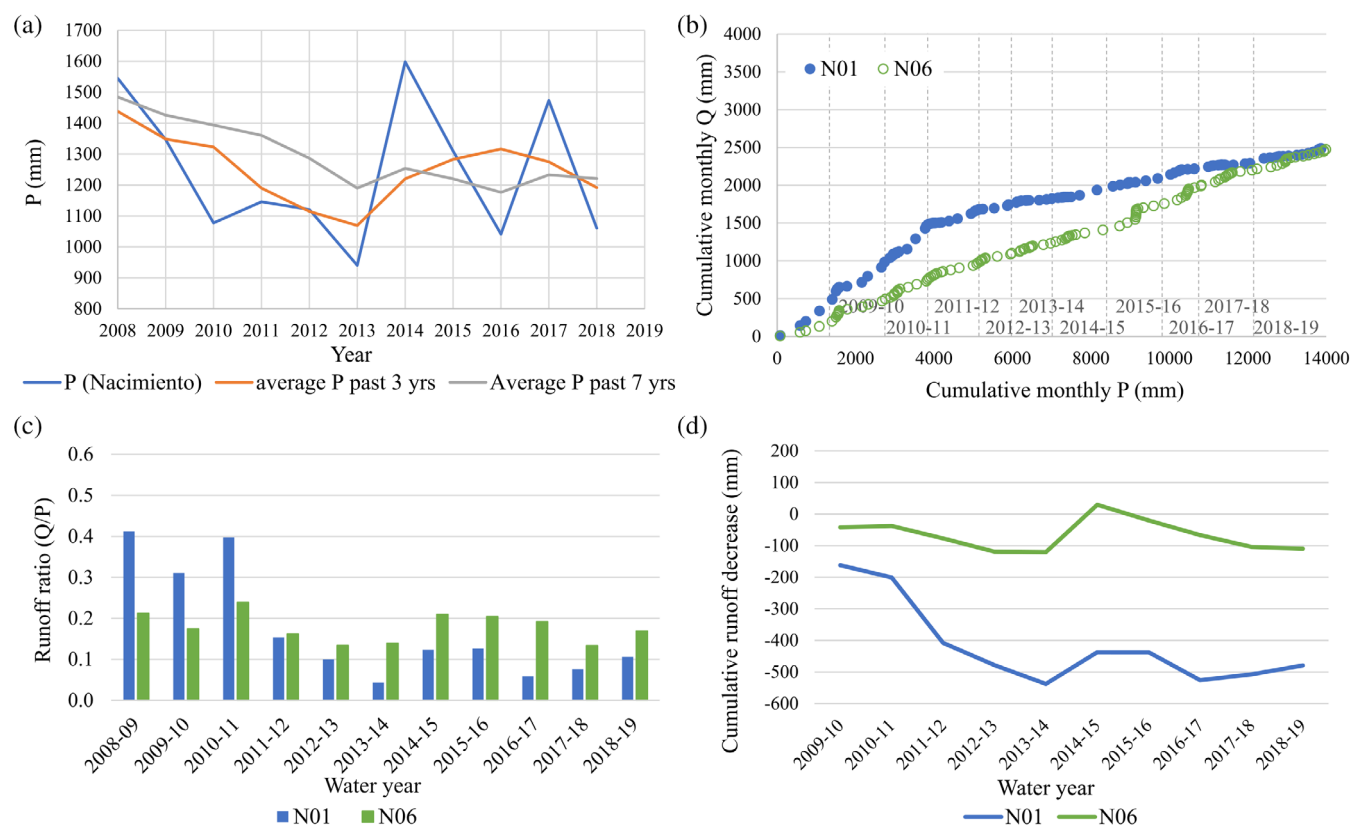


FIGURE 5 Effects of drought and aging past the rotation age of Radiata pine and Eucalyptus plantations (N01 and N06), see Table 2 for details. (a) Annual precipitation (P, mm) at Nacimientos, and 3- and 7-year running mean P; (b) double mass curves of cumulated monthly runoff (Q, mm) versus cumulative monthly P (mm), 2008–2019; (c) annual runoff ratios; (d) cumulative runoff decrease relative to 2008 based on models of Q versus P

(−110 mm) compared with the aging Radiata pine plantation (−479 mm, or ~40% of mean precipitation 2010–2019), relative to runoff in 2008–2009, despite similar cumulative runoff (~2500 mm; Figure 5(b),(d)).

4.1.2 | Thinned Radiata pine plantation (N02) versus unthinned Radiata pine plantation (N01)

We compared streamflow trends of a Radiata pine plantation that was thinned in 2009 (N02, basal area reduced by one-third) and an adjacent unthinned Radiata pine plantation (N01) as both plantations aged from 21 to 33 years (Figure 6). Both catchments have a native vegetation riparian buffer zone representing 7% of catchment area in N01, and 4% in N02 (Table 1). The average runoff ratios of the two catchments (2008–2009 to 2018–2019) did not differ: 0.17 (N01) and 0.18 (N02). Runoff ratios decreased in both catchments from 2010 to 2013 and increased in 2014–2017 following the 3-year running mean P (Figure 6 (a),(c)). The runoff ratio in N02 decreased (<0.25) after thinning of the Radiata pine plantation in 2009, compared with N01, the unthinned Radiata pine plantation (>0.3). However, starting in the second year of the drought (2011–2012), the runoff ratio in the thinned plantation (>0.11) exceeded that of the unthinned plantation (<0.11 in 5 of the 7 years, 2011–2012 to 2018–2019), and the gradients of both double-

mass curves declined. By 2018–2019, the cumulative deficits (~40% of mean annual precipitation 2010–2019) were slightly smaller in the thinned plantation (N02, −423 mm) than in the unthinned plantation (N01, −479 mm), relative to 2008–2009, and cumulative runoff over the period was similar (N01, 2488 mm; N02, 2562 mm; Figure 6(b),(d)).

4.1.3 | Replacement of Radiata pine with Eucalyptus (N03, N04) or rotation of Eucalyptus (N07)

Three catchments offer the opportunity to contrast the effects of 100% clearcutting of Radiata pine (N03, N04) versus Eucalyptus plantations (N07), and replacement with Eucalyptus (N03, N04, N07; Figure 7 and Table 2). In two catchments Radiata pine was harvested and replaced with Eucalyptus (N03, N04), and in one catchment Eucalyptus was harvested and replaced with Eucalyptus (N07; Table 1). All three catchments have a native vegetation riparian buffer zone representing 5%–13% of the catchment area (Table 1). The average runoff ratio (2008–2009 to 2018–2019) was higher in N03 and N04, the two catchments that were initially 22-year-old Radiata pine plantations (0.32 at N03 and 0.28 at N04) compared with N07 that was initially an 8-year-old Eucalyptus plantation (0.13; Figure 7(a),(c)). Runoff ratios in N03 and N04 increased from 0.24 and 0.36 prior to harvest of Radiata pine to >0.5 in

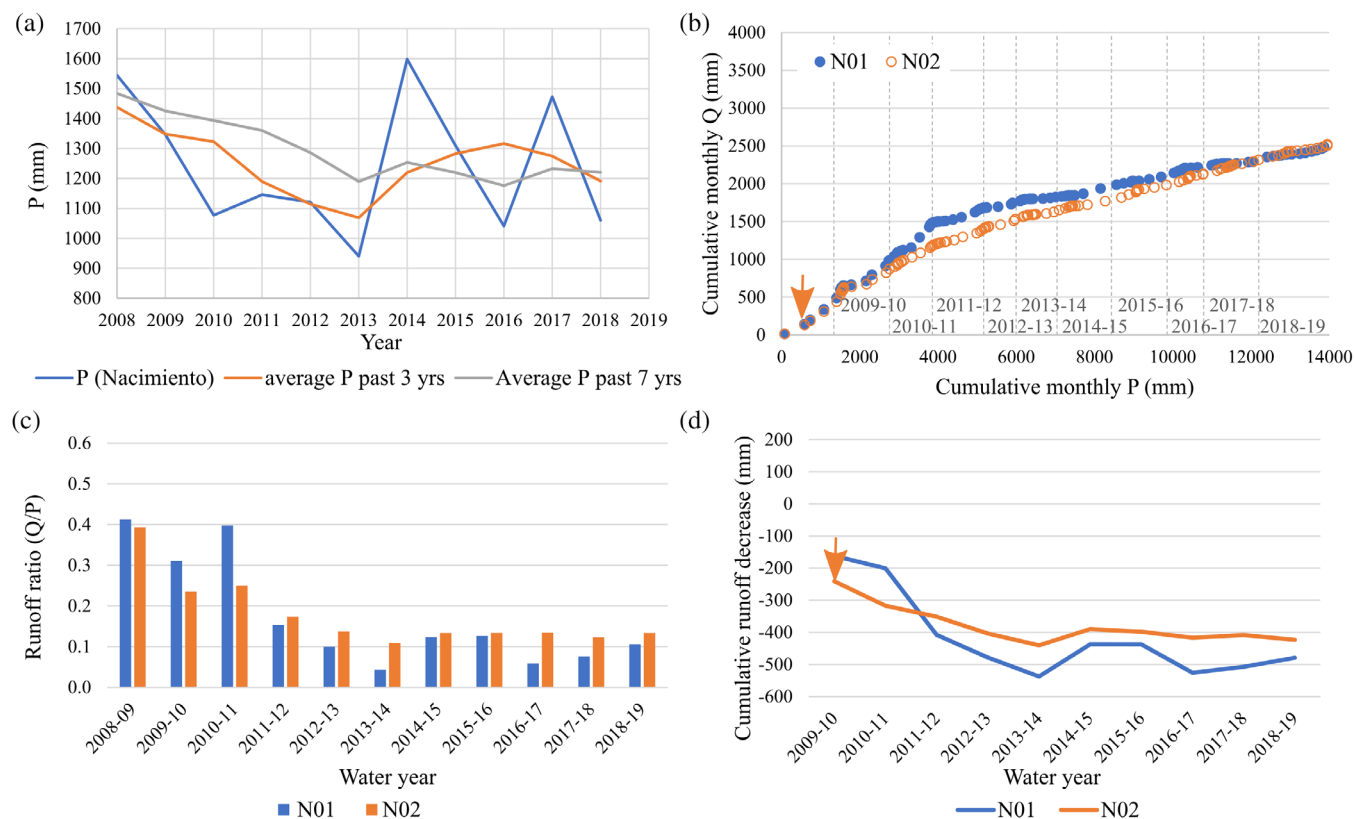


FIGURE 6 Effects of drought and thinning of aging Radiata pine plantations (N01 and N02), see Table 2 for details. (a) Annual precipitation (P, mm) at Nacimientos, and 3- and 7-year running mean P; (b) double mass curves of cumulated monthly runoff (Q, mm) versus cumulative monthly P (mm), 2008–2019; (c) annual runoff ratios; (d) cumulative runoff decrease relative to 2008 based on models of Q versus P. In panels (b)–(d), arrows indicate the timing of forest management events

the year after harvest; these runoff increases were approximately 150 mm or 10%–15% of mean annual precipitation. Runoff ratios decreased in N03 and N04 from 2010 to 2013 and increased slightly in 2014–2017, following the 3-year running mean P. The runoff ratio did not change after harvest of Eucalyptus in N07 (June/July 2011). Gradients of double-mass curves declined after 2001 in N03 and N04, but not at N07. By 2018–2019, these changes resulted in much larger cumulative deficits in the catchments converted from Radiata pine to Eucalyptus (–415 and –471 mm, equivalent to 35%–40% of mean annual precipitation 2010–2019) than in the catchment that was clearcut and replanted with Eucalyptus (–11 mm; Figure 7(d)). The catchments that were converted from Radiata pine had larger cumulative runoff (N03, 3041 mm, N04, 2580 mm) than N07, which had the lowest cumulative runoff of the 11 study catchments (1976 mm; Figure 7(b),(d)).

4.1.4 | Effects of herbicide-treatment, native forest regeneration, and Eucalyptus plantation growth and harvest (N05) versus aging of a Eucalyptus plantation (N06)

Catchment N05 offers the opportunity to assess the effects of full suppression of vegetation and subsequent regrowth, combined

with plantation growth, on streamflow (Table 2 and Figure 8). In N05, vegetation was controlled by herbicide in 2006–2007 in 38% of the area, followed by natural revegetation (native and exotic species) starting in 2008, while 42% of the catchment was initially a 2-year-old Eucalyptus plantation, which was clearcut in 2017 (Table 1). N05 was compared with the aging Eucalyptus plantation (N06). Both catchments had native riparian forest buffers (19% of N05, 14% of N06). The runoff ratio in N05 decreased from 0.86 in 2008–2009 to 0.05 in 2017–2018, with a sharp decline in the double-mass curve gradient in 2011 and increased slightly (to 0.10) after clearcutting of the Eucalyptus plantation (32% of area) in 2017 (Figure 8(b),(c)). Prior to the onset of the drought (2009), regeneration of unmanaged native and exotic vegetation (38% of area) combined with Eucalyptus plantation growth (42% of area) in N05 had produced a cumulative deficit of –532 mm. During the drought, this deficit reached a maximum of –1127 mm in 2017–2018 relative to 2008, which is 87% of mean annual precipitation 2010–2019. In contrast, aging of a Eucalyptus plantation past its rotation age (from 8 to 20 years) in N06 led to a much smaller cumulative water deficit (–110 mm) by 2019. The cumulative runoff (2008–2019) was much higher in the partially herbicide-treated catchment (3407 mm, N05) than in the aging Eucalyptus plantation (2516 mm, N06; Figure 8(b),(d)).

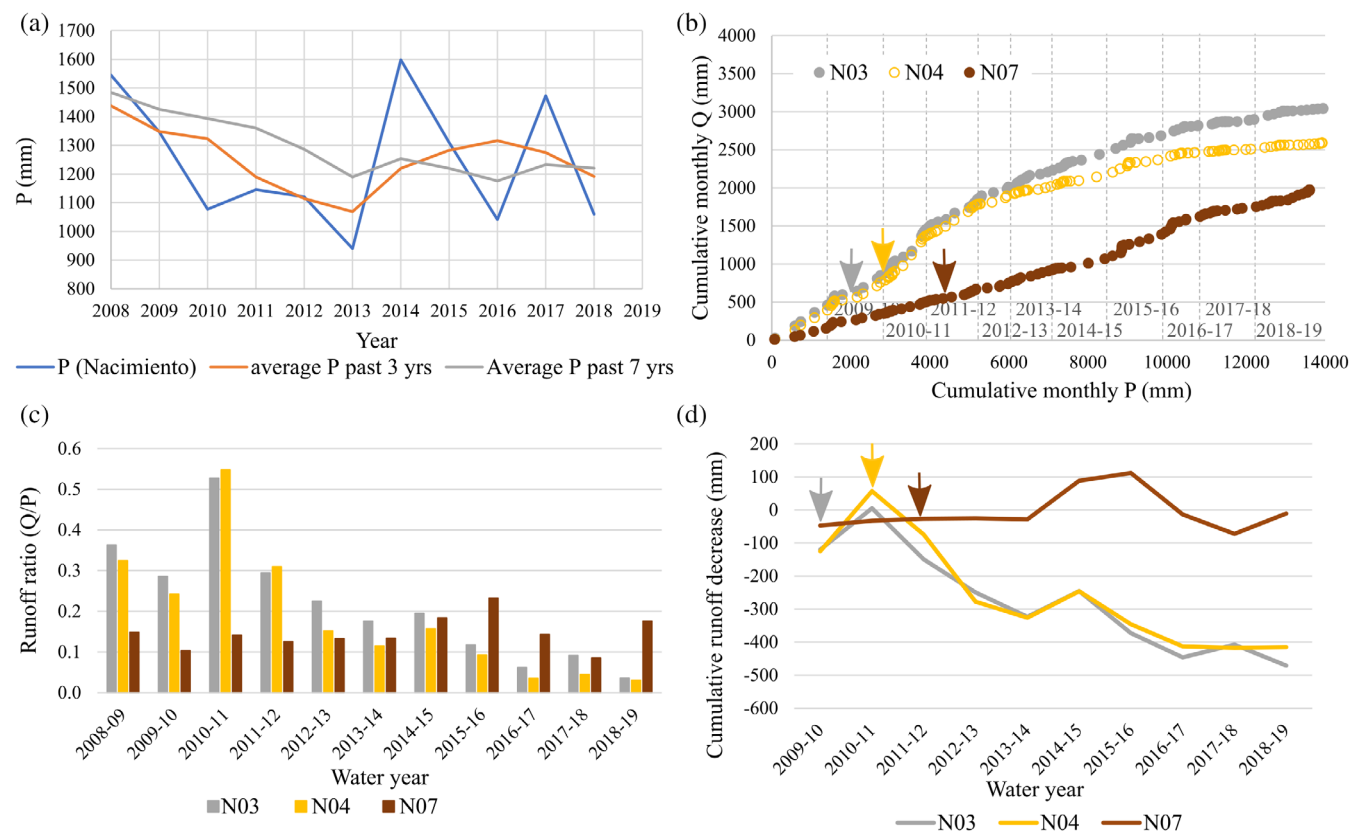


FIGURE 7 Effects of drought and clearcutting of Radiata pine and Eucalyptus plantations and replanting with Eucalyptus (N03, N04 and N07), see Table 2 for details. (a) Annual precipitation (P, mm) at Nacimiento, and 3- and 7-year running mean P; (b) double mass curves of cumulated monthly runoff (Q, mm) versus cumulative monthly P (mm), 2008–2019; (c) annual runoff ratios; (d) cumulative runoff decrease relative to 2008 based on models of Q versus P. In panels (b)–(d), arrows indicate the timing of forest management events

4.2 | Partial harvest treatments in medium catchments (41–414 ha)

4.2.1 | Aging Eucalyptus plantation (N06) nested within partial Eucalyptus harvest (N08)

Catchments N06 and N08 offer the opportunity to examine the effect of an aging Eucalyptus plantation (N06) nested within a larger catchment (N08), of which all the remaining area was partially harvested, and Radiata pine plantations were converted to *Eucalyptus* (Table 2 and Figure 9). In N08, part of the area (~14 ha) was a Radiata pine plantation, harvested in 2010–2011 and planted with Eucalyptus in 2011–2012, and part (~11 ha) was a Eucalyptus plantation harvested in 2011–2012; both were replanted with Eucalyptus in 2013. Both catchments have a native vegetation riparian buffer zone representing 14% of the nested catchment (N06) and 15% of the larger catchment (N08; Table 1). The average runoff ratio (2008–2009 to 2018–2019) was the same in both catchments (0.18; Figure 9(a),(c)). Runoff ratios were similar between the two catchments and ranged from 0.17 to 0.25 prior to the drought or harvest (2008–2011), with little change in the double mass curve gradient after 2011 (Figure 9(b)). After harvest and the onset of the drought (2011–2019), runoff ratios ranged from 0.13 to 0.21 and varied with the 3-year running mean P. These

changes resulted in similar cumulative deficits in the catchment with partial harvest and replanting (N08, –94 mm) and the nested catchment with the aging Eucalyptus plantation (N06, –110 mm), relative to 2008–2009, as well as similar cumulative runoff (N08, 2579 mm, N06, 2516 mm; Figure 9(b),(d)).

4.2.2 | Partial harvest of Radiata pine plantation and conversion to Eucalyptus in two nested catchments with wide riparian buffers (N10, N09)

Catchments N10 and N09 offer the opportunity to examine the effect of partial harvests, in two nested catchments with large riparian buffers (Table 2 and Figure 10). Harvests were primarily of plantations of Radiata pine: 19% of the area was harvested in N10, the nested catchment, and 29% of the area was harvested in N09; all harvests occurred over multiple years (2009–2012) with subsequent replanting with Eucalyptus. The remaining area of both catchments (26%) was in aging Eucalyptus plantations (Table 1). Both catchments have a native vegetation riparian buffer zone representing 50% of the nested catchment (N10) and 42% of the larger catchment (N09; Table 1). The average runoff ratio (2008–2019) was slightly lower in the nested catchment (N10, 0.25) compared with the larger catchment (N09, 0.33; Figure 10(a),(c)). Except for the most recent

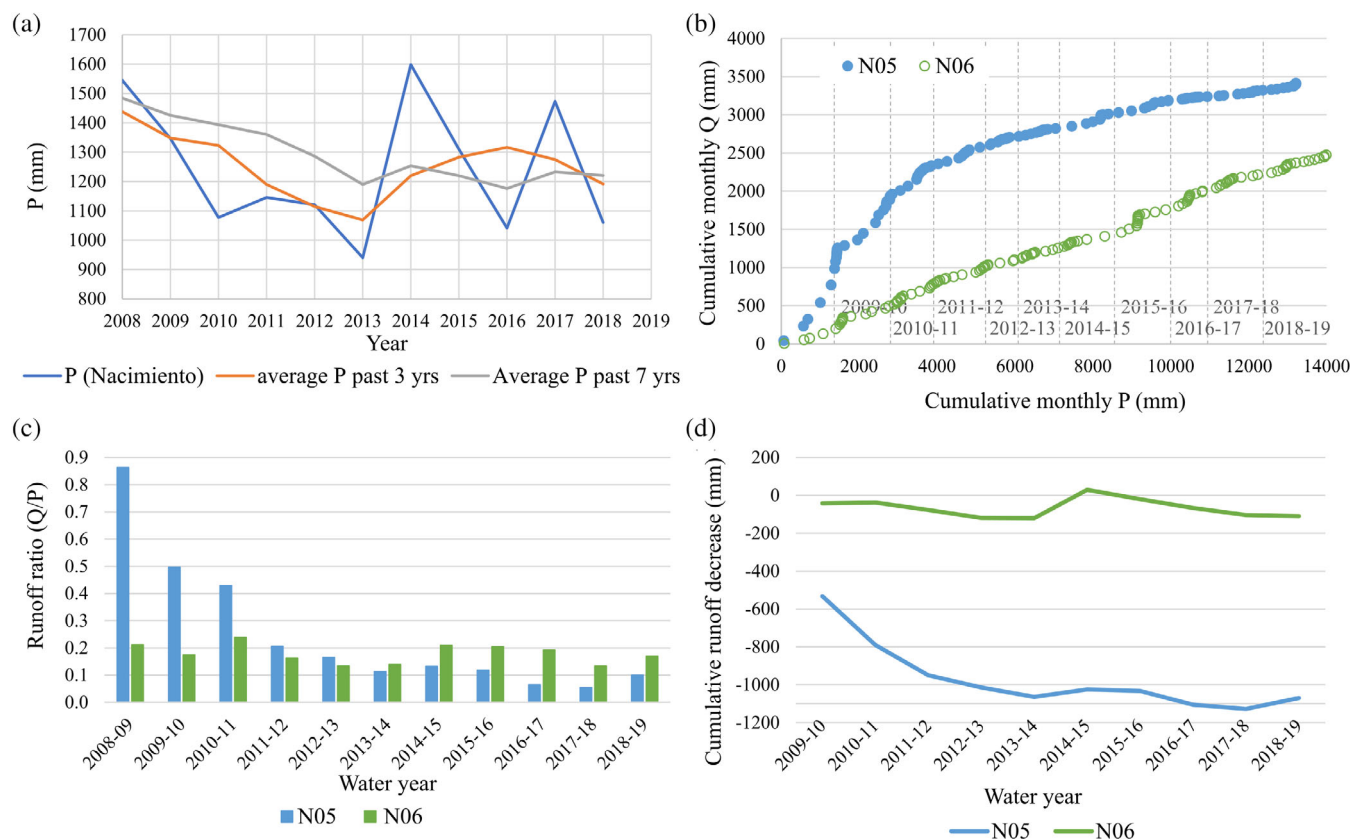


FIGURE 8 Effects of drought and natural regeneration plus Eucalyptus plantation growth (N05) versus aging Eucalyptus plantation (N06), see Table 2 for details. (a) Annual precipitation (P, mm) at Nacimientos, and 3- and 7-year running mean P; (b) double mass curves of cumulated monthly runoff (Q, mm) versus cumulated monthly P (mm), 2008–2019; (c) annual runoff ratios; (d) cumulative runoff decrease relative to 2008 based on models of Q versus P

year of the study (2018–2019) the runoff ratio remained slightly higher in the larger catchment (N09) than the nested catchment (N10), before and after the clearcutting and throughout the drought, with little change in the gradient of the double-mass curve (Figure 10(b)). These changes resulted in a larger cumulative runoff decrease in the larger catchment (N09, –540 mm) compared with the nested catchment (N10, –284 mm), relative to 2008–2009, and relatively high cumulative runoff, especially in the larger catchment (N09, 4469 mm, N10, 3289 mm; Figure 10(b),(d)).

4.2.3 | Varying riparian buffer widths with partial clearcutting and replacement of Radiata pine by Eucalyptus (N08 vs. N10)

Catchments N10 and N08 offer the opportunity to contrast the effects on streamflow of partial harvests and replacement of Radiata pine by Eucalyptus, in catchments with wide (N10) and narrow (N08) native forest riparian buffers (Table 2 and Figure 11). In catchment N08, 25% of area in Radiata pine and 21% of area in Eucalyptus were clearcut in 2010–2011 and replanted with Eucalyptus. In N10, 15% of area in Radiata pine and 4% of area in Eucalyptus was clearcut in 2010–2012. All areas were replanted with Eucalyptus. The native forest riparian buffer

is 15% of catchment area in N08 and 50% in N10 (Table 1). The average runoff ratio (2008–2019) was higher in the catchment with the larger riparian buffer (N10, 0.25) compared with the catchment with the smaller riparian buffer (N08, 0.18). Runoff ratios were higher in the catchment with the larger riparian buffer (N10) before the drought, after clearcutting, and throughout the drought. Runoff ratios increased slightly after harvest in the catchment with the larger riparian buffer (N10), but also decreased more over time after conversion of Radiata pine plantations to Eucalyptus, with little change in the gradient of the double mass curves (Figure 11(b)). These changes resulted in a larger cumulative runoff decrease in the catchment with the larger riparian buffer (N10, –284 mm) compared with the catchment with the smaller riparian buffer (N08, –94 mm) and higher cumulative runoff at the catchment with the larger riparian buffer (N10, 3329 mm) than the catchment with the smaller riparian buffer (N08, 2579 mm; Figure 11(b),(d)).

4.2.4 | Partial harvests in large versus small catchments

Catchment N11 offers the opportunity to contrast streamflow response in a large catchment with plantations of Radiata pine and Eucalyptus

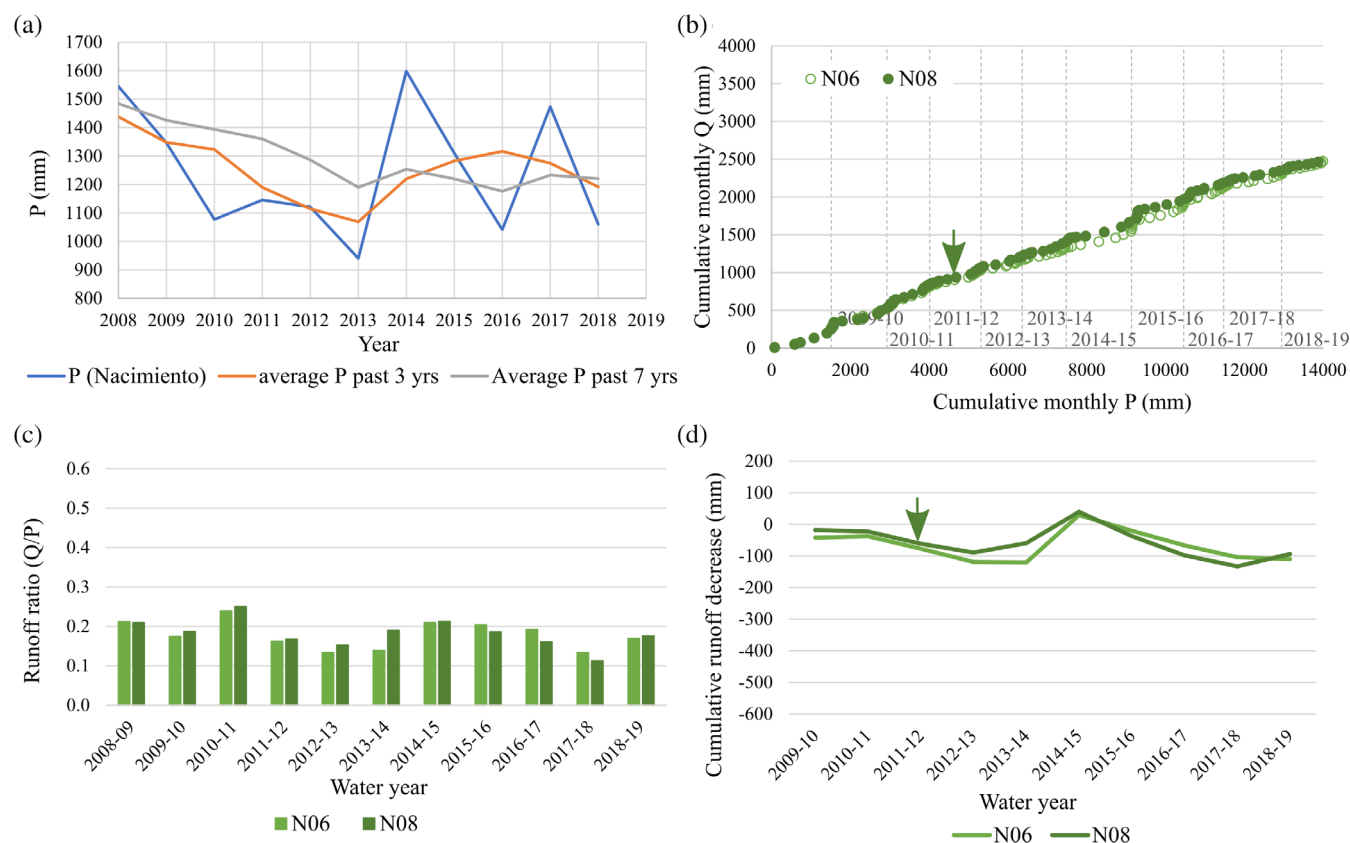


FIGURE 9 Effect of conversion of 25% of catchment area of larger (N08, 55-ha) catchment from Radiata pine and harvest and replanting of Eucalyptus, compared to aging Eucalyptus plantation in upper (nested) portion of the catchment (N06), see Table 2 for details. (a) Annual precipitation (P, mm) at Nacimiento, and 3- and 7-year running mean P; (b) double mass curves of cumulated monthly runoff (Q, mm) versus cumulative monthly P (mm), 2008–2019; (c) annual runoff ratios; (d) cumulative runoff decrease relative to 2008 based on models of Q versus P. In panels (b)–(d), arrows indicate the timing of forest management events

under a system of mosaic forest management with continuous small cuts and replanting of Eucalyptus, versus three small catchments with aging plantations of Radiata pine (N01), aging plantations of Eucalyptus (N06), and harvest of Radiata pine and conversion to Eucalyptus (N03; Table 2 and Figure 12). The average runoff ratio (2009–2019) was slightly higher at the large catchment (N11, 0.25) compared with the smaller catchments (N01, 0.17; N03, 0.22; N06, 0.18). Runoff ratios in N11, N01, and N03 decreased over time, following the 3-year running mean P, with reductions in the gradient of the double-mass curve after 2011 (Figure 12(a)–(c)). The large catchment had the highest runoff ratio of all four catchments in the first year of the study (2008–2009, 0.51) and the last 4 years (2016–2019, 0.14–0.27). Cumulative deficits were similar for the largest catchment (N11, –434 mm), the small catchment with aging Radiata pine (N01, –479 mm) and the small catchment converted from Radiata pine to Eucalyptus (N03, –471 mm), and greater than in the catchment with an aging Eucalyptus plantation (N06, –110 mm). The largest catchment had the largest cumulative runoff of these four catchments over the study period (N11, 3368 mm; Figure 12(b),(d)).

The findings presented above are consistent with output from a simple water-balance model that represents long-term lagged responses of streamflow to increased evapotranspiration associated with plantation establishment, followed by a drought (Figure 13). In Period 1, the

groundwater reservoir receives more than it contributes to streamflow in each year, so the groundwater reservoir grows over time. Streamflow is constant in each time step, with a runoff ratio of about 0.32. In Period 2 (years 11–20), ET increases to 1000 mm to simulate establishment of a plantation or shift from Radiata pine to Eucalyptus. The increase in ET immediately reduces streamflow, and the runoff ratio declines to 0.25. Also, because the sum of ET and soil moisture recharge is now >1000 mm, the contribution to deep soil or groundwater ('to G') ceases, and the groundwater reservoir (G) continues to contribute to streamflow ('from G') until it is exhausted by the end of Period 2. In Period 3 (years 21–30), the loss of contributions from deep soil/groundwater ('from G') to streamflow causes streamflow to decrease further, and the runoff ratio falls to 0.21. In Period 4 (years 31–40), a simulated drought reduces precipitation from 1400 to 1200 mm and this decrease, combined with the lack of inputs from the groundwater reservoir, causes streamflow to decline further, and the runoff ratio falls to 0.08.

5 | DISCUSSION

In this study, vegetation changed in all catchments during the period of study, so no reference catchment was available. Runoff also

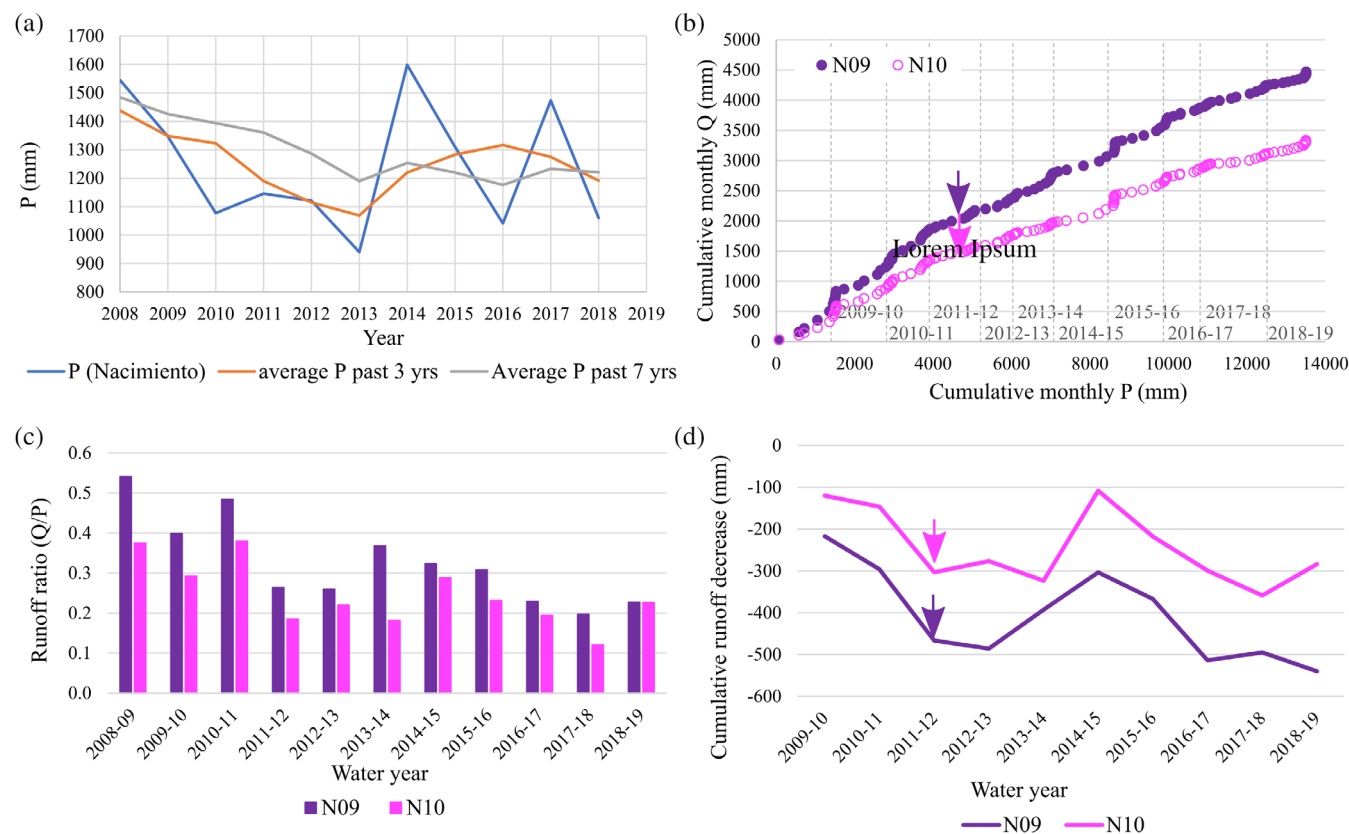


FIGURE 10 Effect of conversion of Radiata pine to Eucalyptus in nested catchments with large riparian buffers (N10, N09), see Table 2 for details. (a) Annual precipitation (P, mm) at Nacimiento, and 3- and 7-year running mean P; (b) double mass curves of cumulated monthly runoff (Q, mm) versus cumulated monthly P (mm), 2008–2019; (c) annual runoff ratios; (d) cumulative runoff decrease relative to 2008 based on models of Q versus P. In panels (b)–(d), arrows indicate the timing of forest management events

changed over time in catchments N01 and N06, despite no change in forest cover area (Figure 5). These two catchments are among those scheduled for a new series of forest operations in the coming years. The anticipated forestry treatments in these catchments underscore the value of estimating streamflow changes using precipitation as the reference, as was done in this study. This approach also may be useful in other similar studies lacking reference catchments or pre-treatment calibration periods.

Multiple decades of afforestation and short-rotation forestry in a Mediterranean climate reduced streamflow over the long term, while drought and shifts from pine to Eucalyptus further reduced streamflow, providing insights into forest hydrology. The study area has faced an uninterrupted sequence of dry years since 2010. The so-called Mega Drought with mean rainfall deficits of 20%–40% affecting Central Chile is unprecedented in recent history, for its longevity and spatial extent (Garreaud et al., 2020). This drought, which has persisted through 2020 (one of the four driest years of the decade), is perhaps a presage the dry conditions projected for this region during the rest of the 21st century (Garreaud et al., 2020). Many studies have linked the drought and plantation forestry to reduced streamflow (Alvarez-Garretón et al., 2019; Iroumé et al., 2006; Iroumé & Palacios, 2013; Little et al., 2009, 2015). However, to our knowledge, this is the first published study of long-term effects of plantation

forestry and drought on streamflow from land managed for commercial plantations by a private company in Chile. The 2.3 million hectares of land managed for commercial plantations in Chile accounts for ~14% of the total forest area and generates >95% of forest sector revenues (INFOR, 2020).

5.1 | Streamflow, forest management, and drought

Collectively these results imply that runoff in these catchments depends on recharge of deep soil moisture reservoirs, which in turn depends on an excess of precipitation over evapotranspiration. The simulation model (Figure 13) demonstrates how deep soil water may have accumulated over the decades prior to the establishment of plantations and prior to the drought, and how these reservoirs were cumulative depleted by the combination of intensive plantation management and drought. Plantation establishment apparently increased evapotranspiration and reduced or eliminated recharge of deep soil moisture reservoirs, especially under Eucalyptus plantations, leading to reductions in runoff. During the drought (2010 onward), the reduction of precipitation further reduced recharge of deep soil moisture and reduced deep soil moisture contributions exacerbated declines in runoff through 2019.

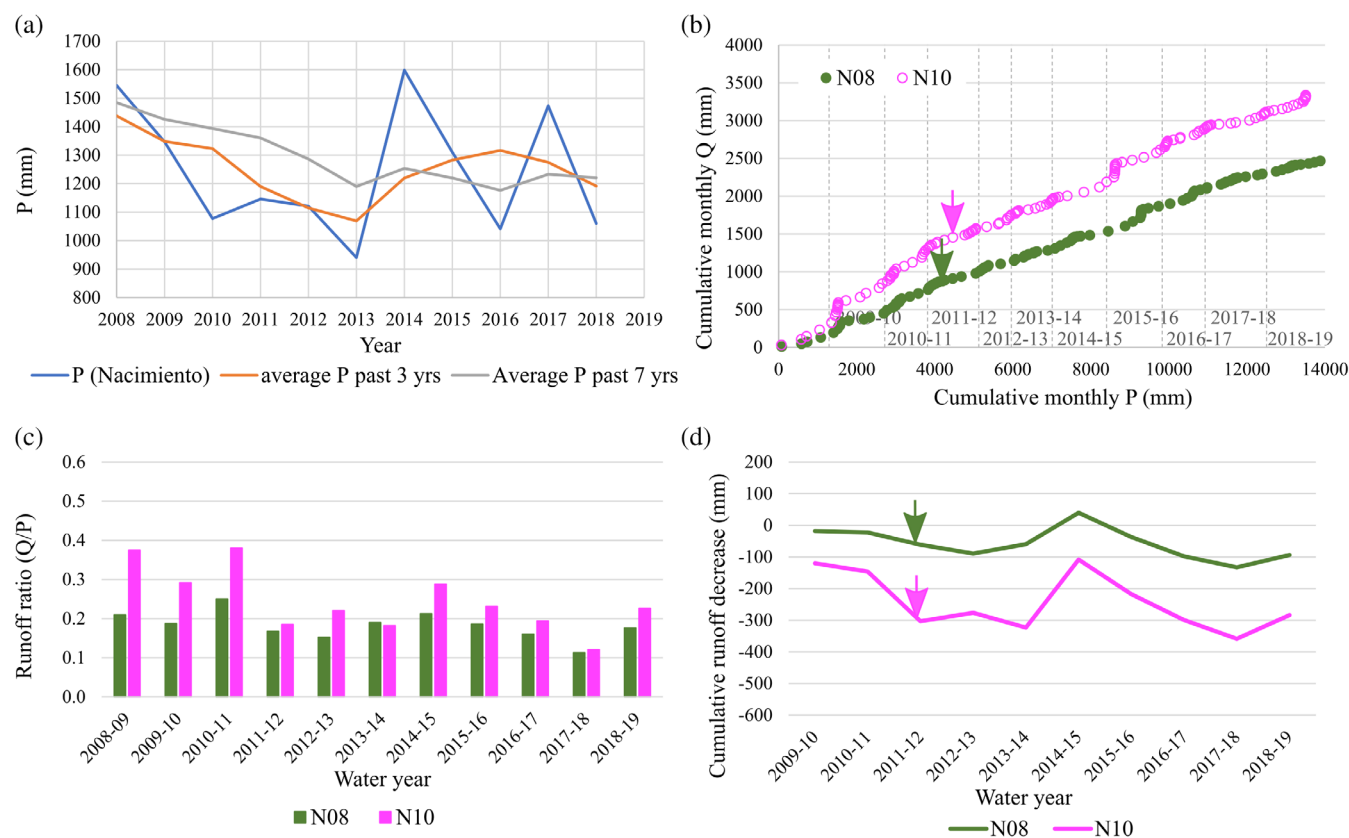


FIGURE 11 Effect of different riparian buffer areas with partial clearcutting and replacement of Radiata pine with Eucalyptus (N08 and N10), see Table 2 for details. (a) Annual precipitation (P, mm) at Nacimiento, and 3- and 7-year running mean P; (b) double mass curves of cumulated monthly runoff (Q, mm) versus cumulated monthly P (mm), 2008–2019; (c) annual runoff ratios; (d) cumulative runoff decrease relative to 2008 based on models of Q versus P. In panels (b)–(d), arrows indicate the timing of forest management events

In most cases in this study, long-term reductions in runoff appeared to be the result of the combined effects of drought and water use by aging plantations and replacement of Radiata pine with Eucalyptus. This interaction is evident from the sharp reduction in gradient of the double mass curves coinciding with the onset of the drought in early 2011 in N01, N03, N04, N05, N06, and N11 (Figures 5, 7, 8, and 12). The mechanisms producing this transition were simulated by the water balance model (Figure 13). Multiple lines of evidence indicate that a sustained reduction in rainfall (Figure 2), combined with increased evapotranspiration from plantations, precluded the recharge of deep soil reservoirs. Evidence includes (1) earlier soil moisture depletion and delayed soil moisture recharge under Eucalyptus plantations compared to the aging Radiata pine plantation (Figure 4(a)), (2) year-round reduced soil moisture under a 3-year-old Eucalyptus plantation compared to an aging Radiata pine plantation (Figure 4(b)), (3) increasing frequency of zero-flow days starting in 2014 in <15-ha catchments (i.e., N01, N02 and N03), (4) smaller runoff reductions in catchments that had been in Eucalyptus plantations since 2000, that is, N06 (Figure 8), and (5) the lack of increase in runoff after clearcutting of a Eucalyptus plantation in N07 (Figure 7). These findings are consistent with documented streamflow reductions under plantations of Eucalyptus in zones with high aridity indices (Ferraz et al., 2019), and they imply that storage of deep soil water is

an important determinant of catchment resilience under climate change (Tague et al., 2008; Vose et al., 2016).

Even after 45–47 years of Radiata pine plantations, higher runoff ratios of the Radiata pine plantations compared with the Eucalyptus plantations at the beginning of this study (2008) indicate that under normal precipitation at this site, Radiata pine plantations permit some recharge of deep soil water, but Eucalyptus plantation growth appeared to prevent deep soil moisture recharge. Converting Radiata pine plantations to Eucalyptus plantations led to long-term decreases in runoff. This fact suggests that water use by Radiata pine is lower than that of Eucalyptus, consistent with many published studies (Huber et al., 2010; Scott, 2005; Scott & Prinsloo, 2008).

Unlike many prior studies, clearcutting did not produce consistent or large increases in streamflow in this study. The small runoff increases in the first year after clearcutting of Radiata pine are at the lower end of responses reported from experiments around the world (Bosch & Hewlett, 1982; Brown et al., 2005; Sahin & Hall, 1996) and are of the same order of magnitude as interception losses measured in the Radiata forests in the study site (Huber et al., 2010). Moreover, rather than increasing streamflow, instead the reduction in evapotranspiration after clearcutting of Eucalyptus apparently recharged depleted soil moisture reservoirs. In a few cases, long-term reductions in streamflow observed in this study appeared to be the result of

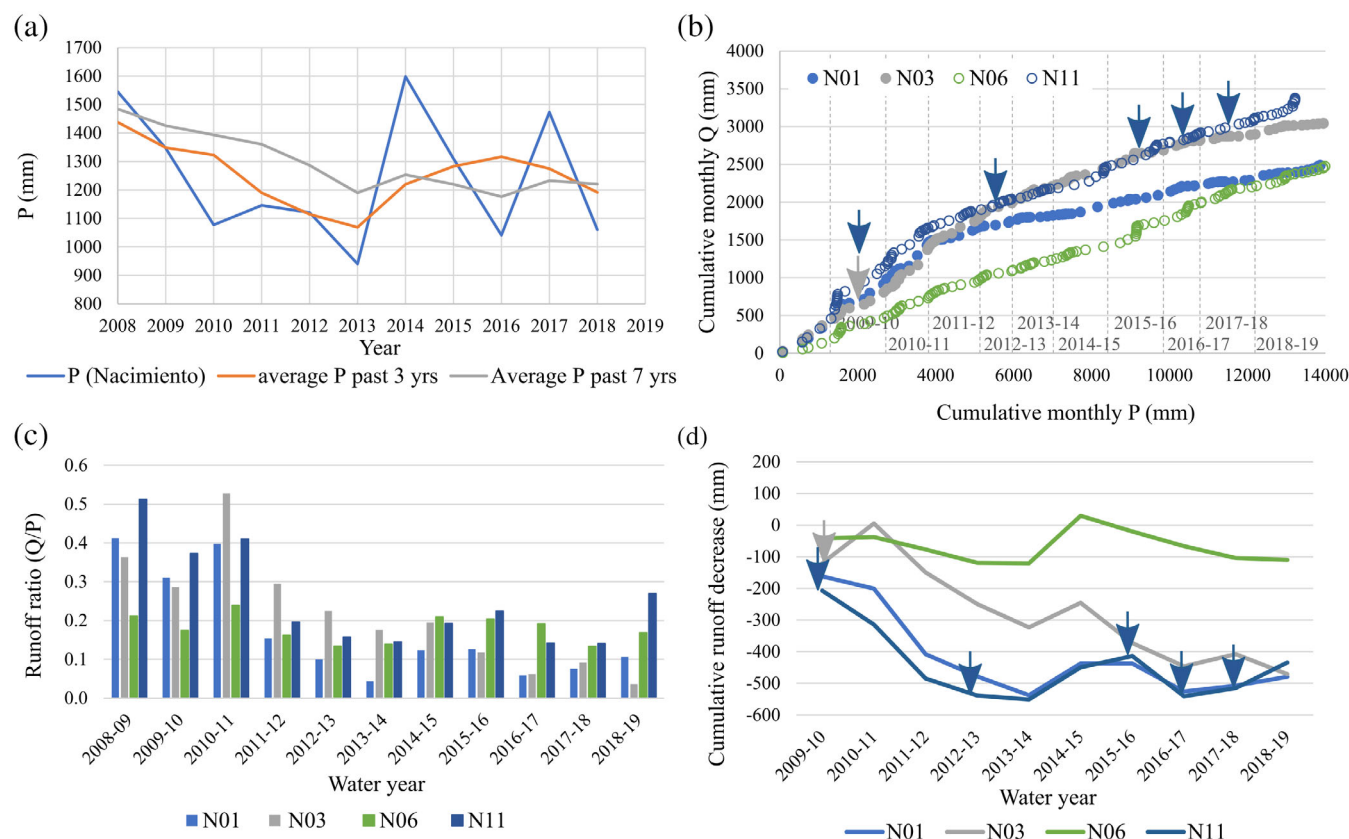


FIGURE 12 Effect of aging Eucalyptus and Radiata pine in large catchment (N11) and aging Radiata pine in small catchment (N01), aging Eucalyptus in small catchment (N06), and conversion of Radiata pine to Eucalyptus in small catchment (N03), see Table 2 for details. (a) Annual precipitation (P, mm) at Nacimientos, and 3- and 7-year running mean P; (b) double mass curves of cumulated monthly runoff (Q, mm) versus cumulative monthly P (mm), 2008–2019; (c) annual runoff ratios; (d) cumulative runoff decrease relative to 2008 based on models of Q versus P. In panels (b)–(d), arrows indicate the timing of forest management events

forest regrowth. These findings are consistent with many studies documenting streamflow response to a change in evapotranspiration and a change in forest cover (Andréassian, 2004; Bosch & Hewlett, 1982; Brown et al., 2005; Sahin & Hall, 1996). Limiting the area that is planted within a catchment (as in N05 at the beginning of the study) might be a forest management option to reduce water consumption (Ferraz et al., 2013; Lima et al., 2012).

The reduction of runoff after thinning of the aging Radiata pine plantation in N02 (Figure 6) was counter to expectations. Evapotranspiration is related to leaf area (Gholz & Clark, 2002; Sun, Alstad, et al., 2011; Sun, Caldwell, et al., 2011), so the reduction in leaf area after thinning would be expected to reduce evapotranspiration and increase water yield. Most studies report that runoff increases after thinning (Andréassian, 2004; Brown et al., 2005; Buttle et al., 2019; Douglass, 1983; Grant et al., 2013; Hawthorne et al., 2013; Lane & Mackay, 2001; Sun et al., 2015), although the increases may last only a few years (Perry & Jones, 2017). However, forest thinning also reduces competition for resources (McLaughlin et al., 2013), and increased light, water, and nutrients may increase transpiration (Bladon et al., 2006; Boggs et al., 2015; Hernandez-Santana et al., 2012) and release understory shrubs and trees (Ares et al., 2010; Tsai et al., 2018), potentially explaining the initial reduction in runoff. The reduction in runoff after thinning in N02 is consistent

with reported reductions in streamflow after drought and insect outbreak-induced tree mortality in arid and semi-arid areas (Goeking & Tarboton, 2020; Guardiola-Claramonte et al., 2011). The effect of thinning of *P. radiata* stands may depend on stand age (Lesch & Scott, 1997). Despite initial reductions in streamflow, the thinned plantation in N02 appeared to be better able to limit evapotranspiration in response to the drought several years after thinning, leading to slightly lower runoff reductions than in the unthinned stand (N01). This finding suggests that thinned plantations of Radiata pine may be more resistant to drought than unthinned plantations. Catchment size, partial harvest, and the width of the riparian zone had interacting effects on streamflow response to the drought. The slightly higher runoff ratios in relatively large catchments suggest that deep subsurface contributions increase with increasing drainage area (Shanley et al., 2002). However, paired comparisons of nested catchments did not reveal a consistent effect of catchment size on long-term responses. The lack of a catchment size effect on streamflow in the catchments with narrow riparian buffers 14%–15% of area, (N06 vs. N08, Figure 8) may be attributable to the onset of the drought (Andréassian, 2004) and immediate reforestation with Eucalyptus. The greater cumulative runoff decline in the larger catchment of the pair with wide riparian buffers (42%–50% of area, N10 vs. N09,

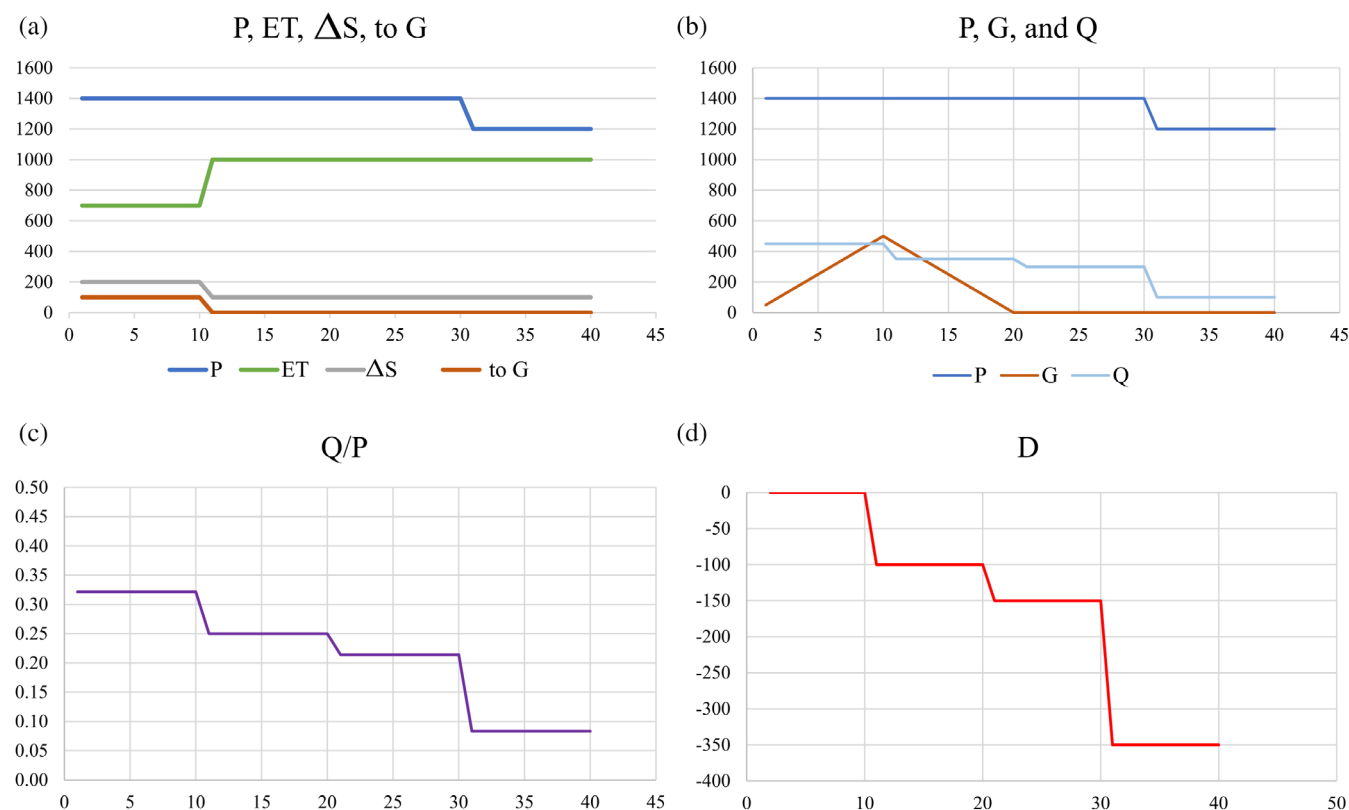


FIGURE 13 A simple mass balance model demonstrates the accumulated effects of intensive plantation establishment and drought on streamflow over a 40-time step simulation. (a) Simulated precipitation (P), evapotranspiration (ET), shallow soil moisture (ΔS), and contributions to deep soil moisture (to G); (b) P, groundwater storage (G), and streamflow (Q); (c) runoff ratio (Q/P); (d) cumulative runoff reduction

Figure 9) may be attributable to the accumulated effects of plantation forestry reducing deep subsurface contributions to streamflow.

The system of mosaic management in the largest catchment (414 ha) rather than its size seems to explain its contrasting streamflow response relative to smaller catchments (7.7–21.1 ha). The largest catchment has plantations of Radiata pine and Eucalyptus managed in a system of mosaics with small cuts and replanting (always with Eucalyptus) throughout the entire study period, while the smaller have been managed with even-aged plantations. A system of mosaic management might help to stabilize water flow across plantation landscapes (Ferraz et al., 2013). Wider riparian buffers were associated with higher runoff ratios. Average runoff ratios for the period 2008–2009 to 2018–2019 were 18% for catchments with narrow buffers and 25%–33% for catchments with wider native vegetation riparian buffer zones (Figures 9–11). The higher runoff ratios in catchments with larger riparian buffers suggest that the native vegetation in the riparian buffers has a lower rate of evapotranspiration which permits greater runoff, as suggested by Lima et al. (2012), Ferraz et al. (2013) and Little et al. (2015).

5.2 | Implications for forestry

The steep and prolonged reductions in runoff associated with the combination of plantation forestry and a severe, persistent drought

raise important questions about how forest plantations can be managed to produce acceptable tradeoffs between wood production and provision of water when climate variability and forest growth interact to reduce streamflow (Burt et al., 2015).

Selection of plantation species may affect streamflow in plantation landscapes. Our results indicate that under normal precipitation at this Nacimiento site, Radiata pine plantations permit some recharge of deep soil water, whereas Eucalyptus plantation growth appeared to prevent deep soil moisture recharge. However, after a 20% reduction in precipitation there was little difference in runoff between covers of Radiata pine and Eucalyptus (Figure 5). A <15% reduction in precipitation, combined with reforestation with Eucalyptus, led to dramatic streamflow declines in Australia (Liu et al., 2019). The low runoff ratios under both Radiata pine and Eucalyptus during drought at Nacimiento indicate that vegetation management, rather than species selection, is necessary to mitigate declining streamflow (Ferraz et al., 2019; Liu et al., 2019; Vose et al., 2016).

Techniques of forest management that have been proposed to limit water yield reductions in plantation landscapes include reductions in tree density (thinning), changes in plantation extent and/or the area devoted to native forest riparian buffers, and a mosaic management system. In this study, reduction of tree density (thinning) did not lead to the expected increase in runoff, although runoff remained higher in the thinned plantation during the drought. An alternative to

thinning could involve setting aside saturated areas of a catchment to promote water conservation (Lima et al., 2012), or increasing the riparian buffer area (Ferraz et al., 2013; Little et al., 2015). Removal of invasive exotic trees (i.e., *P. radiata* and *Eucalyptus spp.*) is necessary to achieve the water conservation benefits of native forest riparian buffers (Huddle et al., 2011). Both approaches would reduce the planted area in a catchment, but they could permit both increased water yield and plantation management to generate commercially viable pulp and timber products.

6 | CONCLUSION

Results of this 11-year study of short-rotation forest plantations managed by a private forestry corporation in south-central Chile reveal the interacting, multi-decadal effects of forest plantations and a severe drought, which have reduced streamflow by 30 to as much as 80% of precipitation in some experimental catchments. Results indicate that both plantations and the drought reduced or eliminated recharge of deep soil moisture reservoirs, eventually reducing streamflow, and revealing a potential threshold condition that is likely to be crossed more frequently under a projected future drier climate. Differential responses of streamflow to varied planted species, forestry treatments, and riparian buffer width indicate that modified forestry practices including wider riparian buffers, removal of exotic trees from riparian buffers, and reduced planted area may achieve water saving benefits. Continued, long-term, place-based research and collaboration are necessary to adapt industrial forestry operations to climate change.

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CONFLICT OF INTEREST

The authors declare no conflicts of interest.

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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REFERENCES

- Adhikary, S. K., Yilmaz, A. G., & Muttill, N. (2015). Optimal design of rain-gauge network in the Middle Yarra River catchment, Australia. *Hydrological Processes*, 29(11), 2582–2599. <https://doi.org/10.1002/hyp.10389>
- Adhikary, S. K., Muttill, N., & Yilmaz, A. G. (2017). Cokriging for enhanced spatial interpolation of rainfall in two Australian catchments. *Hydrological Processes*, 31(12), 2143–2161. <https://doi.org/10.1002/hyp.11163C>
- Alila, Y., Kuras, P. K., Schnorbus, M., & Hudson, R. (2009). Forests and floods: A new paradigm sheds light on age-old controversies. *Water Resources Research*, 45. <https://doi.org/10.1029/2008WR007207>
- Almeida, A., Soares, J., Landsberg, J., & Rezende, G. (2007). Growth and water balance of *Eucalyptus grandis* hybrid plantations in Brazil during a rotation for pulp production. *Forest Ecology and Management*, 251, 10–21.
- Alvarez-Garretón, C., Lara, A., Boisier, J. P., & Galleguillos, M. (2019). The impacts of native forests and Forest plantations on water supply in Chile. *Forests*, 10(6), 473. <https://doi.org/10.3390/f10060473>
- Andréassian, V. (2004). Water and forests: From historical controversy to scientific debate. *Journal of Hydrology*, 291, 1–27.
- Ares, A., Neill, A. R., & Puettmann, K. J. (2010). Understory abundance, species diversity and functional attribute response to thinning in coniferous stands. *Forest Ecology and Management*, 260, 1104–1113.
- Best, A., Zhang, L., McMahon, T., Western, A., & Vertessy, R. (2003). A critical review of paired watershed studies with reference to seasonal flows and climatic variability. CSIRO Land and Water Technical Report 25/03. Murray-Darling Basin Commission, Canberra.
- Bladon, K. D., Silins, U., Landhäuser, S. M., & Lieffers, V. J. (2006). Differential transpiration by three boreal tree species in response to increased evaporative demand after variable retention harvesting. *Agricultural and Forest Meteorology*, 138, 104–119. <https://doi.org/10.1016/j.agrformet.2006.03.015>
- Boggs, J., Sun, G., Domec, J. C., McNulty, S., & Treasure, E. (2015). Clearcutting upland forest alters transpiration of residual trees in the riparian buffer zone. *Hydrological Processes*, 29(24), 4979–4992.
- Bosch, J. M., & Hewlett, J. D. (1982). A review of watershed experiments to determine the effect of vegetation changes on water yield and evapotranspiration. *Journal of Hydrology*, 55, 3–23.
- Bouchard, M., Aquilué, N., Périé, C., & Lambert, M. C. (2019). Tree species persistence under warming conditions: A key driver of forest response to climate change. *Forest Ecology and Management*, 442, 96–104.
- Brown, A. E., Zhang, L., McMahon, T. A., Western, A. W., & Vertessy, R. A. (2005). A review of paired catchment studies for determining changes in water yield resulting from alterations in vegetation. *Journal of Hydrology*, 310(1–4), 28–61.
- Brown, A. E., Western, A. W., McMahon, T. A., & Zhang, L. (2013). Impact of forest cover changes on annual streamflow and flow duration curves. *Journal of Hydrology*, 483, 39–50.
- Burt, T. P., Howden, N. J. K., McDonnell, J. J., Jones, J. A., & Hancock, G. R. (2015). Seeing the climate through the trees: Observing climate and forestry impacts on streamflow using a 60-year record. *Hydrological Processes*, 29, 473–480. <https://doi.org/10.1002/hyp.10406>
- Buttle, J. M., Webster, K. L., Hazlett, P. W., & Jeffries, D. S. (2019). Quickflow response to forest harvesting and recovery in a northern hardwood forest landscape. *Hydrological Processes*, 33, 47–65. <https://doi.org/10.1002/hyp.13310>
- Cisternas, M., Martínez, P., Oyarzun, C., & Debels, P. (1999). Caracterización del proceso de reemplazo de vegetación nativa por

- plantaciones forestales en una cuenca lacustre de la Cordillera de Nahuelbuta, VIII Región, Chile. *Revista Chilena de Historia Natural*, 72, 661–676.
- Dai, A. (2011). Drought under global warming: A review. *Wiley Interdisciplinary Reviews: Climate Change*, 2(1), 45–65.
- Diffenbaugh, N. S., Swain, D. L., & Touma, D. (2015). Anthropogenic warming has increased drought risk in California. *Proceedings of the National Academy of Sciences of the United States of America*, 112(13), 3931–3936.
- Douglass, J. E. (1983). The potential for water yield augmentation from forest management in the eastern United States. *Water Resource Bulletin*, 19(3), 351–358.
- FAO (United Nations Food and Agricultural Organization). (1974). Fortalecimiento del Programa Nacional Forestal, Chile. Pautas para la ordenación de cuencas, la corrección de torrentes y la lucha contra la erosión en Chile. FAO/SF/CHI 26, Informe Técnico 6, Roma, Italia, p. 81.
- FAO (United Nations Food and Agricultural Organization). (2020). Global Forest Resources Assessment 2020—Key findings. Rome.
- Farley, K. A., Jobbágy, E. G., & Jackson, R. B. (2005). Effects of afforestation on water yield: A global synthesis with implications for policy. *Global Change Biology*, 11(10), 1565–1576.
- Ferraz, S. F. B., Lima, W. P., & Rodrigues, C. B. (2013). Managing forest plantation landscapes for water conservation. *Forest Ecology and Management*, 301, 58–66. <https://doi.org/10.1016/j.foreco.2012.10.015>
- Ferraz, S. F. D. B., Rodrigues, C. B., García, L. G., Alvares, C. A., & Lima, W. D. P. (2019). Effects of eucalyptus plantation on streamflow in Brazil: Moving beyond the water use debate. *Forest Ecology and Management*, 453, 1–10.
- Garreaud, R. D., Boisier, J. P., Rondanelli, R., Montecinos, A., Sepúlveda, H. H., & Veloso-Aguila, D. (2020). The central Chile mega drought (2010–2018): A climate dynamics perspective. *International Journal of Climatology*, 40(1), 421–439.
- Gholz, H. L., & Clark, K. L. (2002). Energy exchange across a chronosequence of slash pine forests in Florida. *Agricultural and Forest Meteorology*, 112, 87–102. [https://doi.org/10.1016/S0168-1923\(02\)00059-X](https://doi.org/10.1016/S0168-1923(02)00059-X)
- Goeking, S. A., & Tarboton, D. G. (2020). Forests and water yield: A synthesis of disturbance effects on streamflow and snowpack in western coniferous forests. *Journal of Forestry*, 118(2), 172–192.
- Grant, G. E., Tague, C. L., & Allen, C. D. (2013). Runoff after thinning watering the forest for the trees: An emerging priority for managing water in forest landscapes. *Frontiers in Ecology and the Environment*, 11(6), 314–321.
- Gronsdahl, S., Moore, R. D., Rosenfeld, J., McCleary, R., & Winkler, R. (2019). Effects of forestry on summertime low flows and physical fish habitat in snowmelt-dominant headwater catchments of the Pacific Northwest. *Hydrological Processes*, 33(25), 3152–3168.
- Guardiola-Claramonte, M., Troch, P. A., Breshears, D. D., Huxman, T. E., Switanek, M. B., Durcik, M., & Cobb, N. S. (2011). Decreased streamflow in semi-arid basins following drought-induced tree die-off: A counter-intuitive and indirect climate impact on hydrology. *Journal of Hydrology*, 406(3–4), 225–233.
- Hargreaves, G. H., & Samani, Z. A. (1982). Estimating potential evapotranspiration. *Journal of Irrigation and Drainage Division, American Society of Civil Engineers*, 108(IR3), 223–230.
- Hawthorne, S. N., Lane, P. N., Bren, L. J., & Sims, N. C. (2013). The long term effects of thinning treatments on vegetation structure and water yield. *Forest Ecology and Management*, 310, 983–993.
- Hernandez-Santana, V., Asbjornsen, H., Sauer, T., Isenhardt, T., Schultz, R., & Schilling, K. (2012). Effects of thinning on transpiration by riparian buffer trees in response to advection and solar radiation. *Acta Horticulturae*, 951, 225–231. <https://doi.org/10.17660/ActaHortic.2012.951.27>
- Hervé, F., Faundez, V., Calderón, M., Massonne, H. J., & Willner, A. P. (2007). Metamorphic and plutonic basement complexes. In T. Moreno & W. Gibbons (Eds.), *The geology of Chile* (pp. 5–25). The Geological Society.
- Heilmayr, R., Echeverría, C., Fuentes, R., & Lambin, E. F. (2016). A plantation-dominated forest transition in Chile. *Applied Geography*, 75, 71–82. <https://doi.org/10.1016/j.apgeog.2016.07.014>
- Huber, A., Iroumé, A., Mohr, C., & Frêne, C. (2010). Effect of Pinus radiata and Eucalyptus globulus plantations on water resources in the coastal range of biobio region, Chile. *Bosque*, 31, 219–230.
- Huddle, J. A., Awada, T., Martin, D. L., Zhou, X., Pegg, S. E., & Josiah, S. J. (2011). Do invasive riparian woody plants affect hydrology and ecosystem processes? *Great Plains Research*, 21, 49–71.
- INFOR (Instituto Forestal). (2020). Chilean statistical yearbook of forestry. Statistical Bulletin N°174, Instituto Forestal. Retrieved from <https://wef.infor.cl/publicaciones/anuario/2020/Anuario2020.pdf>
- Iroumé, A., Mayen, O., & Huber, A. (2006). Runoff and peak flow responses to timber harvest and forest age in southern Chile. *Hydrological Processes*, 20(1), 37–50.
- Iroumé, A., & Palacios, H. (2013). Afforestation and changes in forest composition affect runoff in large river basins with pluvial regime and Mediterranean climate, Chile. *Journal of Hydrology*, 505, 113–125.
- Jackson, R. B., Jobbágy, E. G., Avissar, R., Roy, S. B., Barrett, D. J., Cook, C. W., Farley, K. A., Le Maitre, D. C., McCarl, B. A., & Murray, B. C. (2005). Trading water for carbon with biological carbon sequestration. *Science*, 310(5756), 1944–1947.
- Jones, J., Almeida, A., Cisneros, F., Iroumé, A., Jobbágy, E., Lara, A., Lima, W. D. P., Little, C., Llerena, C., Silveira, L., & Villegas, J. C. (2017). Forests and water in South America. *Hydrological Processes*, 31(5), 972–980.
- Jones, J. A., Achterman, G. L., Augustine, L. A., Creed, I. F., Ffolliott, P. F., MacDonald, L., & Wemple, B. C. (2009). Hydrologic effects of a changing forested landscape—challenges for the hydrological sciences. *Hydrological Processes*, 23, 2699–2704.
- Lane, P. N., & Mackay, S. M. (2001). Streamflow response of mixed-species eucalypt forests to patch cutting and thinning treatments. *Forest Ecology and Management*, 143, 131–142.
- Lara, A., Little, C., Urrutia, R., McPhee, J., Álvarez-Garretón, C., Oyarzún, C., Soto, D., Donoso, P., Nahuelhual, L., Pino, M., & Arismendi, I. (2009). Assessment of ecosystem services as an opportunity for the conservation and management of native forests in Chile. *Forest Ecology and Management*, 258(4), 415–424.
- Lesch, W., & Scott, D. F. (1997). The response in water yield to the thinning of Pinus radiata, Pinus patula and Eucalyptus grandis plantations. *Forest Ecology and Management*, 99, 295–307.
- Lima, W. P., Laprovitera, R., Ferraz, S. F. B., Rodrigues, C. B., & Silva, M. M. (2012). Forest plantations and water consumption: A strategy for hydrosolidarity. *International Journal of Forestry Research*, 2012. <https://doi.org/10.1155/2012/908465>
- Little, C., Lara, A., McPhee, J., & Urrutia, R. (2009). Revealing the impact of forest exotic plantations on water yield in large scale watersheds in south-central Chile. *Journal of Hydrology*, 374(1–2), 62–170.
- Little, C., Cuevas, J. G., Lara, A., Pino, M., & Schoenholtz, S. (2015). Buffer effects of streamside native forests on water provision in watersheds dominated by exotic forest plantations. *Ecology*, 8(7), 1205–1217.
- Liu, N., Harper, R. J., Smettem, K. R. J., Dell, B., & Liu, S. (2019). Responses of streamflow to vegetation and climate change in southwestern Australia. *Journal of Hydrology*, 572, 761–770.
- McGinley, K., Alvarado, R., Cubbage, F., Diaz, D., Donoso, P. J., Jacovine, L. A. G., De Silva, F. L., MacIntyre, C., & Zalazar, E. M. (2012). Regulating the sustainability of forest management in the Americas: Cross-country comparisons of forest legislation. *Forests*, 3(3), 467–505.

- McLaughlin, D. L., Kaplan, D. A., & Cohen, M. J. (2013). Managing forests for increased regional water yield in the southeastern U.S. coastal plain. *Journal of the American Water Resources Association*, 49, 1–13. <https://doi.org/10.1111/jawr.12073>
- Melnick, D., Bookhagen, B., Strecker, M. R., & Echtler, H. P. (2009). Segmentation of megathrust rupture zones from fore-arc deformation patterns over hundreds to millions of years, Arauco peninsula, Chile. *Journal of Geophysical Research*, 114, B01407. <https://doi.org/10.1029/2008JB005788>
- Millán, J., & Carrasco, P. (1993). La forestación en la VIII Región. In F. Faranda & O. Parra (Eds.), *Proyecto Eula-Chile. Elementos cognoscitivos sobre el recurso suelo y consideraciones generales sobre el ordenamiento agroforestal. Serie Propuestas de ordenamiento Vol. 4* (pp. 75–84). Editorial Universidad de Concepción.
- Mohr, C. H., Montgomery, D. R., Huber, A., Bronstert, A., & Iroumé, A. (2012). Streamflow response in small upland catchments in the Chilean coastal range to the MW 8.8 Maule earthquake on February 27th 2010. *Journal of Geophysical Research*, 117, F02032. <https://doi.org/10.1029/2011JF002138>
- Oliver, M. A., & Webster, R. (1990). Kriging: A method of interpolation for geographical information systems. *International Journal of Geographical Information Systems*, 4(3), 313–332. <https://doi.org/10.1080/02693799008941549>
- Peel, M. C., Finlayson, B. L., & McMahon, T. A. (2007). Updated world map of the Köppen-Geiger climate classification. *Hydrology and Earth System Sciences*, 11(5), 1633–1644.
- Perry, T. D., & Jones, J. A. (2017). Summer streamflow deficits from regenerating Douglas-fir forest in the Pacific Northwest, USA. *Ecology*, 98(10), e1790.
- Saatchi, S., Asefi-Najafabady, S., Malhi, Y., Aragão, L. E., Anderson, L. O., Myneni, R. B., & Nemani, R. (2013). Persistent effects of a severe drought on Amazonian forest canopy. *Proceedings of the National Academy of Sciences of the United States of America*, 110(2), 565–570.
- Sahin, V., & Hall, M. J. (1996). The effects of afforestation and deforestation on water yields. *Journal of Hydrology*, 178(1/4), 293–309.
- Salas, C., Donoso, P. J., Vargas, R., Arriagada, C. A., Pedraza, R., & Soto, D. P. (2016). The forest sector in Chile: An overview and current challenges. *Journal of Forestry*, 114(5), 562–571.
- Schlatter, J., Grez, R., & Gerding, V. (2003). *Manual para el reconocimiento de suelos* (3rd ed., p. 114). Universidad Austral de Chile.
- Shanley, J. B., Kendall, C., Smith, T. E., Wolock, D. M., & McDonnell, J. J. (2002). Controls on old and new water contributions to stream flow at some nested catchments in Vermont, USA. *Hydrological Processes*, 16, 589–609. <https://doi.org/10.1002/hyp.312>
- Scott, D. F. (2005). On the hydrology of industrial timber plantations. *Hydrological Processes*, 19(20), 4203–4206.
- Scott, D. F., & Prinsloo, F. W. (2008). Longer-term effects of pine and eucalyptus plantations on streamflow. *Water Resources Research*, 44, W00A08. <https://doi.org/10.1029/2007WR006781>
- Segura, C., Bladon, K. D., Hatten, J. A., Jones, J. A., Hale, V. C., & Ice, G. G. (2020). Long-term effects of forest harvesting on summer low flow deficits in the coast range of Oregon. *Journal of Hydrology*, 585, 124749.
- Silveira, L., & Alonso, J. (2009). Runoff modifications due to the conversion of natural grasslands to forests in a large basin in Uruguay. *Hydrological Processes*, 23(2), 320–329.
- Stovall, A. E., Shugart, H., & Yang, X. (2019). Tree height explains mortality risk during an intense drought. *Nature Communications*, 10(1), 1–6.
- Sun, G., Alstad, K., Chen, J. Q., Chen, S. P., Ford, C. R., Lin, G. H., Liu, C. F., Lu, N., McNulty, S. G., Miao, H. X., Noormets, A., Vose, J. M., Wilske, B., Zeppel, M., Zhang, Y., & Zhang, Z. Q. (2011). A general predictive model for estimating monthly ecosystem evapotranspiration. *Ecology*, 92(2), 245–255.
- Sun, G., Caldwell, P. V., Noormets, A., Cohen, E., McNulty, S. G., Treasure, E., Domec, J. C., Mu, Q., Xiao, J., John, R., & Chen, J. (2011). Upscaling key ecosystem functions across the conterminous United States by a water-centric ecosystem model. *Journal of Geophysical Research*, 116, G00J05. <https://doi.org/10.1029/2010JG001573>
- Sun, G., Caldwell, P. V., & McNulty, S. G. (2015). Modelling the potential role of forest thinning in maintaining water supplies under a changing climate across the conterminous United States. *Hydrological Processes*, 29, 5016–5030. <https://doi.org/10.1002/hyp.10469>
- Tague, C., Grant, G. E., Farrell, M., Choate, J., & Jefferson, A. (2008). Deep groundwater mediates streamflow response to climate warming in the Oregon cascades. *Climatic Change*, 86, 189–210. <https://doi.org/10.1007/s10584-007-9294-8>
- Tricallotis, M., Gunningham, N., & Kanowski, P. (2018). The impacts of forest certification for Chilean forestry businesses. *Forest Policy and Economics*, 92, 82–91.
- Tsai, H.-C., Chiang, J.-M., McEwan, R. W., & Lin, T.-C. (2018). Decadal effects of thinning on understory light environments and plant community structure in a subtropical forest. *Ecosphere*, 9(10), e02464. <https://doi.org/10.1002/ecs2.2464>
- Ulloa, H., Iroumé, A., Lenzi, M. A., Andreoli, A., Alvarez, C., & Barrera, V. (2011). Material leñoso de gran tamaño en dos cuencas de la Cordillera de la Costa de Chile con diferente historia de uso del suelo. *Bosque*, 32, 235–245.
- Vose, J. M., Miniati, C. F., Luce, C. H., Asbjornsen, H., Caldwell, P. V., Campbell, J. L., Grant, G. E., Isaak, D. J., Loheide, S. P., II, & Sun, G. (2016). Ecophysiological implications of drought for forests in the United States. *Forest Ecology and Management*, 380, 335–345.
- Ziegler, A. D., Negishi, J. N., Sidle, R. C., Noguchi, S., & Nik, A. R. (2006). Impacts of logging disturbance on hillslope saturated hydraulic conductivity in a tropical forest in peninsular Malaysia. *Catena*, 67, 89–104. <https://doi.org/10.1016/j.catena.2006.02.008>

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