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RESEARCH AND OBSERVATORY CATCHMENTS: THE LEGACY AND THE FUTURE

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# Streamflow response to native forest restoration in former *Eucalyptus* plantations in south central Chile

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## Abstract

Global increases in intensive forestry have raised concerns about forest plantation effects on water, but few studies have tested the effects of plantation forest removal and native forest restoration on catchment hydrology. We describe results of a 14-year paired watershed experiment on ecological restoration in south central Chile which documents streamflow response to the early stages of native forest restoration, after clearcutting of plantations of exotic fast-growing *Eucalyptus*, planting of native trees, and fostering natural regeneration of native temperate rainforest species. Precipitation, streamflow, and vegetation were measured starting in 2006 in four small (3 to 5 ha) catchments with *Eucalyptus globulus* plantations and native riparian buffers in the Valdivian Coastal Reserve. Mean annual precipitation is 2500 mm, of which 11% occurs in summer. Streamflow increased, and increases persisted, throughout the first 9 years of vigorous native forest regeneration (2011 to 2019). Annual streamflow increased by 40% to >100% in most years and >150% in fall and summer of some years. Streamflow was 50% to 100% lower than before treatment in two dry summers. Base flow increased by 28% to 87% during the restoration period compared to pre-treatment, and remained elevated in later years despite low summer precipitation. Overall, these findings indicate that removal of *Eucalyptus* plantations immediately increased streamflow, and native forest restoration gradually restored deep soil moisture reservoirs that sustain base flow during dry periods, increasing water ecosystem services. To our knowledge this is the first study to assess catchment streamflow response to native forest restoration in former forest plantations. Therefore, the results of this study are relevant to global efforts to restore native forest ecosystems on land currently intensively managed with fast-growing forest plantations and may inform policy and decision-making in areas experiencing a drying trend associated with climate change.

**KEYWORDS**
base flow, climate change, ecological restoration, ecosystem services, paired-catchment experiment, Valdivian rainforest

## 1 | INTRODUCTION

Intensive forestry accounts for the highest rates of recent forest change globally (Hansen et al., 2013), raising questions about effects of forest plantations on water (Creed et al., 2019; Creed & van Noordwijk, 2018). Despite benefits from intensive plantation forestry (Paquette & Messier, 2010), afforestation with fast-growing tree species reduces streamflow (Farley et al., 2005; Filoso et al., 2017; Vertessy, 2001) and lowers groundwater tables (Lu et al., 2018). These issues are vividly illustrated in South America, which has among the highest global rates of native forest loss and plantation forest establishment (Jones et al., 2017). In south central Chile, much of the area of native temperate rainforest has been converted to fast growing plantations of exotic *Pinus radiata* and *Eucalyptus* species, or to shrublands, agriculture, and pastureland (Aguayo et al., 2009; Echeverria et al., 2006; Miranda et al., 2016; Olson & Dinerstein, 1998). These changes have been associated with declining annual and summer runoff (Iroumé & Palacios, 2013; Lara et al., 2009; Little et al., 2009), as well as reduced plant diversity (Altamirano et al., 2007) and carbon storage (Hall et al., 2012; Heilmayr et al., 2020).

Despite widespread interest in restoration of native forests, little is known about their hydrologic effects. Native forest restoration aims to increase ecosystem services such as water provision and regulation (Benayas et al., 2009; Clewell & Aronson, 2013; Little & Lara, 2010), but few studies have examined the hydrologic effects of native forest restoration. Filling of ditches constructed for past timber production led to increased soil moisture in a restored temperate mixed broadleaved forest in Denmark (Mazziotta et al., 2016). Restoration of riparian vegetation and channels also has been linked to hydrologic responses, such as reductions in flooding (Palmer et al., 2014). However, to our knowledge, no studies have examined catchment streamflow response to native forest restoration in former forest plantations.

This study addresses a gap in knowledge about hydrologic response to the early stages of forest restoration. We describe a 14-year (2006 to 2019) catchment study, which covers the response of streamflow to the first 9 years of a native forest restoration process that will require at least 130 to 180 years to attain mature or old-growth forest structure (Lara et al., 2013). After 5 years of pre-treatment streamflow measurements (2006–2010), *Eucalyptus globulus* plantations in the treated watersheds were clear-cut in 2011, seedlings of native *Nothofagus dombeyi* tree species were planted, and the sites were protected to foster regeneration of other native plant species, while one watershed remained covered by *E. globulus*. The study is located in the Valdivian Coastal Reserve in south central Chile, a Nature Conservancy (TNC) reserve on former private industrial forest land. This study is one of the longest catchment experiments in South America, and to our knowledge, the only one involving a long-term effort to restore native forests on land formerly in short-rotation intensively managed forest plantations.

We addressed the following questions:

1. How did streamflow respond to the early stages of restoration of native forests in former *Eucalyptus* plantations?
2. How does streamflow in catchments under restoration compare to streamflow from a catchment that remained a *Eucalyptus* plantation?

## 2 | STUDY SITE AND METHODS

### 2.1 | Study site and experimental treatments

The study was conducted in the Valdivian Coastal Reserve on the coast of south central Chile (39°58′S, 73°33′W) (Figure 1). The paired

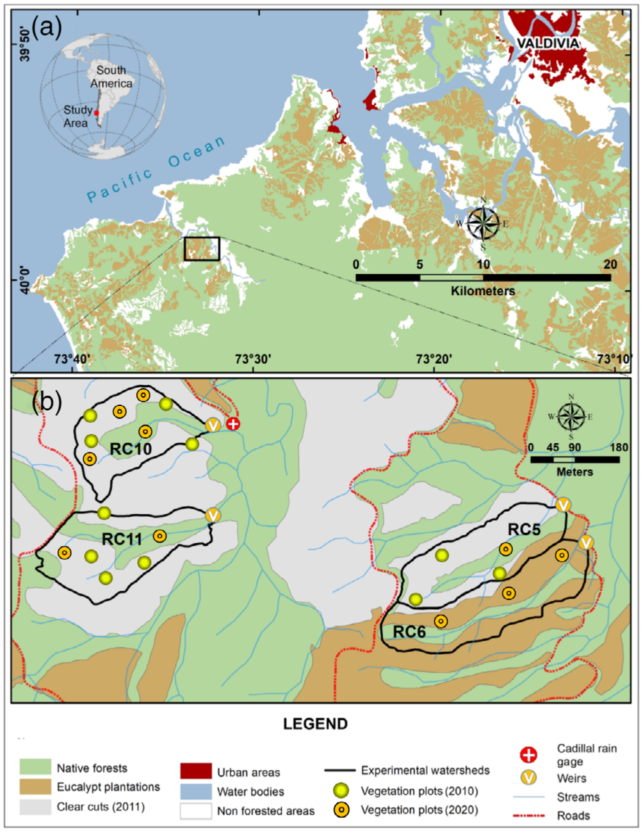


**FIGURE 1** Study site location. (a) The study is located in the Valdivian Coastal Reserve, on the coast of south central Chile, southwest of the city of Valdivia. (b) The study catchments are located in a landscape which as of 2020 consists of remnant plantations of non-native *Eucalyptus globulus* (established in 1999), areas where these plantations were clearcut in 2011 and are under restoration to native forests, native forests in riparian buffers and other areas. Long-term measurement locations are shown for precipitation, streamflow, and vegetation. Sampling of native vegetation in 2020 included all the plots indicated as measured in this year and some of the ones measured since 2010

watershed experiment involved (1) a restoration treatment consisting of clearcutting of *E. globulus* plantations followed by planting of a native tree species (*N. dombeyi*) and natural regeneration in three catchments (RC5, RC10, RC11), and (2) a reference consisting of retention of the previously established plantation of *E. globulus* in a fourth catchment (RC6, Figures 1 and 2). Catchment size ranges from 3.7 to 5.3 ha, elevation ranges from 6 to 195 m, and mean slope gradient is 41% to 47% (Table 1). This study covers 5 years prior to the implementation of the treatments (2006 to 2010) and 9 years after the treatments (2011 to 2019) (Figure 2). We used the catchment designations established in studies of early response of native forest restoration, hydrology, and biogeochemistry in these catchments (Cuevas et al., 2018; Lara et al., 2013; Little et al., 2015).

Precipitation and streamflow have been monitored since 2006 (Figure 1). Mean annual precipitation is 2500 mm, and 90% of precipitation occurs in fall, winter, and spring (2006–2019). Mean annual temperature measured between 2006–2010 was 11.5°C (Little

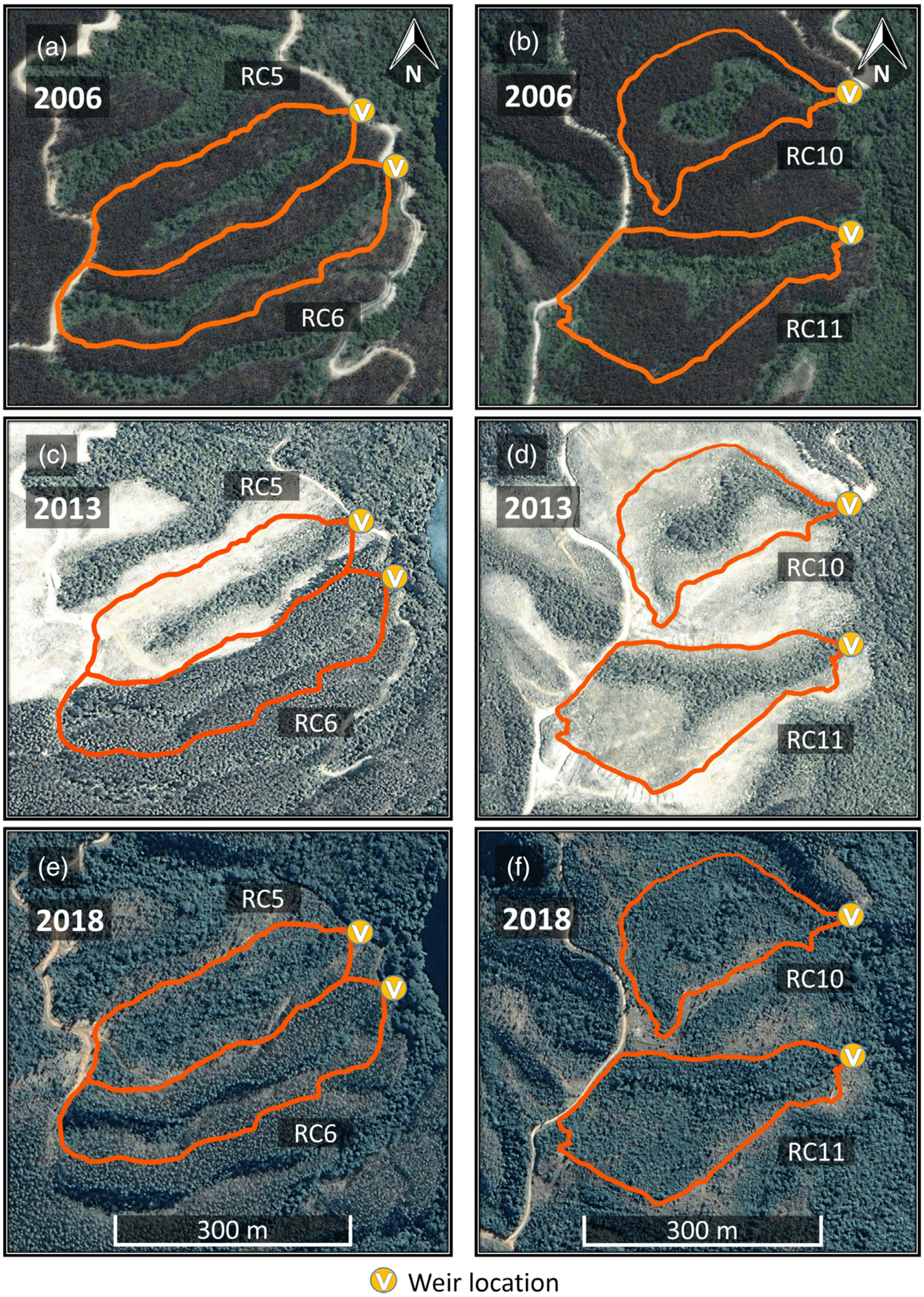


**FIGURE 2** Catchments in the study site (a,c,e) RC5 and RC6; (b,d,f), RC10 and RC11. (a,b) before clearcutting (2006), (c,d) 2 years after clearcutting (2013), and (e,f) 7 years after clearcutting (2018). RC6 is a *Eucalyptus* plantation established in 1999 (i.e., aged 7 to 20) years during the study, and RC5, RC10 and RC11 were *Eucalyptus* plantations also established in 1999 that were clearcut in 2011 and are under restoration to native forests, involving planting of the native tree species, *Nothofagus dombeyi*, and natural regeneration of several species (trees, shrubs, ferns). *Eucalyptus* plantations were established by clearcutting and burning native forests. All catchments retain a streamside buffer of native forest

et al., 2015). The geology consists of Paleozoic metamorphic rocks, partially overlaid by Tertiary marine sediments with a slope of 60%, hence bedding planes are steeper than the surface topography. Soils have a volcanic origin and are Typic Haplohumults (Ultisols, Hueycolla series) with a low pH (4.2–4.8) (CIREN, 2001).

Vegetation of the study site underwent multiple changes prior to the initiation of the paired catchment experiment. Initial vegetation of the study site was Valdivian temperate evergreen forest, which occurs in areas of abundant annual precipitation (2000 to 5000 mm) from near sea level to nearly 1000 m in the Andes and the Coastal Cordillera from 38°30′ to 47°S (Veblen et al., 1996). These forests are dominated by 14 native tree species, all of which are endemic to south central Chile and adjacent areas of Argentina (Donoso, 2006, Table S4 in Data S1). Historically, native forests of the study site (green areas in Figure 1) were selectively cut by local people for wood and wood fuels. Between 1993 and 1999, 3000 ha of native forests in this area were clear-cut, burned, and converted to exotic *Eucalyptus* plantations (Lara et al., 2014; Little et al., 2013; Figures 1 and 2a,b). By Chilean law, when plantations were established, native forest was retained within prescribed riparian buffer zones around each stream (green areas around streams in Figure 1, pale green areas around streams in Figure 2a,b). In 2003, The Nature Conservancy purchased an area of 500 km$^2$ from the timber company that established the *Eucalyptus* plantations and created a reserve (Reserva Costera Valdiviana) to

**TABLE 1** Characteristics of the study catchments

| Catchment name | RC5 | RC6 | RC10 | RC11 |
|---|---|---|---|---|
| Area (ha) | 3.74 | 5.26 | 3.43 | 4.28 |
| Harvest date | Apr 2011 | - | Feb-Apr 2011 | Feb-Apr 2011 |
| Elevation (m asl) | 6 to 107 | 6 to 124 | 116 to 164 | 115 to 195 |
| Mean slope (%) | 46.6 | 45.2 | 41 | 42.7 |
| Buffer width (m) | 29.6 | 29.2 | 45 | 34.4 |
| Buffer area (%) | 23.9 | 30.6 | 36.9 | 25.3 |
| % cover *Eucalyptus* (2006–2010) | 76.1 | 69.4 | 63.1 | 74.8 |
| *Eucalyptus*, 2010, before clear-cut | | | | |
| Mean height (m) | 22.4 | 17.9 | 15 | 17.8 |
| Mean diameter at breast height (cm) | 19.1 | 12 | 20 | 15.2 |
| Basal area ($m^2$/ha) | 60.2 | 37.8 | 63.0 | 47.9 |
| *Eucalyptus*, 2020 | | | | |
| Mean height (m) | - | 25.9 | - | - |
| Mean diameter at breast height (cm) | - | 20.9 | - | - |
| Basal area ($m^2$/ha) | 3.1 | 60.7 | - | 1.3 |

*Note:* At the beginning of the study (2006), all catchments were covered by *Eucalyptus* plantations established in 1999. RC5, RC10 and RC11 were clearcut in 2011 and replanted with seedlings of native *Nothofagus dombeyi*; RC6 remained a *Eucalyptus* plantation. Pre-clearcutting values for *Eucalyptus* height, dbh, and basal area are based on four plots inventoried in 2010 by Masisa S.A. (Víctor Guerrero, personal communication). Height estimates for *Eucalyptus* in 2020 are based on models from Masisa S.A. (Jorge Echeverría, personal communication). Diameter and basal area of *Eucalyptus* in RC5 and RC11 in 2020 correspond to *Eucalyptus* trees (>5 cm dbh) that regenerated from seeds of nearby stands or sprouted from cut stumps (Table 4, Figure S3 in Data S1).

protect rainforests and coastal marine ecosystems. At the start of the experiment in 2006, vegetation in the study catchments consisted of 7-year-old commercial plantations of *E. globulus* occupying 64% to 76% of catchment area (Figure 2a,b), and native forest in streamside buffers occupying 24% to 36% of catchment area (Figure 2a,b; Table 1).

Details of experimental treatments are as follows. In the catchments subjected to the restoration treatment (RC5, RC10 and RC11), *Eucalyptus* plantations were clear-cut in February to April 2011 (Figures 1 and 2c,d; Table 1) and planted with *N. dombeyi* seedlings in 2011 and 2012 to achieve a mean initial density of 1500 seedlings/ha (Lara et al., 2014). *N. dombeyi* is a dominant species in the forests of south central Chile that may reach 40 m in height (Donoso, 2006). It was chosen because it is a pioneer fast-growing species that is present in the Reserve, and therefore it was expected to rapidly form closed-canopy forest stands (Lara et al., 2013). The restoration treatment (light grey areas in Figure 1) included fencing to exclude cattle and direct application of herbicide (glyphosate) to the cut stumps of *Eucalyptus* to prevent sprouting. Herbicide was applied in catchments RC10 and RC11, but not in catchment RC5; this permitted assessment of how sprouting from *Eucalyptus* stumps affected native forest establishment. Restoration treatments fostered regeneration of native trees (14 species), via seeding in from nearby forest stands and sprouting from roots and stumps, as well as regeneration of shrubs, ferns and epiphytes present in the understory of *Eucalyptus* stands before clearcutting (total 74 species, Lara et al., 2013, 2014) (Figure 2e,f).

The paired-catchment study was initiated as a collaborative agreement among Universidad Austral de Chile (UACh), The Nature Conservancy (TNC), and Masisa S.A., a private forestry company. Masisa S.A. harvested *Eucalyptus* plantations and planted native tree species in a 45-ha pilot area within the Valdivian Coastal Reserve. In conjunction with TNC and Masisa S.A., UACh managed the design and planning of the restoration experiment including monitoring of streamflow, precipitation and permanent vegetation plots. TNC owns, protects and manages the site (Little et al., 2013).

## 2.2 | Field data collection

In order to capture spatial variability, precipitation records have been collected since February 2006 at six sites in openings across a range of elevation. Precipitation is measured at 15-min intervals using tipping-bucket gages (Model DAVIS 7852; Davis Instruments. Hayward, CA. USA) with a resolution of 0.2 mm, equipped with HOBO event loggers (Onset Computer Corporation. Bourne, MA. USA). A complete record of daily precipitation for the period April 2006 through March 2020 was created for the rain gage named Cadillal (Figure 1), which is closest to the four study catchments and has the longest continuous record. Missing data due to instrument failure, low battery, etc. (7% of observations from 2009 to 2019) were filled based on linear relationships with the other five precipitation gages ($R^2$ 0.90–0.98, Table S1 in Data S1).

Streamflow is measured using 90° V-notch weirs constructed in 2006 (RC5, RC6) and 2008 (RC10, RC11) (Little et al., 2015). The water year starts in April (fall) of the named year and ends in March (summer) of the following year. Stage height was measured manually for water years 2006 to 2008 in RC5 and RC6 and using automated measurements at all catchments for water years 2009 to present. Atmospheric pressure and water pressure at the weir were measured at all stream gaging locations using pressure transducers (HOBO U20-001, with a resolution of 4 mm). Data were downloaded, compiled at 15-min resolution, quality checked, converted to discharge and summarized at the daily scale. Mean daily streamflow for each day of the record was expressed on a unit-area basis (mm). Missing values of daily streamflow were filled based on adjacent values (for gaps of 1 to 3 days) and relationships with precipitation (see below) for longer gaps. Analyses reported here used observed streamflow for RC5 and RC6 (2006 through 2019) and RC10 and RC11 (2009 through 2019) and filled values for RC10 and RC11 (2006 through 2008) (see below).

*Eucalyptus* plantations were surveyed by Masisa S.A., in 2010, prior to clear-cutting. Vegetation in the restored areas of the catchments was sampled in 2010, 2012, 2014 and 2016 ($n = 3$ plots in RC5, $n = 4$ in RC10, and $n = 4$ in RC11) (Figure 1b). Vegetation was resampled in 2020 in the native forest riparian buffer ($n = 1$ plot in RC5, RC10 and RC11), in the *Eucalyptus* plantation ($n = 3$ new plots in RC6) and in the restored areas ($n = 3$ original plots in RC5, $n = 4$ in RC10, including 1 original plot and 3 new plots, and $n = 4$ in RC11, including 3 of the original plots and 1 new plot in RC 11) (Figure 1b). The number of seedlings (<2 m height), and the cover of all non-tree species was recorded in 10, 1-m radius subplots distributed at 3 m intervals along the N-S cardinal axes of the 500 $m^2$ plots. The numbers, height, and dbh of saplings (>2 m, <5 cm dbh), and trees (dbh ≥ 5 cm) of *N. dombeyi*, *Eucalyptus*, and other regenerating native species were measured in one (saplings) or two (trees) 125 $m^2$-quadrants in each plot (Tables S3 and S4, Figure S3 in Data S1).

## 2.3 | Data analyses

Three methods were applied to estimate the effects of the treatment on streamflow: (1) double-mass plots and runoff ratios; (2) a before-after analysis contrasting post-treatment streamflow to pre-treatment streamflow, 2006 to 2010; and (3) a before-after, control-impact analysis using precipitation and streamflow data for the pre-treatment water years 2009 and 2010. In addition, a base flow separation analysis was performed on the daily data, and seasonal base flow values were correlated to prior precipitation. Analyses were conducted at the multi-year, annual (April to March water year), and seasonal time scales. Seasons were defined as austral fall (April to June), austral winter (July to September), austral spring (October to December), and austral summer (January to March). These methods and their advantages and limitations are described below.

### 2.3.1 | Runoff ratios and double-mass curves

Runoff ratios (Q/P, where Q = streamflow and P = precipitation) were calculated for each year and season. Double-mass curves of cumulative streamflow versus cumulative precipitation were constructed for all study catchments for the period of record. Runoff ratios and double mass curves include the effects of topography, geology, vegetation, and climate on streamflow.

### 2.3.2 | Before-after analysis

A before-after analysis of streamflow was conducted following the method of Swank and Douglass (1974). The average and standard deviation of streamflow during the pre-treatment period was calculated for each catchment. The treatment effect Δ was the difference between observed streamflow in each year of the post-treatment (under restoration) period and the average pre-treatment streamflow,

$$\Delta_t = Q_t - Q \tag{1}$$

where $Q_t$ = streamflow in period $t$ and $Q$ = average streamflow for the pre-treatment period. The pre-treatment period was water years 2006 to 2010. For the 2006 to 2008 water years, the analysis used measured streamflow for RC5 and RC6 and daily streamflow modelled using precipitation for RC10 and RC11 (see below).

### 2.3.3 | Observed versus predicted analysis

A before-after, control-impact analysis can be used to estimate streamflow changes between a treated and a control catchment, which is assumed to be stationary (Eberhardt & Thomas, 1991). However, many catchment studies lack a control which is stationary (Jones & Post, 2004). For example, in this study, the catchment with *Eucalyptus* (RC6) grew from 7 to 20 years of age from 2006 to 2019 and basal area increased from 38 to 61 $m^2$/ha (Table 1). Precipitation data provide an alternative "control" for a before-after control-impact analysis, whereby the relationship of precipitation to streamflow in the pre-treatment period can be used to predict expected streamflow after the treatment, and the response to treatment is determined as the difference between predicted and observed streamflow. We used this approach in our analysis. This approach may be applicable to other studies where control watersheds are lacking.

Daily antecedent precipitation was calculated from the complete daily precipitation record:

$$AP_t = P_t + P_{t-1}{}^k \tag{2}$$

where $AP_t$ = antecedent precipitation on day $t$, $P_t$ = precipitation on day $t$, and $k$ = exponent indicating the "memory" of past precipitation events. Two values of $k$ (0.7 and 0.9) were selected to represent relatively short ($k = 0.7$) and long ($k = 0.9$) memory.

Linear models were fitted to predict daily streamflow ($Q_t$) as function of daily antecedent precipitation (using two values of $k$) for each month during the two-year pre-treatment period:

$$Q_t = \alpha + \beta AP_t \tag{3}$$

The relationship of streamflow to precipitation was estimated in each catchment for water years 2009 and 2010, the pre-treatment period when all catchments were instrumented with sensors and data loggers recording streamflow at 15-min intervals. This produced four models of daily precipitation (2009, 2010, each with $k = 0.7$ and $k = 0.9$) for each month of the year. Daily values of streamflow ($Q_t$) were estimated for all days in the period of record using each of these four models, and the average of the predicted values from the four models and its standard error was determined for each day in the record. Use of the average predicted value for each month accounted for differences in antecedent precipitation (between 2009 and 2010) and differences in streamflow responses to antecedent precipitation (k = 0.7 vs. k = 0.9). The treatment effect, $\Delta$, was then determined as the difference:

$$\Delta = Q'_t - Q_{t.} \tag{4}$$

where $Q'_t$ = observed streamflow (mm) and $Q_t$ = predicted streamflow (mm) for each day in the record. The values of $\Delta$ were summed by year and by season.

We validate the approach by comparing predicted to observed discharge during the pre-treatment period, and use that validation to establish the practical significance limits for detecting change. Predicted values of seasonal streamflow were within $+/-$ 80 mm of observed values, and were evenly distributed as positive and negative deviations (Figure S1a in Data S1). In relative terms (i.e., %), predicted seasonal values were within $+/-$ 40% of observed values (Figure S1b in Data S1). Changes were considered to be practically significant when they were more than 50 mm or 40% different than predicted. This level of uncertainty is comparable to confidence intervals obtained from long-term studies of paired catchments (e.g., Jones & Post, 2004; Perry & Jones, 2017).

The before-after control-impact approach differs from the before-after method in two respects: (1) the first method uses precipitation data as the "control", whereas the second method has no control and uses only discharge data, and (2) the two approaches use different pre-treatment periods. The before-after method used a five-year pre-treatment period, including once a day stage height observations from 2006 to 2008 at RC5 and RC6, and estimated average daily streamflow based on precipitation for 2006 to 2008 at RC10 and RC11 (Table S2 in Data S1). In contrast, the before-after control-impact approach used 2009 to 2010 as the pre-treatment period, when automated measurements of streamflow at 15-min intervals began and continue to today. We present the results of both analysis approaches and compare them in the discussion section.

### 2.3.4 | Base flow separation and memory

Total daily streamflow was separated into quick flow and base flow following the method of Chapman and Maxwell (1996). Base flow was calculated as:

$$Qb(i) = \frac{k}{2-k} Qb\,(i-1) + \frac{1-k}{2-k} Q(i) \tag{5}$$

where $Q_b$ = base flow (mm), $Q$ = total streamflow (mm) and $k$ is a parameter ranging between 0 and 1. Higher values of $k$ increase the fraction of total streamflow represented by Qb. After testing different $k$ values ranging from 0.4 to 0.97, we chose $k = 0.95$ for spring and summer and $k = 0.90$ for fall and winter.

The influence of past precipitation on streamflow in each catchment ("memory") was estimated by correlating seasonal streamflow to precipitation in the current and past seasons.

## 3 | RESULTS

### 3.1 | Streamflow response to restoration of native forests

Streamflow increased in the catchments under restoration (2011–2019), relative to the pre-treatment period when automated records were available (2009–2010), but precipitation changed by <2% (Table 2). Over the post-treatment period (2011–2019) streamflow increased by 73% at RC5, 69% at RC10 and 18% at RC11 (restored) and by 24% at RC6 (*Eucalyptus*) (see discussion).

Catchments differed substantially in the relationship of runoff to precipitation (Table 3, Figure 3). In the pre-treatment period (2006–2010), runoff ratios were higher in RC11 (0.77) and RC6 (0.57) than in RC5 and RC10 (0.4) (Table 3). After clear-cutting of *Eucalyptus* in RC5, RC10 and RC11, the slopes of the double mass curves increased in all catchments, indicating increased runoff ratios (Figure 3). From 2011 to 2019, the greatest increase in streamflow and runoff ratios occurred at RC10 (restored), and lesser increases occurred at RC5 and RC11 (restored), as well as at RC6 (*Eucalyptus*; Tables 2 and 3; see discussion).

In most post-treatment years, annual streamflow increased by >200 mm based on the before-after method (Figure 4a) and by 40% to 130% based on the before-after, control-impact method (Figure 4b). Controlling for precipitation (the before-after control-impact method), streamflow increased by more than 50% at RC5 and RC10 six or more years of the post-treatment period (Figure 4b, Table 3).

Seasonal streamflow response in absolute terms (mm) in the three catchments under restoration (RC5, RC10, RC11) was greatest in winter, followed by fall, spring, and summer, based on the before-after method (Figure 5, Figure S2 in Data S1). Percent change in streamflow controlling for precipitation (the before-after control-impact method),

**TABLE 2** Annual (water year) streamflow and precipitation (mm) in the four study catchments, and percent difference (% diff) for each year relative to the pre-treatment mean (2009–2010), which includes the period when automated (15-min) stream gage records began

| | RC5 (restored) | | RC6 (*Eucalyptus*) | | RC10 (restored) | | RC11 (restored) | | Precipitation | |
|---|---|---|---|---|---|---|---|---|---|---|
| Year | mm | % diff | mm | % diff | mm | % diff | mm | % diff | mm | % diff |
| 2006 | 1374 | | 1469 | | 1146 | | 2299 | | 3148 | 28 |
| 2007 | 739 | | 943 | | 701 | | 1304 | | 1558 | −37 |
| 2008 | 1329 | | 1530 | | 1034 | | 1885 | | 2427 | −1 |
| 2009 | 793 | 15 | 1526 | 2 | 1097 | 10 | 1923 | 1 | 2804 | 14 |
| 2010 | 590 | −15 | 1464 | −2 | 901 | −10 | 1873 | −1 | 2347 | −4 |
| 2011 | 714 | 3 | 1808 | 21 | 1961 | 96 | 2540 | 34 | 2694 | 10 |
| 2012 | 1371 | 98 | 1855 | 24 | 2168 | 117 | 2853 | 50 | 2806 | 14 |
| 2013 | 1120 | 62 | 1892 | 27 | 1767 | 77 | 2361 | 24 | 2603 | 6 |
| 2014 | 2088 | 202 | 2160 | 44 | 1845 | 85 | 2274 | 20 | 2725 | 11 |
| 2015 | 1168 | 69 | 1799 | 20 | 1582 | 58 | 2107 | 11 | 2554 | 4 |
| 2016 | 771 | 11 | 1090 | −27 | 870 | −13 | 1565 | −18 | 1977 | −20 |
| 2017 | 1605 | 132 | 2292 | 53 | 2138 | 114 | 2565 | 35 | 2916 | 19 |
| 2018 | 1200 | 73 | 2050 | 37 | 1616 | 62 | 2114 | 11 | 2385 | −3 |
| 2019 | 756 | 9 | 1677 | 12 | 1291 | 29 | 1866 | −2 | 2144 | −13 |
| Ave, 2009–10 | 692 | | 1495 | | 999 | | 1898 | | 2576 | |
| Ave, 2011–19 | 1199 | | 1847 | | 1693 | | 2249 | | 2534 | |
| % change, 2011–2019 versus 2009–2010 | | 73 | | 24 | | 69 | | 18 | | −2 |

was higher in summer and fall than in winter and spring (Figure 6). Fall runoff ratios increased by 164% in RC5 (restored) and 106% in RC10 (restored) in 2011–2019 relative to pre-treatment (2009–2010, Table 3). Streamflow increased by 100%–150% in fall and summer of several years in all catchments under restoration (RC5, RC10 and RC11). Some differences were apparent in streamflow responses depending on the method used for analysis (see discussion).

## 3.2 | Vegetation recovery in catchments under restoration

Vegetation cover of non-tree species from natural regeneration increased rapidly after clearcutting and planting of *Nothofagus* seedlings in RC5, RC10 and RC11 (Figure 2, Table 4). Cover of non-tree vegetation reached a maximum of 102% to 162% in 2016 (canopy cover estimates include overlapping layers), and then declined in 2020 as cover of planted and naturally regenerated tree species increased (Table S3, Figure S3 in Data S1). By 2020, vegetation cover of tree species ranged from 48% (RC5) to 78% (RC10; Table 4).

Although *Eucalyptus* recruited from stump sprouting in RC5 and from seeds in all three catchments, densities of native tree species increased dramatically from 2012 to 2020 in vegetation plots in restored areas (Table 4, Table S4, Figure S3 in Data S1). Despite some differences, tree basal area in 2020 was similar in the restored areas of all three catchments (RC5, RC10 and RC11) (Table 4). In 2020, tree basal area in the restored areas of RC5, RC10 and RC11 (6 to 11 $m^2$/ha) was still much lower than in the *Eucalyptus* plantation (RC6, 61 $m^2$/ha) or the native forest riparian zones of all four catchments (38 to 68 $m^2$/ha) (Tables 1 and 4, Figure 2). In summary, as of 2020, vegetation in catchments under restoration (RC5, RC10 and RC11) had less basal area and more species diversity compared to the *Eucalyptus* plantation (RC6).

## 3.3 | Factors affecting streamflow response to native forest restoration

Streamflow response in absolute terms (mm) to clearcutting of *Eucalyptus* plantations and the early stages of native forest restoration varied with precipitation, based on the before-after analysis. Annual and summer precipitation varied twofold over the study period (Table 5), as did runoff ratios (Table S2, Figure S4a in Data S1). High absolute increases in seasonal streamflow (200 to >400 mm) occurred in winter and fall of several years during the restoration period, with a maximum increase (>600 mm) in fall of 2014 when the highest fall precipitation of the entire record occurred (1040 mm) (Table 5, Figure 5a,b). The largest absolute reductions in streamflow (−200 mm) occurred in fall and winter of 2016, when combined fall and winter precipitation was ~1100 mm compared to the average of ~1800 mm (Table 5, Figure 5a,b).

Streamflow response during the early stages of native forest restoration varied among catchments, as shown by the relationship of precipitation to streamflow (the before-after, control-impact

TABLE 3 Effect of pre-treatment period on runoff ratio response to clearcutting and planting of native forest. RC5, RC10 and RC11 (restoration); RC6 (*Eucalyptus*)

| Runoff ratio | RC5 | RC6 | RC10 | RC11 |
|---|---|---|---|---|
| Annual | | | | |
| 2006–2010 | 0.40 | 0.57 | 0.40 | 0.77 |
| 2009–2010 | 0.27 | 0.58 | 0.39 | 0.74 |
| 2011–2019 | 0.47 | 0.73 | 0.66 | 0.88 |
| % change, 2011–19 versus 2006–10 | 17 | 26 | 63 | 15 |
| % change, 2011–19 versus 2009–10 | 75 | 24 | 70 | 19 |
| Fall | | | | |
| 2006–2010 | 0.25 | 0.35 | 0.27 | 0.73 |
| 2009–2010 | 0.17 | 0.38 | 0.28 | 0.77 |
| 2011–2019 | 0.44 | 0.56 | 0.59 | 0.87 |
| % change, 2011–19 versus 2006–10 | 73 | 60 | 119 | 20 |
| % change, 2011–19 versus 2009–10 | 164 | 47 | 106 | 13 |
| Winter | | | | |
| 2006–2010 | 0.63 | 0.82 | 0.65 | 0.95 |
| 2009–2010 | 0.41 | 0.78 | 0.66 | 0.94 |
| 2011–2019 | 0.61 | 0.92 | 0.92 | 1.01 |
| % change, 2011–19 versus 2006–10 | −3 | 13 | 41 | 7 |
| % change, 2011–19 versus 2009–10 | 47 | 18 | 39 | 7 |
| Spring | | | | |
| 2006–2010 | 0.34 | 0.63 | 0.38 | 0.75 |
| 2009–2010 | 0.28 | 0.66 | 0.32 | 0.64 |
| 2011–2019 | 0.36 | 0.76 | 0.47 | 0.73 |
| % change, 2011–19 versus 2006–10 | 6 | 21 | 23 | −3 |
| % change, 2011–19 versus 2009–10 | 27 | 16 | 48 | 13 |
| Summer | | | | |
| 2006–2010 | 0.16 | 0.39 | 0.14 | 0.44 |
| 2009–2010 | 0.15 | 0.50 | 0.13 | 0.39 |
| 2011–2019 | 0.17 | 0.58 | 0.19 | 0.62 |
| % change, 2011–19 versus 2006–10 | 6 | 49 | 33 | 42 |
| % change, 2011–19 versus 2009–10 | 9 | 17 | 46 | 61 |

approach). Streamflow increased by 50 to more than 100% in the first 2 years after clear-cutting of *Eucalyptus* (2011 and 2012) in two restored catchments (RC10 and RC11) where *Eucalyptus* stumps were treated with herbicide (Figure 4b). Fall and summer streamflow responses in restored catchments with low runoff ratios (RC5, RC10, runoff ratios 0.2 to 0.5) were two times greater than in a restored catchment with a high runoff ratio (RC11, runoff ratio 0.5 to 0.8), or in the catchment which remained in a *Eucalyptus* plantation (RC6, runoff ratio 0.6) (Figure 6, Figure S4b in Data S1).

Base flow varied with precipitation and among catchments. Base flow accounted for 42% to 45% of total flow in fall, 50% in winter, and 52 to 54% in spring on average over the study period in all catchments (Figure S5 in Data S1). Summer base flow was lower and more variable in dry years (2013 to 2015) and in the restored catchments with low runoff ratios (RC5 and RC10, base flow 37% to 41% of total) compared to the catchments with high runoff ratios (RC11 [restoration] and RC6 [*Eucalyptus*], base flow 50% to 53% of total) (Figure S5 in Data S1).

Base flow increased in the early stages of native forest restoration compared to the pre-treatment period under *Eucalyptus* plantations (Table 6), and increases were greatest in catchments with low runoff ratios. Summer base flow declined more rapidly and reached levels an order of magnitude lower during each dry season in the restored catchments with low runoff ratios (RC5 and RC10, Figure S4 in Data S1) than in the catchments with high runoff ratios (RC11 [restoration] and RC6 [*Eucalyptus*]), especially in the pre-treatment period (2006 to 2010) and the first five post-treatment years (2011 to 2015) (Figure 7). In all catchments, base flow in fall and winter was significantly positively related to precipitation in the same season, and winter base flow was significantly related ($R > 0.6$, $p < 0.05$) to fall precipitation. Summer base flow was significantly positively related to spring precipitation at RC5 (restoration) and RC6 (*Eucalyptus*) (Figure 8).

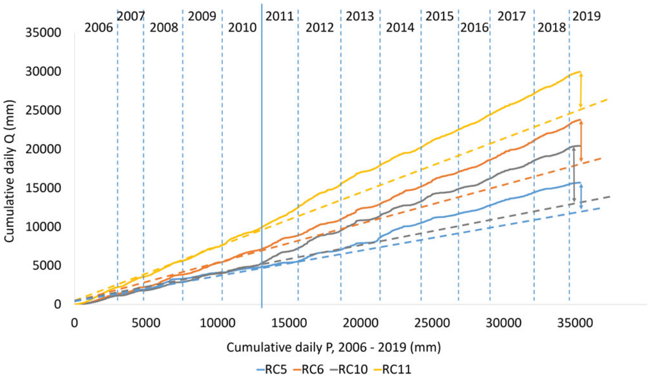


**FIGURE 3** Double-mass curves of accumulated daily streamflow (Q) versus accumulated daily precipitation (P), both in mm for the 2006–2019 period. Vertical dashed lines indicate the beginning of each water year. Solid vertical line indicates the date of completion of clearcutting of *Eucalyptus* plantations and starting the period of native forest restoration in RC5, RC10 and RC11. (April 2011). Diagonal dashed lines are the trend lines projected from the pre-treatment period for each catchment. Double-ended arrows indicate the difference between observed cumulative streamflow and predicted streamflow based on the pre-treatment relationship

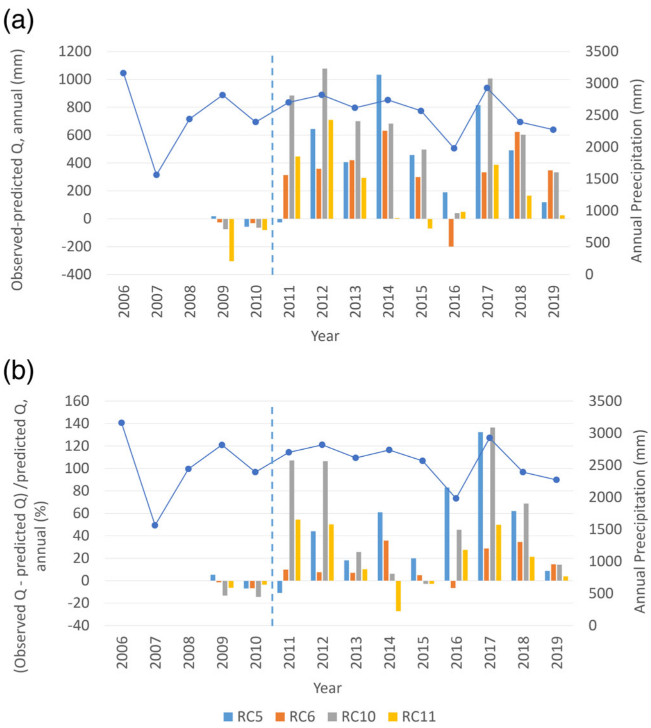


**FIGURE 4** Annual precipitation (blue lines) and annual streamflow response (coloured bars) to clearcutting of *Eucalyptus* plantations and growth of native forests under restoration. (a) Observed minus predicted streamflow (mm), (b) observed minus predicted streamflow as % of predicted. Vertical dashed line indicates the date of completion of clearcutting of *Eucalyptus* plantations and starting the period of native forest restoration in RC5, RC10 and RC11. (April 2011). Streamflow for 2006 to 2008 is not shown, because models fitted using data collected with 15-min gaging could not be applied to these years, when stage was measured manually once per day and only in catchments RC5 and RC6

Base flow increased in all restored catchments in years six to nine after restoration began (2017 to 2019) (Figure 9). Increases in base flow in 2011 to 2019 relative to the pre-treatment (2009–2010) varied from 28% to 87% in the restored catchments (RC5, RC10 and RC11), and were least in the restored catchment (RC11) with the highest runoff ratio and the greatest summer base flow (Table 6, Figures S4 and S5 in Data S1). Despite below average precipitation during the last 2 years (2018 and 2019), annual baseflow remained higher in the restored catchments (RC5, RC10, RC11) than the catchment with the *Eucalyptus* plantation (RC6) (Table 4, Figure 9, Figures S3 and S6 in Data S1).

## 4 | DISCUSSION

Global increases in intensive forestry have raised concerns about forest plantation effects on water, but no studies have tested the effects of the removal of exotic fast-growing forest plantations and native forest restoration on catchment hydrology. Results of a 14-year paired watershed experiment involving ecological restoration in south central Chile demonstrate that streamflow and base flow increased during the first 9 years of native forest restoration after clearcutting of plantations of exotic fast-growing *Eucalyptus* and planting of native temperate rainforest species. These findings are relevant to concerns about reduced streamflow attributed to intensive plantation forestry using non-native species in South America and southern Africa (Alvarez-Garreton et al., 2019; Ferraz et al., 2013; Ferraz et al., 2019; Garcia et al., 2018; Huber et al., 2008; Lara et al., 2009; Little et al., 2009; Scott & Gush, 2017). These findings are also relevant globally, such as in North America, where evidence is accumulating that intensively managed plantations of native species can reduce streamflow (Gronsdahl et al., 2019; Perry & Jones, 2017; Segura et al., 2020). Drought and climate change can exacerbate these reductions (Crampe et al., 2021; Iroumé et al., 2021). The findings presented here indicate that native forest restoration may offset expected streamflow reductions from climate change and help meet Sustainable Development Goals. (e.g., Creed et al., 2019; Galleguillos et al., 2021).

The age, species, and tree density of the *Eucalyptus* plantations in this study and the catchment pre-treatment runoff ratios were representative of those in *Eucalyptus* and other exotic forest plantations in south-central Chile and Brazil (e.g., Ferraz et al., 2019; Huber et al., 2008; Iroumé et al., 2020). The magnitude of streamflow response in this long-term experiment is roughly consistent with the change in streamflow associated with forestry plantations in a large-scale observational study in Chile (Alvarez-Garreton et al., 2019). After removal of *Eucalyptus* plantations followed by 9 years of native forest restoration, increases in streamflow in absolute terms (mm) were highest and more consistent from year to year in fall and winter, and low and inconsistent in spring and summer, whereas relative streamflow changes (%) were highest in the fall and summer, as shown in many paired watershed studies (e.g., Jones & Post, 2004). This finding implies that evapotranspiration rates were lower in the

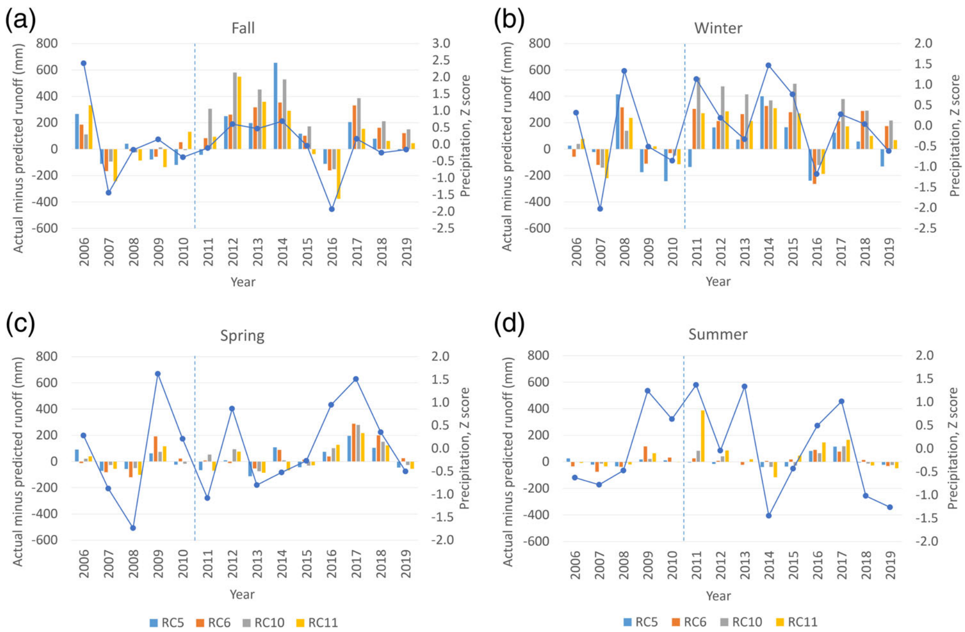


**FIGURE 5** Seasonal precipitation (blue lines) and seasonal streamflow response (mm) to early stages of native forest restoration, based on before-after analysis (coloured bars) (water years 2006 to 2019). Post-treatment streamflow difference from pre-treatment mean (2006 to 2010) (mm) for each year by season: (a) austral fall (April-June), (b) austral winter (July-September), (c) austral spring (October-December), (d) austral summer (January-March). Data for streamflow for 2006 to 2008 in RC10 and RC11 were estimated from precipitation (see methods). Vertical dashed line indicates the date of completion of clearcutting of *Eucalyptus* plantations and starting the period of native forest restoration in RC5, RC10 and RC11 (April 2011)

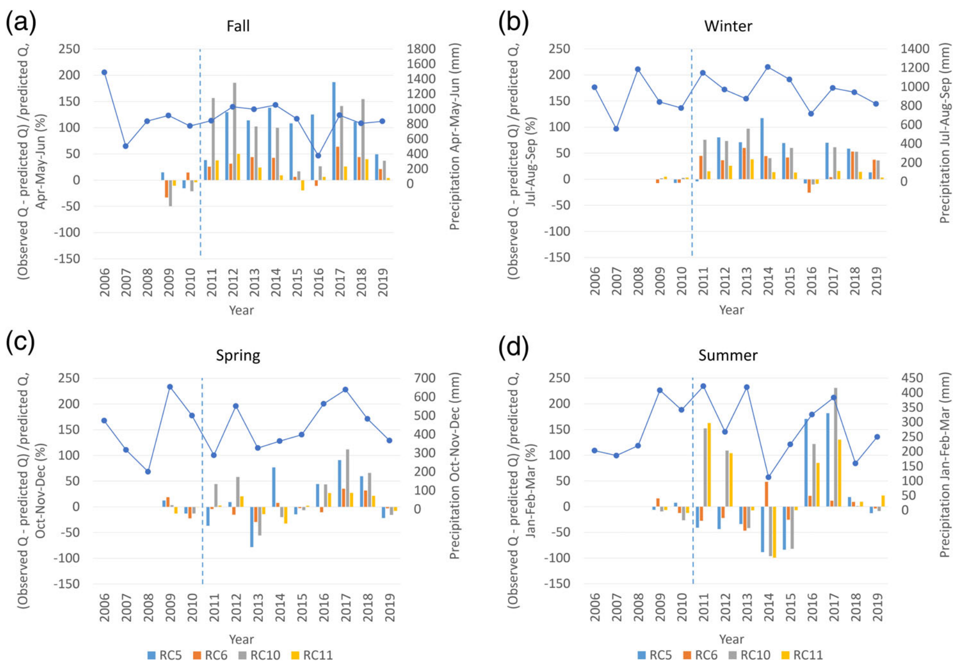


**FIGURE 6** Seasonal precipitation (blue lines) and seasonal streamflow response (percentage change) to early stages of native forest restoration, based on before-after, control-impact analysis using the pre-treatment relationship of precipitation to streamflow in each catchment (2009 and 2010). Columns are observed minus predicted streamflow as % of predicted. (a) Austral fall (April to June), (b) austral winter (July to September), (c) austral spring (October to December), (d) austral summer (January to March). Streamflow for 2006 to 2008 is not shown, because models fitted using data collected with continuous gaging could not be applied to these years, when stage was measured manually once per day and only in catchments RC5 and RC6. Vertical dashed line indicates the date of completion of clearcutting of *Eucalyptus* plantations and starting the period of native forest restoration in RC5, RC10 and RC11 (April 2011)

**TABLE 4** Means and standard deviations of vegetation cover; density of seedlings, saplings, and adult trees; and basal area in 2020 in the restored catchments (RC5, RC10 and RC11)

| | RC5 | | RC10 | | RC11 | |
|---|---|---|---|---|---|---|
| | Restored area | Buffer | Restored area | Buffer | Restored area | Buffer |
| Vegetation cover (%) | | | | | | |
| Non-tree species | 42 ± 14 | 61 | 37 ± 13 | 51 | 83 ± 38 | 95 |
| Tree species | 48 ± 27 | 100 | 78 ± 9 | 98 | 64 ± 33 | 100 |
| Seedling density (N/ha) | | | | | | |
| *Eucalyptus globulus* | 0 | 0 | 0 | 0 | 0 | 0 |
| Native species | 4244 ± 1470 | 82 484 | 9077 ± 10 377 | 5414 | 1911 ± 1133 | 13 057 |
| *N* of species | 7 | 10 | 12 | 4 | 6 | 9 |
| Sapling density (N/ha) | | | | | | |
| *E. globulus* | 0 | 0 | 0 | 0 | 0 | 0 |
| All native species | 8560 ± 6773 | 6320 | 8720 ± 2620 | 5040 | 7120 ± 5142 | 4160 |
| *Nothofagus dombeyi* | 520 ± 170 | 0 | 280 ± 130 | 0 | 240 ± 196 | 0 |
| Other native species | 8213 ± 6674 | 6320 | 8440 ± 2643 | 5040 | 6880 ± 5118 | 4160 |
| *N* of species | 10 | 10 | 12 | 11 | 9 | 10 |
| Tree density (N/ha) | | | | | | |
| *E. globulus* | 227 ± 122 | 0 | 0 | 0 | 40 ± 57 | 0 |
| All native trees | 613 ± 705 | 3080 | 1350 ± 360 | 2880 | 1180 ± 815 | 1640 |
| *N. dombeyi* | 520 ± 635 | 0 | 1080 ± 271 | 0 | 860 ± 863 | 0 |
| Other native species | 93 ± 83 | 3080 | 270 ± 208 | 2880 | 320 ± 242 | 1640 |
| *N* of species | 5 | 8 | 5 | 12 | 8 | 11 |
| Saplings+trees (N/ha) | | | | | | |
| *N. dombeyi* (mean) | 650 ± 877 | 0 | 1360 ± 374 | 0 | 1100 ± 687 | 0 |
| *N. dombeyi* survival % | 65 ± 71 | - | 89 ± 22 | - | 77 ± 47 | - |
| Basal area ($m^2$/ha) | | | | | | |
| *E. globulus* | 3.1 ± 2.7 | 0 | 0 | 0 | 1.3 ± 1.9 | 0 |
| All native trees | 2.9 ± 3.0 | 38 | 9.0 ± 2.8 | 46 | 9.8 ± 8.2 | 68 |
| *N. dombeyi* | 2.6 ± 2.7 | 0 | 8.2 ± 2.7 | 0 | 8.6 ± 7.5 | 0 |
| Other native species | 0.3 ± 0.3 | 38 | 0.9 ± 0.6 | 46 | 1.1 ± 0.9 | 68 |
| Total basal area (mean) | 6.0 ± 3.9 | 38 | 9.0 ± 2.8 | 46 | 11.0 ± 8.7 | 68 |

*Note:* Buffer = native forest riparian buffer. Other native tree species are naturally regenerated (listed in Table S4 in Data S1). $N = 4$ plots in the restored area (except for RC5 where $N = 3$) and N = 1 plot in the buffer. Seedlings were ≤2 m in height; saplings were >2 m in height and <5 cm dbh; trees were ≥5 cm dbh. Survival (%) of *N. dombeyi* is calculated relative to the mean initial density of planted trees in the plots measured in 2012, except for the plots established in 2020 in which the mean initial plantation density (1500 seedlings/ha) was used.

early stages of native forest restoration, consistent with their lower basal area compared to the former *Eucalyptus* plantation.

## 4.1 | Restoration of base flow

This study provides the first evidence from a paired catchment experiment that the early stages of native forest restoration can increase base flow and dry season (summer, fall) flow. Subsurface flows vary among study catchments, as indicated by differences in runoff ratios (Figure S4 in Data S1) and intra-annual variability in base flow (Figures 7 and 8, Figures S5and S6 in Data S1). Subsurface flows as deep as 6–8 m can be observed on road cuts in the study area under saturated soil conditions in winter. The underlying geology includes Tertiary marine sediments whose bedding planes dip at a slope of 60% (CIREN, 2001), steeper than surface slopes (41% to 47%, Table 1), which may convey subsurface flow among these small catchments.

Replacement of *Eucalyptus* plantations with the early stages of native forest restoration appears to explain increased base flow in the last 3 years of the study in the catchments undergoing restoration (RC5, RC10, RC11) and no change in base flow in the catchment which remained a *Eucalyptus* plantation (RC6) (Figure 9). High evapotranspiration by *Eucalyptus* plantations may have depleted deep soil moisture reservoirs in RC5, RC10 and RC11 prior to 2011, as shown in other studies (Iroumé et al., 2021). The lower basal area of young

**TABLE 5** Precipitation (mm) by season and water year (April 1 to March 31)

| Year | Annual (Apr–Mar) | Fall (Apr–Jun) | Winter (Jul–Sep) | Spring (Oct–Dec) | Summer (Jan–Mar) |
|---|---|---|---|---|---|
| 2006 | 3148 | 1478 | 994 | 473 | 203 |
| 2007 | 1558 | 498 | 557 | 317 | 186 |
| 2008 | 2427 | 823 | 1184 | 200 | 220 |
| 2009 | 2804 | 901 | 840 | 654 | 409 |
| 2010 | 2347 | 767 | 776 | 463 | 342 |
| 2011 | 2694 | 836 | 1147 | 289 | 422 |
| 2012 | 2806 | 1017 | 970 | 552 | 267 |
| 2013 | 2603 | 983 | 874 | 327 | 419 |
| 2014 | 2725 | 1040 | 1209 | 364 | 112 |
| 2015 | 2554 | 854 | 1078 | 398 | 224 |
| 2016 | 1977 | 373 | 715 | 563 | 326 |
| 2017 | 2916 | 906 | 987 | 639 | 384 |
| 2018 | 2385 | 801 | 942 | 483 | 160 |
| 2019 | 2144 | 824 | 820 | 367 | 133 |
| average | 2506 | 864 | 935 | 435 | 272 |
| SD | 412 | 254 | 187 | 135 | 110 |
| CV | 0.16 | 0.29 | 0.20 | 0.31 | 0.41 |
| % | 100 | 34 | 37 | 17 | 11 |
| min | 1558 | 373 | 557 | 200 | 112 |
| max | 3148 | 1478 | 1209 | 654 | 422 |
| range | 1591 | 1105 | 652 | 454 | 310 |
| range as % of average | 63 | 128 | 70 | 104 | 114 |

**TABLE 6** Mean monthly base flow (mm) and precipitation (mm), and percent change in base flow relative to the pre-treatment periods in the study catchments

| | RC5 | RC6 | RC10 | RC11 | Precipitation |
|---|---|---|---|---|---|
| 2006–2019 | | | | | |
| mean | 46 | 72 | 59 | 85 | 211 |
| SD | 52 | 58 | 65 | 70 | 143 |
| CV | 1.1 | 0.8 | 1.1 | 0.8 | 0.7 |
| 2006–2010 | | | | | |
| mean | 39 | 58 | 38 | 71 | 206 |
| SD | 45 | 49 | 41 | 65 | 156 |
| CV | 1.2 | 0.8 | 1.1 | 0.9 | 0.8 |
| 2009–2010 | | | | | |
| mean | 28 | 65 | 39 | 72 | 215 |
| SD | 23 | 38 | 40 | 60 | 124 |
| CV | 0.8 | 0.6 | 1.0 | 0.8 | 0.6 |
| 2011–2019 | | | | | |
| mean | 50 | 80 | 71 | 93 | 214 |
| SD | 55 | 61 | 73 | 72 | 136 |
| CV | 1.1 | 0.8 | 1.0 | 0.8 | 0.6 |
| % change, 2011–2019 versus 2006–2010 | 28 | 38 | 87 | 31 | 4 |
| % change, 2011–2019 versus 2009–2010 | 79 | 23 | 82 | 29 | −1 |

*Note:* Periods include the full study (2006–2019), before treatment (2007–2010 and 2009–2010) and after treatment (2011–2019). The treatment involved clear-cutting and planting of native forest in 2011 in RC5, RC10 and RC11; RC6 remained a *Eucalyptus* plantation.

regenerating native forests in RC5, RC10 and RC11 may have permitted recharge of deep soil moisture and gradual recovery of base flow in restored catchments over the period from 2011 to 2019. These findings confirm inferences from other studies linking forests plantations and drought to long-term changes in base flow and dry-season flow (Garreaud et al., 2017; Gronsdahl et al., 2019; Iroumé et al., 2005, 2006; Perry & Jones, 2017; Segura et al., 2020; Silveira et al., 2016).

Streamflow percent increases in response to native forest restoration were highest at two catchments (RC5 and RC10) which had the least base flow, as indicated by low runoff ratios and high summer base flow sensitivity to variation in precipitation, whereas streamflow responses were lower at the restored catchment (RC11) which had the greatest base flow, as indicated by high runoff ratio and low summer base flow sensitivity to variation in precipitation (Figure 4, Table 3, Figure S6 in Data S1). These findings are consistent with other studies showing that catchment hydrology can moderate streamflow response to change in vegetation and climate (Spencer et al., 2020; Tague et al., 2008; Vose et al., 2016).

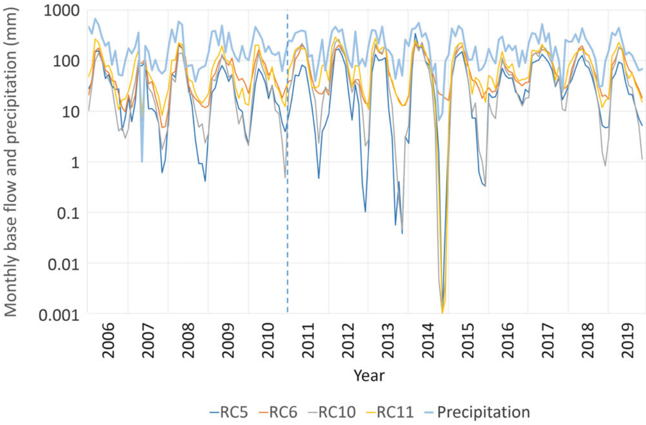


**FIGURE 7** Monthly base flow and precipitation, 2006 – 2019. Note log scale on Y axis. Vertical dashed line indicates the date of completion of clearcutting of *Eucalyptus* plantations and starting the period of native forest restoration in RC5, RC10 and RC11 (April 2011)

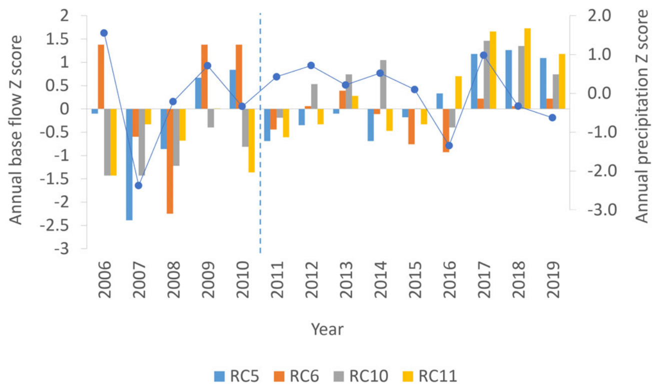


**FIGURE 9** Standardized departures (Z scores) of annual precipitation (blue lines) and annual base flow as a percent of total flow (coloured bars) for watersheds RC5, RC6, RC10 and RC11. Vertical dashed line indicates the date of completion of clearcutting of *Eucalyptus* plantations and starting the period of native forest restoration in RC5, RC10 and RC11. (April 2011)

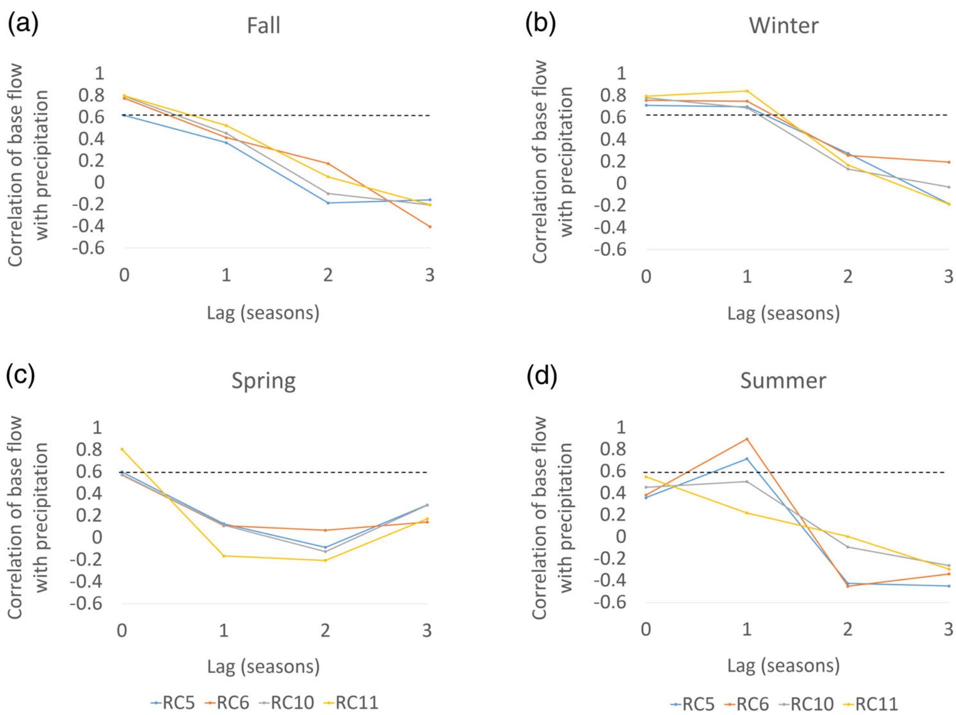


**FIGURE 8** Correlation of base flow with prior precipitation, by season. (a) Austral fall, (b) Austral winter, (c) Austral spring, (d) austral summer, based on data from water years 2009 to 2019. The correlation of base flow with precipitation in that season is shown at the lag of zero. The correlation of base flow in that season with precipitation in the previous 1, 2, or 3 seasons is shown at the lag of 1, 2, 3, respectively. Correlations >0.6 are statistically significant ($p$ < 0.05)

Several factors may explain the unexpected initial increase in streamflow (mm) in the catchment where a *Eucalyptus* plantation was retained (RC6) after clearcutting of an adjacent catchment (RC5) (Figures 1, 2, 4 and 5). First, the clearcutting of the *Eucalyptus* plantation in RC5 may have spilled over into RC6, as implied by a narrow clearcut area that extends into RC6 (Figures 1b and 2c) and a logging road in RC5 that terminates at the catchment boundary with RC6 (Figure 2c). Second, as in other coastal forests (e.g., Brauman et al., 2010), cloudwater and fog interception may be significant contributors to precipitation. Clearcutting of the *Eucalyptus* plantations in the restored catchments (RC5, RC10 and RC11), which are located to the northwest (windward) of RC6 (*Eucalyptus*) may have increased cloudwater interception and thus streamflow in the catchment with the remaining *Eucalyptus* plantation (RC6). Third, the delayed response of streamflow to clearcutting in the restored catchment (RC5, Figure 3), the lower runoff ratio in RC5 compared to the catchment with the *Eucalyptus* plantation (RC6) (Figure S4 in Data S1), and the steeply dipping bedding planes of the underlying geology (CIREN, 2001) all might contribute to subsurface flow from RC5 to RC6. Nevertheless, the before-after, control-impact analysis demonstrates that the increase in streamflow at RC6 is relatively small compared to increases in the restored catchments (RC5, RC10 and RC11, Figures 4b and 6).

## 4.2 | Differences among methods used to detect streamflow change

Results of the two methods used in this study illustrate the tradeoffs between using longer, reconstructed records versus shorter, automated records, and between using before-after comparisons only, versus using precipitation as a control. The before-after analysis [Equation (1)] uses runoff data only and includes a longer pretreatment period, but streamflow data were collected manually only once a day at two catchments and were reconstructed based on precipitation because automated records were lacking at two catchments, and it presents effects as absolute changes (mm) (Figures 4a and 5). In contrast, the before-after, treated-control analysis [Equations (2)–(4)] uses precipitation as a control for streamflow, included a shorter pretreatment period when automated stream gaging records were available, and it presents effects as relative change (%) (Figures 4b and 6). The before-after runoff-only method is sensitive to precipitation, showing small absolute reductions in the spring of 2013 and summers of 2013 to 2015 and large absolute reductions in streamflow in fall and winter of 2016 (Figure 5). In contrast, the before-after, control-impact method controls for precipitation and demonstrates that the reductions in 2013 to 2015 are quite large, whereas the reductions of 2016 are quite small, when precipitation is taken into account (Figure 6). Thus, the method that controls for precipitation more accurately reveals effects of vegetation on streamflow. The before-after, control-impact method (Figures 4b and 6) also reveals how responses vary among the catchments with different runoff ratios (Figure S4 in Data S1) and base flow (Figure 7, Figures S5 and S6 in Data S1). Therefore, the method that controls for precipitation more clearly distinguishes the effects of restoration treatments in RC5, RC10 and RC11 from the response in the catchment that remained a *Eucalyptus* plantation (RC6) (Figures 4b an 6). The differences between these methods underscore the importance of collecting precipitation data and using them as a reference, especially when control catchments are lacking (see Iroumé, Jones & Bathurst this special issue).

## 4.3 | Implications for the future

This study also indicates that the early stages of native forest restoration in areas of former exotic forest plantations may counteract streamflow reductions in response to long-term drying trends. Despite reduced total streamflow in dry years, base flow in the restored catchments (RC5, RC10 and RC11) increased over the 9 years of restoration (2011–2019), and in years six to nine, including the dry years of 2018 and 2019, annual base flow percent was consistently higher than the long term mean in the restored catchments but not in the *Eucalyptus* catchment (RC6) (Figure 9, Table 6). The gradual recovery of annual base flow in restored catchments throughout the 9 years of native forest restoration (Figure 9, Figure S3 in Data S1, Table 4), and the pronounced increase in base flow during the last 3 years of the study, despite low precipitation in the last 2 years of the study, imply that native forest restoration has the potential to restore deep soil moisture reservoirs that sustain base flow during dry periods, and therefore may enhance the resilience of restored catchments to drought.

Climate models project continued drying in Chile throughout the present century (Boisier et al., 2016; Bozkurt et al., 2018; Garreaud et al., 2017). Ongoing studies, such as this one, are needed to understand how native forest restoration influences streamflow response to climate change throughout South America. Ideally, a long-term study program would consider how streamflow response to native forest restoration depends on former forest plantation species (e.g., *Eucalyptus*, *Pinus*), stand density and age, as well as soil type, native forest composition, density and diversity along climatic gradients.

# 5 | CONCLUSIONS

Recent increases in industrial plantation forestry globally, combined with calls for native forest conservation and restoration, raise questions about how native forest restoration affects hydrology. Using a novel, before-after, treated-control analysis, this study demonstrated that the first 9 years of native forest restoration in former *Eucalyptus* plantations increased streamflow and base flow in the Valdivian Coastal Reserve of south-central Chile. To our knowledge this study is the first to test streamflow response to native forest restoration in former fast-growing forest plantations. Clear-cutting of *Eucalyptus* plantations and replacement with young planted and naturally regenerating native forest species produced a persistent increase in total streamflow and a gradual increase in base flow, whereas base flow remained low in a catchment with a 7 to 20 year-old *Eucalyptus* plantation. These findings are consistent with the interpretation that the early stages of native forest restoration can restore streamflow in areas of former intensively managed fast-growing plantations. The results presented here are relevant to global efforts to restore native forest ecosystems on land currently intensively managed with fast-growing forest plantations and may inform policy and decision-making in areas experiencing a drying trend associated with climate change.

This catchment forest restoration study is a long-term effort. The native forests under restoration are young (8 years old) and will continue to change and affect streamflow as they grow. The development of a fully stocked, multi-tier forest is expected to take 50 to 70 years, and conditions comparable to old-growth Valdivian rainforest will require 130 to 180 or more years (Lara et al., 2013). Continued monitoring of these experimental catchments is essential to understand how native forest succession influences streamflow in the long term.

This long-term forest hydrology research and monitoring program has been possible due to a diverse institutional arrangement involving academic, NGO, and forest industry partners, and a sequence of grants from various agencies throughout this period. Maintaining long-term catchment studies is a major challenge in Chile, which like many countries in Latin America lacks a national funding program for long-term catchment or ecosystem research. The basic research findings about hydrology and forest succession and their relevance to key policy decisions about water and forest ecosystems in the context of climate change, as shown by this study, underscore the importance of continuation and expansion of long-term catchment forest hydrology studies in Chile and elsewhere in the global South.

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## DATA AVAILABILITY STATEMENT

Daily precipitation and streamflow data covering the period April 2006-March 2019 used in this article is available to any user at: http://www.cr2.cl/datos-cuencas-restauracion-reservavaldiviana/.

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## SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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