

Exotic tree plantations in the Chilean Coastal Range: Balancing effects of discrete disturbances, connectivity and a persistent drought on catchment erosion

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Abstract

The Coastal Range in the Mediterranean segment of the Chilean active margin is a soil mantled landscape able to store fresh water and potentially support a biodiverse native forest. In this landscape, human intervention has been increasing soil erosion for ~200 yr, with the last ~45 yr experiencing intensive management of exotic tree plantations. At the same time, this landscape has been affected by a prolonged megadrought, and how the anthropogenic disturbances and hydrometeorologic trends affect sediment transport is not yet well understood.

In this study we calculate a decadal-scale catchment erosion rate from suspended sediment loads and compare it with a 10⁴-year-scale catchment denudation rate estimated from detritic 10Be. We then contrast these rates against the effects of discrete disturbances and hydroclimatic trends. Erosion/denudation rates are similar on both time scales, i.e. 0.018 ± 0.005 mm/yr and 0.024 ± 0.004 mm/yr, respectively. Recent human-made disturbances include logging operations during each season and a dense network of forestry roads, which increase structural sediment connectivity. Other disturbances include the 2010 M_w 8.8 Maule earthquake, and two widespread wildfires in 2015 and 2017.

A decrease in suspended sediment load is observed during the wet seasons for the period 1986-2018 coinciding with a decline in several hydroclimatic parameters. The low 10⁴-year denudation rate agrees with a landscape dominated by slow soil creep. The low 10-year-scale erosion rate and the decrease in suspended sediments, however, conflicts with both the observed disturbances and increased structural (sediment) connectivity. These observations suggest that, either suspended sediment loads and, thus, catchment erosion, are underestimated, and/or that decennial sediment detachment and transport were smeared by decreasing rainfall and streamflow. Our findings indicate that human-made disturbances and hydrometeorologic trends may result in opposite, partially offsetting effects on recent sediment transport, but both contribute to the degradation of the landscape.

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13 In this study we calculate a decadal-scale catchment erosion rate from suspended sediment loads and
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29 Introduction

30 Over 75% of Earth's ice-free land has been altered by humans (Ellis and Ramankutty, 2008), with severe
31 consequences for sediment transport during the Anthropocene (Syvitski et al., 2022). Land Use and Land
32 Cover Changes (LULCC) are important in increasing soil erosion (Borrelli et al., 2020). Human-made forests
33 – or better, tree plantations (DellaSala, 2020) – are frequently disturbed by logging and the implementation
34 of forestry roads. Such disturbances may intensify soil erosion (e.g., Schuller et al., 2013; Sidle and Ziegler,
35 2012), as may heavy machinery traffic (e.g., Malmer and Grip, 1990), wildfires and terracing (e.g., Martins
36 et al., 2013). Short rotational cycles, i.e. the period between planting, harvesting, and replanting of tree
37 plantations, also change hillslope stability by cycles of root strength decay and recovery, which in turn
38 promote landsliding and debris flows (Imaizumi et al., 2008; Montgomery et al., 2000). Ultimately, all such
39 processes may modify sediment trajectories and storage on hillslopes and along rivers (Wainwright et al.,
40 2011) with long-lasting impacts on sediment yields for periods of 10-100 years (Moody and Martin, 2009;
41 Bladon et al., 2014).

42 The Chilean Coastal Range (CCR) in its Mediterranean section (35 - 37.5° S) is a landscape of gentle
43 and largely convex hillslopes. Here, forests, soils and water are closely coupled (Galleguillos et al., 2021).
44 This morphology results from relatively slow denudation rates by soil creep on regolith-mantled landscapes

45 (Roering et al., 2007), yet modified by the underlying bedrock (Gabet et al., 2021). Currently, the remnants
 46 of secondary native forest stand on soils as thick as 2 m (Soto et al., 2019), suggesting such minimum
 47 soil depths under undisturbed conditions. In the absence of snow storage, these soils form a major fresh
 48 water supply along the Mediterranean CCR, which many rural communities rely on. Thus, decision-making
 49 regarding land management is strategic for the resilience of these communities (e.g., Gimeno et al., 2022),
 50 especially under recent (Garreaud et al., 2020) and projected (IPCC, 2021) conditions of water scarcity.

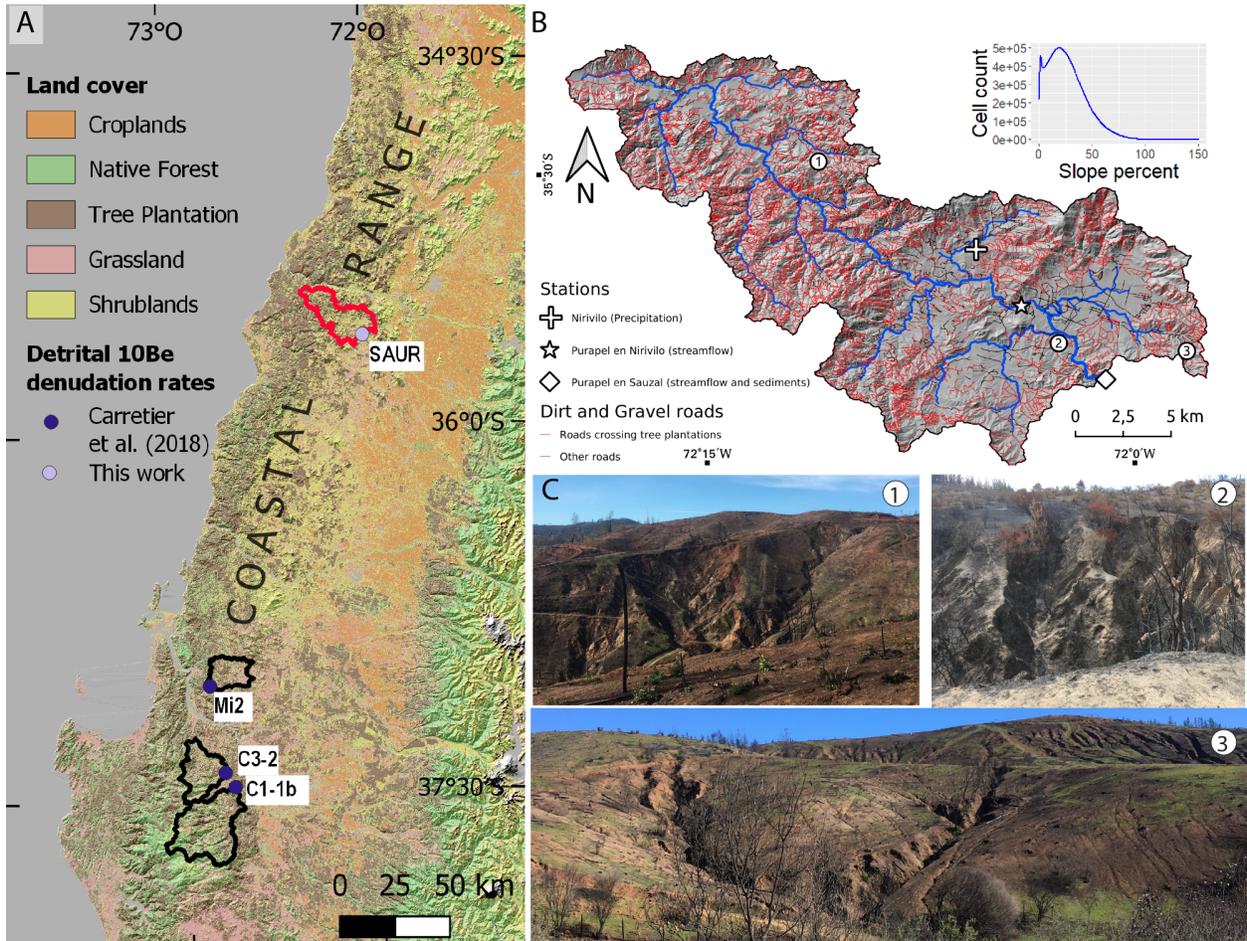


Figure 1: Study region. A. Land cover in the Coastal Range (Zhao et al., 2016) and catchments with published detrital ¹⁰Be denudation rates outlined in black (Carretier et al., 2018). The Purapel catchment, which denudation rate is presented in this work, is represented in red. B. Purapel catchment. All the detected forestry roads intersecting tree plantations and the position of photos in C are shown. Elevation data comes from a 5-m resolution LiDAR DTM obtained in 2009. C. Photos captured on hillslopes of Purapel catchment.

51 The CCR has experienced deforestation for more than 200 years (Armesto et al., 2010) intensifying soil
 52 erosion, as has been recognized by Bianchi-Gundian (1947) and Chilean governments in the middle of 20th
 53 century (IREN, 1965). From the beginning of 20th century, governments blamed environmental issues due to
 54 deforestation to promote the expansion of tree plantations (e.g., CONAF and MINAGRI, 2016; Pizarro et al.,
 55 2020). The most relevant transformation of land cover began with the law DL 701 (1974) to subsidize the

Name	Denudat. rate (mm/yr)	Denudat. rate unc. (mm/yr)	Char. time (kyr)	Lat	Lon	Catch. area (km ²)	Analyzed grain size (mm)	[¹⁰ Be] (at/g)	[¹⁰ Be] unc. (at/g)	Standard material	Source
SAUR	0.024	0.004	25	-35.6197	-72.0171	406	[0.5,1]	143751	5469	STD-11	This work
Mi2	0.037	0.006	16	-37.0488	-72.8614	235	[0.5,1]	93772	4280	4325	Carretier et al. (2018)
C3-2	0.039	0.007	15	-37.4052	-72.7976	357	[0.5,1]	97896	8272	4325	Carretier et al. (2018)
C1-1b	0.041	0.010	14	-37.4652	-72.7495	739	[0.5,1]	113680	20735	4325	Carretier et al. (2018)

Table 1: Published and new detrital ¹⁰Be denudation rates in the Mediterranean CCR. Denudation rates and their uncertainties were calculated with procedures described in Carretier et al. (2018). Characteristic time refers to the quartz residence time within a particle mean free path in rocks of 60 cm, and represent a timescale for steadily erosion (Lal, 1991). ¹⁰Be concentrations and their uncertainties were analyzed in the CEREGE laboratory with the indicated standard.

56 forestry sector (Manuschevich, 2020). This law and following political action accelerated LULCC, which in
57 practice transformed degraded lands, shrublands and native forest into industrially managed tree plantations
58 (Heilmayr et al., 2016). From ~450,000 ha of tree plantations in 1974 (Barros, 2018), their spatial extent
59 increased to at least some 2.8 ± 0.2 million ha in 2011 (Heilmayr et al., 2016), mostly within the Mediterranean
60 CCR (Fig. 1).

61 In Chile, tree plantations are managed mostly as monocultures of fast-growing *Eucalyptus* spp or *Pinus*
62 *Radiata*. The rotation cycles are as short as 9-12 and 18-25 years, respectively (INFOR, 2004; Gerding,
63 1991). As a consequence, the CCR ranks among the highest worldwide in terms of combined forest loss and
64 gain (Hansen et al., 2013). (Hansen et al., 2013) identified tree cover, forest loss and gain from Landsat
65 imagery which in turn provide time-series of spectral metrics at each pixel. Clear-cut areas in Chilean tree
66 plantations are generally detectable at the Landsat resolution scale because the clear-cuts usually expand
67 over entire hillslopes (Fig. 2). Such practice is permitted by current Chilean law, as clear-cutting requires
68 environmental impact assessments only for harvest areas ≥ 500 ha/yr or $\geq 1,000$ ha/yr in Mediterranean
69 and Temperate regions, respectively (*Artículo Primero, Título I, Artículo 3, m.1* at Chilean Law 19.300,
70 2013).

71 Tree plantations frequently are intersected by dense networks of logging roads. These roads are intended to
72 facilitate access and use of heavy forest machinery, storage and transport of timber, as well as the subsequent
73 (re-)plantation. Logged hillslopes, like logging roads, are important sediment sources during storms and after
74 wet-season clear-cutting (Schuller et al., 2013, 2021; Aburto et al., 2020). For example, Aburto et al. (2020)
75 reported highest post-harvest soil loss in a catchment sustaining a one-year-old plantation. Post-harvest
76 erosion is mainly rainfall triggered (Aburto et al., 2020; Schuller et al., 2013) and after exceeding specific
77 rainfall intensity thresholds (Mohr et al., 2013). The erosional work efficacy depends on the logging season,
78 which is higher for wet season logging (Mohr et al., 2014). At the storm to yearly scale (10^{-4} - 10^0 yr), roads
79 are prime sources and routers of sediments in catchments covered by tree plantations (Schuller et al., 2013).
80 This is not surprising, since they remain bare and prone to compaction by heavy machinery transit. These
81 roads often intersect streams, which form bypasses to preferentially route sediment (Fig. 2), increasing the
82 efficacy of mass transfer within a geomorphic system, or sediment connectivity (Wohl et al., 2019). In this
83 case, road networks modify the pathways of runoff and sediments, and may also modify thresholds of rainfall
84 to trigger sediment detachment and transport (for example, due to soil compaction), potentially affecting

85 the structural and functional components of sediment connectivity, as defined by Wainwright et al. (2011).
86 This shift is also relevant to constraining off-site impacts of soil erosion (Boardman et al., 2019).

87 Despite the increase in structural connectivity, sediment mobilization depends mostly on specific thresh-
88 olds of rainfall. For example, hydrologic connectivity to initiate runoff in recently logged areas required a
89 threshold of 20 mm/hr in rainfall simulations on tree plantations near Nacimiento (Mohr et al., 2013). In
90 the absence of long term records of rainfall intensities, hydro climatic trends on rainfall and streamflow are
91 relevant to interpret catchment erosion. In Central Chile (30-39°S), rainfall decreased at ca. 4% per decade
92 between 1960 and 2016 (Boisier et al., 2018b), culminating in an unprecedented megadrought starting 2010
93 (Garreaud et al., 2020).

94 While the erosional response of logging is largely indisputable, hydrologic responses to tree harvest are
95 ambiguous. On the one hand, logging may increase streamflow discharge in general and peak flow in particular
96 (Iroumé et al., 2006), logging may also decrease streamflow discharge due to enhanced groundwater recharge
97 immediately after logging (Mohr, 2013). The distinct responses may most likely vary with tree species
98 and age, harvest size, forestry treatment (thinning, clear cutting, replanting), riparian buffer width, and
99 especially, with the moisture storage decrease under recent drought conditions, which exacerbated declines
100 in runoff (Iroumé et al., 2021).

101 In addition to the mega-drought, recent increase in both magnitude and frequency in wildfire affects
102 relatively more tree plantations compared to alternative land cover (Bowman et al., 2019). This is likely
103 because fuel is more abundant under dense plantation cover that connect large continuous tracts of the
104 landscape. Instead, native species are more patchy (Gómez-González et al., 2017, 2018).

105 While the observed disturbances affecting the vegetation cover predict high sediment yields in rivers (e.g.,
106 Reneau et al., 2007; Brown and Krygier, 1971), the long and persistent decline in rainfall (Méndez-Freire
107 et al., 2022; Tolorza et al., 2019) together with the high water demands of tree plantations is expected to
108 reduce sediment detachment and mobilization assuming fluvial transport-limited conditions. To evaluate the
109 impacts of these opposite responses and their potential effects in land degradation, we explore the catchment
110 scale erosion of the Purapel river (406 km² of drainage area). To this end, we combine two distinct temporal
111 scales (10⁴ and 10⁻¹ yr), explore discrete disturbance events (2017 and 2015 wildfire, 2010 earthquake, wet-
112 season logging), and calculate sediment connectivity associated with forestry roads.

113 **Materials and methods**

114 **The Purapel catchment**

115 The Purapel river drains the eastern flank of the CCR. The climate is Mediterranean type. Mean annual
116 rainfall is 845 mm, and mean minimum and maximum air temperatures are 7.2 and 20.3°C, respectively,
117 and the fluvial system is exclusively pluvial (Álvarez-Garretón et al., 2018). The catchment is 406 km² and
118 dominated by metamorphic (47.5%) and granitic (44.3%) lithologies. Elevation ranges between 164 and 747
119 m a.s.l. Most hillslopes are gentle (hillslope gradients around 16%), largely convex, and incised by gullies
120 that converted this landscape into badlands (Fig. 1). CIREN (2021) classified most of those hillslopes as
121 severely affected by soil erosion. The dominant soil types are Inceptisols and Alfisols (Bonilla and Johnson,
122 2012). Soil properties are highly variable in space. Yet, soils under tree plantations are generally thinner
123 and depleted in soil organic matter. Throughout the entire soil profile, the soil bulk densities of Eucalyptus

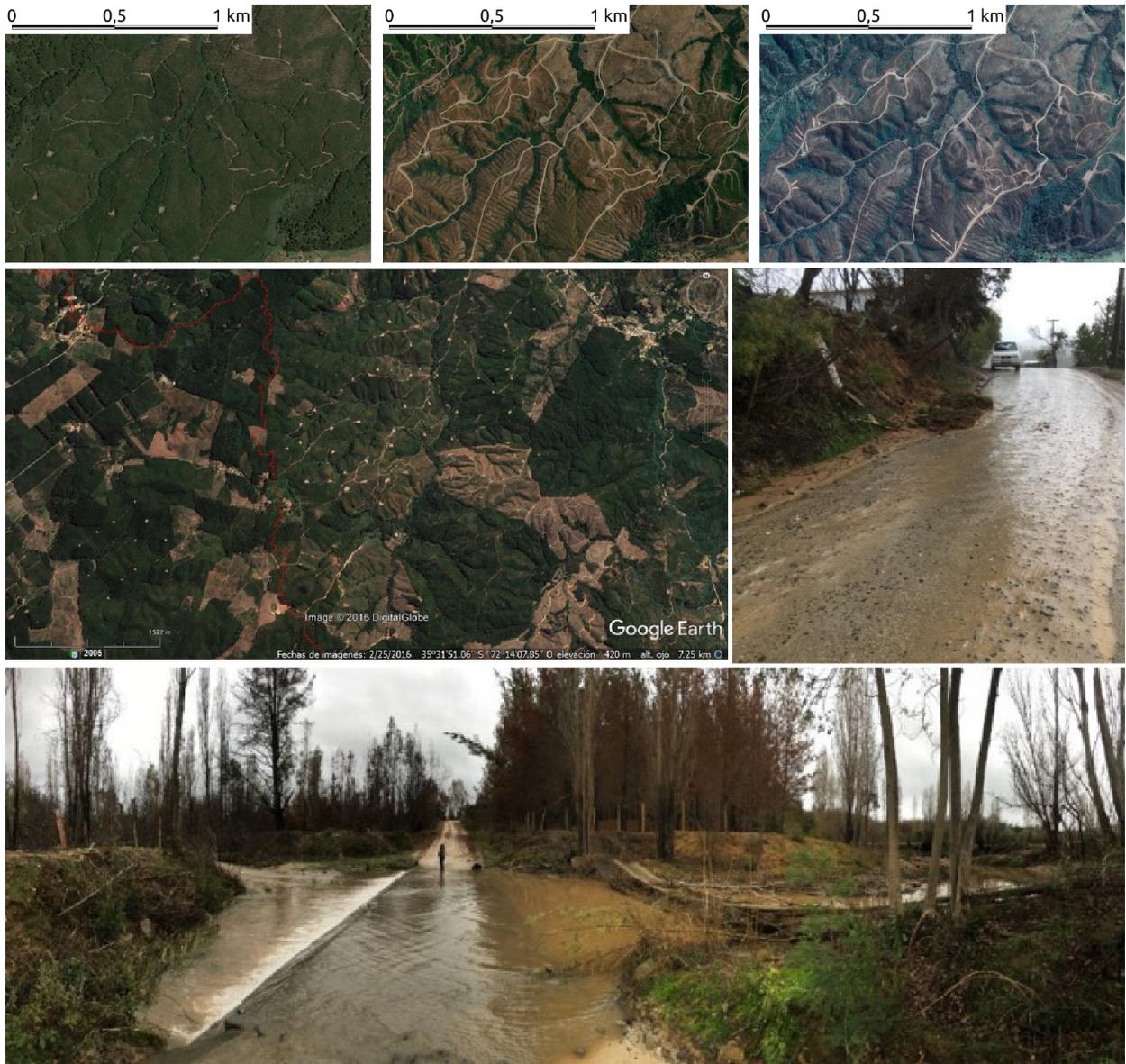


Figure 2: Details of forest roads in the Purapel catchment under different stages of the tree plantation rotational cycle and their connection to streams.

124 $(1.38 \pm 0.08$ to $1.58 \pm 0.12 \text{ g/cm}^3)$ and Pine (1.28 ± 0.18 to $1.53 \pm 0.13 \text{ g/cm}^3$) stands are higher than
 125 under native forests (0.89 ± 0.27 to $1.25 \pm 0.24 \text{ g/cm}^3$) for depths between 0 to 60 cm (Soto et al., 2019).

126 Analysis of hydrometeorologic data

127 Due to the high spatio-temporal variability of rainfall, we tested local trends for available hydrometeoro-
 128 logical data. To this end, we applied the Mann-Kendall test (Helsel et al., 2020) on time series of several
 129 hydrological variables. We also applied LOWESS smoothing (Cleveland, 1981) as a graphical expression of
 130 the main trends. We first evaluated the completeness of the data (supplementary material 1) and applied
 131 autocorrelation tests.

132 Rainfall, potential evapotranspiration and streamflow data from satellite and national stations are avail-
133 able in Mawüim (<https://mawun.cr2.cl/>) and CAMELS-CL (<https://camels.cr2.cl/>) sites. Suspended
134 sediment data is available in the Chilean General Directorate of Water (DGA) site ([https://snia.mop.
135 gob.cl/BNAConsultas/reportes](https://snia.mop.gob.cl/BNAConsultas/reportes)).

136 We analyzed annual and seasonal rainfall and potential evapotranspiration for several periods using
137 both in situ (Nirivilo station) and gridded (CR2MET) data. The CR2MET product merges the ERA-
138 Interim reanalysis, local topographic data, and the calibration with an updated national rain-gauge network
139 (CR2MET, Boisier et al., 2018a). For annual data we excluded years with less than 330 data points and any
140 month with less than 27 data points.

141 We also analyzed streamflow and suspended sediment loads to test for trends on annual, seasonal and
142 monthly basis. The DGA estimated daily streamflows from single gauge stage readings using calibrated rating
143 curves. Roughly once a month, the rating curves are updated by manual current meter measurements. The
144 suspended sediment concentrations (SSC) were sampled on a daily-scale, too. All samples were obtained
145 close to the water surface in vicinity of the water stage. The samples were filtered using a cotton linter
146 cellulose paper with 80% of collection efficiency for particles larger than $0.3 \mu m$ (Advantec Qualitative Filter
147 Papers 2, written communication from DGA operator). Then, they were dried, and combusted for 2 hours
148 at 550-600°C in laboratories of the DGA (Solar, 1999).

149 The streamflow and SSC time series contain gaps. The gaps, however, are not seasonally clustered.
150 Gaps during the dry season are mostly related to ceased streamflow (personal communication from DGA
151 operator). We calculated daily suspended sediment discharge (t/day) as the product of streamflow discharge
152 (m^3/s) and suspended sediment concentration SSC (mg/l), assuming those instantaneous measurements as
153 representative of the entire day, thus converting seconds to day (Pepin et al., 2010). In addition, we calculated
154 the number of data, the percentiles and the mean value of suspended sediment discharge for single hydrologic
155 years, and the number of data and mean value of the three hydrometric parameters (streamflow, SSC and
156 sediment discharge) from monthly to annual scales.

157 For annual streamflow and suspended sediments, we excluded the quantiles or averages for years with
158 less than 185 data points and/or any month with less than 15 data points (around 50%). For seasonal
159 streamflow and suspended sediments, we excluded seasons with less than 60 data points (around 66.6%).
160 Here we define seasons as Summer (DJF), Autumn (MAM), Winter (JJA) and Spring (SON). We calculated
161 the daily baseflow at Purapel en Sauzal station with the Lyne and Hollick filter (Ladson et al., 2013), which is
162 a standard approach used in several studies (e.g. Li et al., 2022; Huang et al., 2021; Teutschbein et al., 2015;
163 Zhang et al., 2017). We used several α values between 0.5 and 0.95 and $n.reflected=30$ days as parameters.

164 Catchment-wide erosion and denudation rates

165 We obtained catchment-wide erosion rates for Purapel river at the gauge “Río Purapel en Sauzal” using
166 two approaches for different time scales, short-term (decadal) from suspended sediments and long-term (10^3
167 to 10^4 yrs) from detrital ^{10}Be . We calculated the long-term denudation rate to establish a benchmark to
168 compare the recent sediment yields against. In most fluvial catchments the long-term rates exceed the
169 short-term rates (Covault et al., 2013). This picture, however, may flip vice versa if soil erosion is high
170 (Hewawasam et al., 2003; Vanacker et al., 2007). A limitation of our approach is the fact that detrital ^{10}Be
171 rates include physical erosion and chemical weathering rates (von Blanckenburg and Willenbring, 2014),

172 while suspended sediment yields account only for physical erosion of very fine sediment (Summerfield and
173 Hulton, 1994), which excludes bedload and dissolved load. Thus, we regard our short-term erosion rates as
174 minimum rates for landscape lowering.

175 For the short-term, we calculated the mean specific sediment discharge ($\text{t}/\text{km}^2/\text{yr}$) as the average of all
176 records (06/1985 to 11/2018) on a yearly scale and normalized by catchment area (Pepin et al., 2010). We
177 estimated resulting erosion rate (mm/year) assuming a mean soil bulk density of $2.6 \text{ g}/\text{cm}^3$ (Carretier et al.,
178 2018).

179 For the long-term, we assume the ^{10}Be concentrations within fluvial sands are proportional for catchment-
180 wide averaged denudation rate (von Blanckenburg, 2005; Granger and Schaller, 2014). This rate integrates
181 over a characteristic timescale that is inversely proportional to the denudation rate. These timescales are
182 commonly longer than 10^3 years (Covault et al., 2013). We therefore regard the ^{10}Be derived rates as a
183 reference that largely excludes recent human disturbances but includes low frequency and high magnitude
184 erosion events (Kirchner et al., 2001). We obtained a bulk sample of fluvial sands from the active river bed
185 along a cross section close to the water stage “Río Purapel en Sauzal”. To this end, we use a standard
186 sampling protocol, collecting sands from the surface at three locations within ~ 10 m distance. We mixed all
187 samples and sieved to a grain size fraction 0.5-1 mm. The mixed sand sample was processed at the French
188 AMS ASTER facility in CEREGE (Standard STD-11).

189 Land cover changes

190 The Purapel catchment has experienced high rates of LULCC since the 19th century. This was largely
191 due to the extensive increase in wheat production caused by the gold rushes in California and Australia
192 (Cortés et al., 2022). Later on, between 1955 and 2014 tree plantations increased from (a minimum of) 10.27
193 (Hermosilla-Palma et al., 2021) to 203.5 km^2 (Zhao et al., 2016). Recently, two large wildfires burned the
194 catchment: In 2015 14% of the catchment area burned. In 2017 almost the entire catchment burned (95%)
195 (Tolorza et al., 2022).

196 To describe recent LULCC in this catchment, we use land cover maps both from compiled sources (1955,
197 1975 and 2017) and from our own (1986, 2000, 2005, 2010 and 2015):

- 198 • The 1955 and 1975 land cover maps of Hermosilla-Palma et al. (2021) cover the headwaters of the
199 Purapel catchment (157 km^2). These maps were made interpreting the land cover from the 1:70,000
200 aerial photograph (Hycon flight) for 1955, and from the 60 m resolution Landsat-2 MMS and the
201 1:30,000 aerial photographs of 1978 (CH-30 flight) for 1975.
- 202 • We used Landsat Surface Reflectance products to identify land cover classes during dry seasons of 1986,
203 2000, 2005, 2010 and 2015. We classified unburned land cover using the Maximum Likelihood Classifier
204 (Chuvieco, 2008) which we trained and validated with 20 and 10 polygons for each class, respectively.
205 We validated the results with field observations during 2014-2015. We sub-classified burned surfaces
206 into low, moderate and severe fire according to the differences in NBR index of pre- and post- fire
207 images (thresholds $\langle 0.1 - 0.269 \rangle$, $\langle 0.27 - 0.659 \rangle$, $\langle 0.66 - 1.3 \rangle$ Key and Benson, 2006).
- 208 • The Land cover map of 2017 was made by Tolorza et al. (2022) with pre-fire Sentinel and LiDAR
209 data. Here, this classification was resampled to 30 m resolution, to be compatible with LANDSAT
210 classifications.

211 Logging roads and sediment connectivity

212 To identify changes in the structural connectivity we applied the Connectivity Index (IC , dimensionless)
213 using the weighting factor (W , dimensionless) of (Cavalli et al., 2013). IC is a semi-quantitative approach
214 to describe the degree of coupling between hillslopes and a target (for example, the stream network):

$$IC = \log_{10} \left(\frac{\overline{WS}\sqrt{A}}{\sum_i \frac{d_i}{W_i S_i}} \right) \quad (1)$$

215 , where \overline{W} and \overline{S} (m/m) are the average weighting factor and slope gradients on the upslope contributing
216 area (A , m²), respectively. d_i (m), W_i (dimensionless) and S_i (m/m) are the path length, the weighting
217 factor and the slope gradient on the i th cell in downslope towards a target.

218 W is calculated from a DTM to account for the effect of topographic roughness. The Roughness Index
219 (RI , m) is the standard deviation of the residual topography. The residual topography refers to the difference
220 between the original DTM and a smoothed version obtained by averaging DTM values on a 5×5 (=25) cell
221 moving window:

$$RI = \sqrt{\frac{\sum_i^{25} (x_i - x_m)^2}{25}} \quad (2)$$

222 , where x_i (m) is the value of one specific cell of the residual topography within the moving window, and x_m
223 (m) is the mean of all 25 window cells. The weighting factor is calculated as:

$$W = 1 - \frac{RI}{RI_{max}} \quad (3)$$

224 , where RI_{max} is the maximum value of RI in the study area.

225 We quantified changes in sediment connectivity due to the forestry roads, RC , as

$$RC = IC_{rs} - IC_s \quad (4)$$

226 , where the subscripts s and rs refer to the stream network and and to the stream network including roads.
227 We fed the model with a mapped forestry road network obtained from images available in the OpenLayers
228 plugin of QGIS and post-2017-fire Sentinel compositions.

229 Disturbances in vegetation

230 We used the Breaks For Additive Season and Trend algorithm (BFAST, Verbesselt et al., 2010) on a LAND-
231 SAT collection to detect disturbances in vegetation at the pixel scale, i.e. ≥ 30 m. In the Purapel catchment,
232 disturbances > 30 m are mostly due to wildfires and/or clear-cuts. Such disturbances lean on the seasonal
233 behavior of the NDVI index on a time series of LANDSAT surface reflectance (Level 2, Collection 2, Tier 1)
234 for the period from 09/1999 to 10/2021. Clouds were filtered using the QA band which uses the CFMask
235 algorithm (Foga et al., 2017). We used the same parameter set as Cabezas and Fassnacht (2018), namely
236 the threshold value for disturbances set to 93 manually labeled reference polygons with fire events, clear-cuts
237 and constant tree-cover. It's worth mentioning, that we applied a sieve filter to the results. Hence, only

238 disturbances greater than 1 ha were considered. We trained the algorithm with the Landsat time series of
239 1999 to 2001. Given the disturbance regime of Purapel catchment (two large wildfires and possible loggings
240 each 9 to 25 years) we run BFAST anticipating three possible breaks for the period 2002-2021. The accu-
241 racy assessment was performed on 35 manually drawn polygons that were randomly distributed across the
242 catchment.

243 Results

244 Hydro climatic trends

245 At the annual scale at Nirivilo rainfall station, most data of the period 1962-2015 passed our completeness
246 assessment criteria (53 of 54 years). In the case of CR2MET, the longest period analyzed here is 1979-2019.
247 Judging from Mann-Kendall tests and LOWESS smoothing, we did not find a single trend for the longest
248 interval of records (1962-2015). Nevertheless, for the period after 1979, we see decreasing non-monotonic
249 trends for rainfall both at Nirivilo station and for CR2MET product. That decrease is steeper for 2000-2019,
250 but less pronounced for intermediate intervals such as 1986-2018. During 1986-2018, however, a decrease in
251 seasonal rainfall is observed for Autumn, at the beginning of the hydrologic year (Fig. 3). Generally, the
252 Aridity Index (AI) follows similar decreasing trends as is the case for rainfall. For only 2 years (1982 and
253 2002) the AI was higher than 1. During all other years, potential evapotranspiration exceeded rainfall, thus
254 indicating persistently dry conditions across this catchment.

255 Streamflow data is available at Purapel en Nirivilo between 1979 and 2019 and at Purapel en Sauzal
256 between 1981-2019. At the annual scale, only 20 and 22, respectively, discontinuous years passed the com-
257 pleteness test. For Purapel en Sauzal streamflow data, results of baseflow separation are in the supplementary
258 material 2. We selected the results obtained with $\alpha=0.7$ for further trend analysis, given the observed mag-
259 nitudes and shape of the baseflow time series. For the Suspended Sediment Concentration data, the longest
260 period is 1985-2018, but only 15 discontinuous years passed the completeness test. Because most of the an-
261 nual time-series failed the autocorrelation and completeness tests, here we report only the seasonal analysis
262 for Purapel en Sauzal station (Fig. 4). Although none of those time-series is monotonic, the sharp decrease
263 in suspended sediment concentrations is clear for the three wetter seasons (Autumn, Winter and Spring).

264 Catchment-wide erosion and denudation rates

265 ^{10}Be denudation rater resulted in 0.024 ± 0.004 mm/yr (table 1), assuming a soil bulk density of 2.6 t/m^3 .
266 This rate translates into a sediment yield of $62.4 \pm 10.4 \text{ tkm}^{-2}\text{yr}^{-1}$. This rate integrates over a characteristic
267 timescale of ~ 25 kyrs. Together with published data, detrital ^{10}Be denudation rates in the CCR point to
268 between 0.02 and 0.05 mm/yr (table 1 Carretier et al., 2018), which are low compared to the global data for
269 catchments of similar size (Covault et al., 2013).

270 Given the data completeness test we assume the decadal catchment-wide erosion rate from suspended
271 sediments to be a conservative estimation. Following Pepin et al. (2010) we calculated the mean specific
272 sediment discharge for all the records between 1985 and 2018 and a 30% of error (Pepin et al., 2010). For
273 the Purapel catchment we estimate $46.99 \pm 14.09 \text{ tkm}^{-2}\text{yr}^{-1}$, equal to 0.018 ± 0.005 mm/yr, assuming the
274 same soil bulk density. Both rates do not statistically differ (Fig. 5).

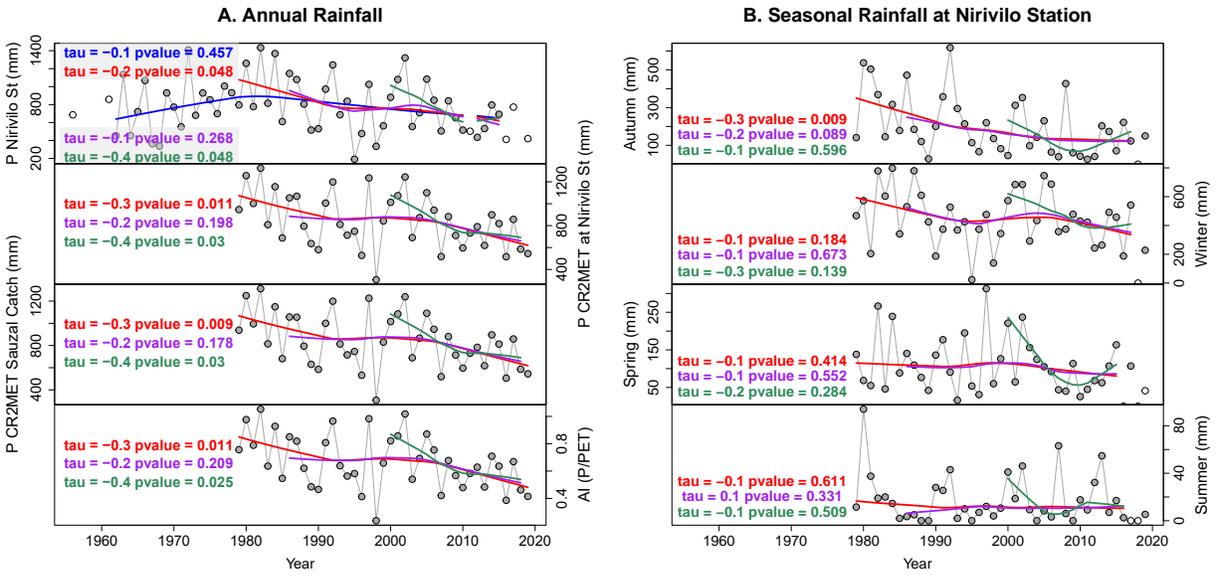


Figure 3: Annual and seasonal rainfall and annual aridity index (AI) at Purapel catchment. Main monotonic trends are tested with Mann-Kendall and LOWESS smoothing for 1962-2015 (blue), 1979-2019 (red), 1986-2018 (purple) and 2000-2018 (green). Unfilled circles are discarded data. A. Annual rainfall and AI time series. B. Seasonal time series for Nirivilo station.

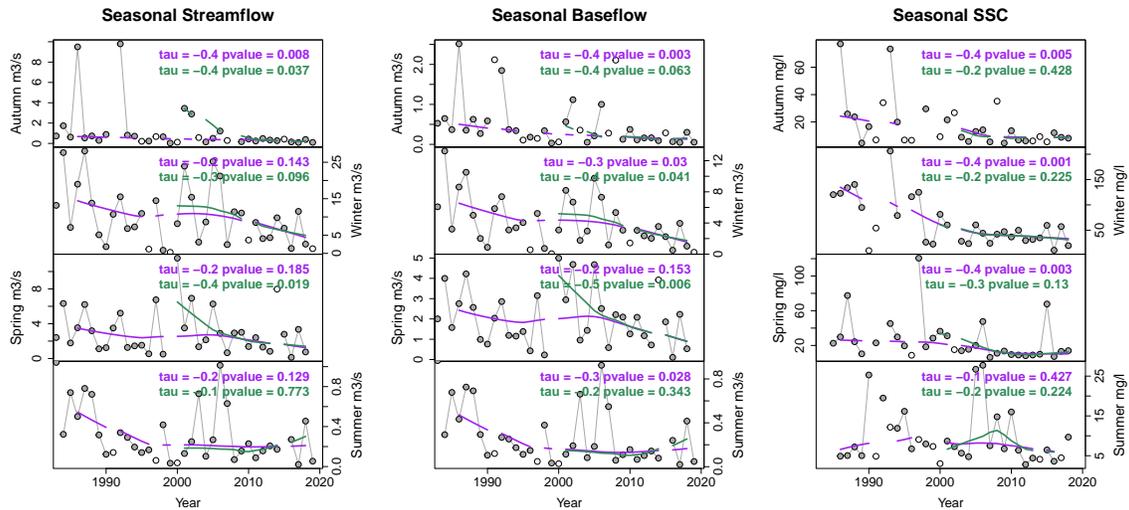


Figure 4: Mean seasonal streamflow, baseflow and suspended sediment concentrations at “Purapel en Sauzal” station. Main monotonic trends are tested with Mann-Kendall and LOWESS smoothing for 1986-2018 (purple) and 2000-2018 (green). Unfilled circles are discarded data. A. Streamflow at Purapel en Sauzal station. B. Baseflow at Purapel en Sauzal station. C. Suspended sediment concentrations at Purapel en Sauzal station.

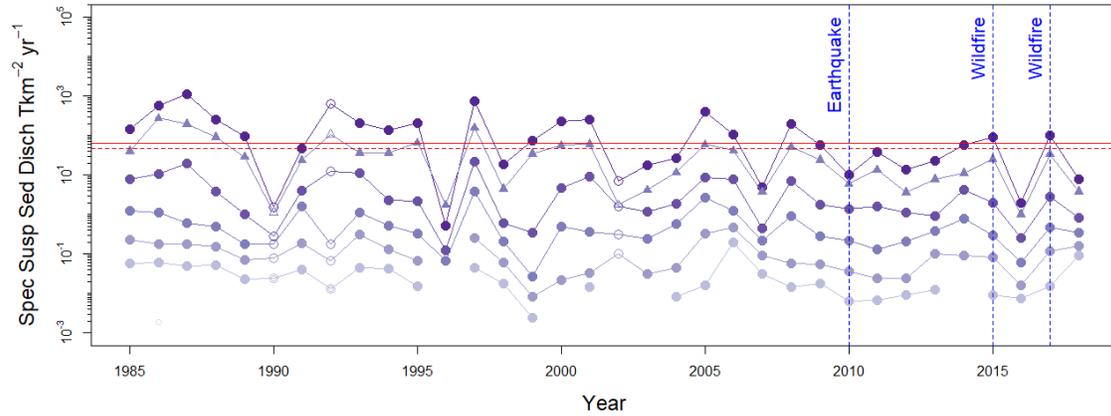


Figure 5: Denudation and specific suspended sediment discharge at Purapel en Sauzal gauge. Distributions of suspended sediment discharge for individual hydrologic years (March to Feb). Purple circles show percentiles (0.05, 0.25, 0.5, 0.75 and 0.95) and purple triangles show the mean. Filled symbols represent years with more than 185 daily data. Catchment erosion/denudation rates are indicated in red. Solid line is the sediment yield equivalent to the ^{10}Be denudation rate, dashed line is the average of all suspended sediment records.

275 Recent land cover changes

276 We developed five land cover maps for the period 1986-2015. The overall classification accuracy ranged
 277 between 83% and 92%. We distinguished between tree plantations, native forests, shrublands and seasonal
 278 grasslands. Seasonal grasslands included bare surfaces, seasonal pasture and sparse vegetation. We also
 279 classified seasonal grasslands to separate recently logged areas (clear-cuts) from other poorly vegetated
 280 areas.

281 Fig. 6 shows that the upper catchment was covered by a minimum of 1,000 ha of tree plantations and
 282 5,500 ha of shrublands in 1955 (Hermosilla-Palma et al., 2021). Between the 1980s and the beginning of
 283 21st century, the most prominent change comprised the transition from seasonal grasslands and shrublands
 284 into tree plantations. The first two classes covered a minimum of 23,550 ha in 1986 and 13,050 ha on 2005.
 285 During the same period, tree plantations expanded from 8,090 to 20,980 ha. Between the wildfires of 2015
 286 and 2017, seasonal grasslands and shrublands together expanded to $\sim 20,300$ ha (Fig. 6).

287 Landscape disturbances

288 The result of our mapped road network is illustrated in Fig. 1. Using this road network on a 5 m resolution
 289 LiDAR, we estimate some 18,000 ha of increased sediment connectivity, resulting in $RC > 0$ (Fig. 7). RC
 290 values exceeding the 95-percentile (> 3.12) are 1,986 ha. That surface of high RC is mostly located on
 291 hilltops: 1,966 ha (i.e. 99%) resulted in upstream contributing area < 1 ha. Particularly these topographic
 292 settings exceed an empirical threshold between high and low connectivity for a mountain catchment, i.e.
 293 -2.32 (Martini et al., 2022). In the Purapel catchment the area above this threshold increased from 1,120
 294 to as much as 6,570 ha simply due to the dense road network. This quantification, however, is done with a
 295 digital terrain model of coarser resolution compared to the original study of Martini et al. (2022) (5 m vs

296 0.5 to 2.5 m).

297 Based on our BFAST modeling, we obtained monthly time series of disturbances for 2002-2019 that we
298 aggregate at the seasonal scale. We achieved a confusion matrix with a balanced accuracy of 0.86 and a F1
299 score of 0.69. For the complete period (Fig. 8A) 13,640 ha of the Purapel catchment (33.7%) experienced
300 one break in the NDVI time series, 16,810 ha (41.5 %) showed two breaks and 5,010 ha (12%) presented
301 three breaks. The undisturbed 12.8% included tree plantation stands that remained unlogged, and seasonal
302 grasslands that remained poorly vegetated. Considering the seasonality (Fig. 8B), the 2015 and 2017
303 wildfires disturbed the catchment in the summer (dry season). Both wildfires were detected in $\sim 5,000$ and
304 24,000 ha, respectively. The disturbances that follow in area ($\sim 2,000$ ha in 2002 and 1,910 ha in 2007)
305 occurred during Autumn, corresponding to the first wet season of the hydrologic year. The largest surface
306 disturbed during a Winter and a Spring were 770 ha each in 2006 and 2009, respectively.

307 Compared to the dNBR classification for 2017 (Tolorza et al., 2022), the BFAST results detected lower
308 burned areas for the 2017 wildfire (33,618 vs 24,299 ha). This difference could be explained by the better
309 capabilities of the dNBR index to detect burned areas, since it is a dedicated method to classify burned
310 surfaces based in the NBR index of a pre- and a post- fire image (Key and Benson, 2006), while the BFAST
311 algorithm was applied here on the NDVI, which is a index more suitable to detect the density of vegetation,
312 and thus more sensitive to clear cuts.

313 Discussion

314 Both ^{10}Be denudation rate and suspended sediment erosion rate are surprisingly similar (Fig. 5). Hence,
315 we argue that the suspended sediment samples capture at least the effects of erosion events recorded on the
316 long-term. Both rates are low for fluvial catchments between 100-1,000 km^2 on a global scale (Covault et al.,
317 2013). Yet, those rates are similar to 3 tributaries of the Biobío river draining the eastern CCR, which are
318 between 0.037 ± 0.006 and 0.042 ± 0.008 mm/yr (Carretier et al., 2018). The low ^{10}Be denudation rate
319 agrees with a landscape dominated by slow soil creep with occasional mass wasting triggered by earthquakes.
320 There were only two reported landslides after the 2010 within the catchment area (Serey et al., 2019). Short
321 term erosion does not exceed the long term denudation, as in other highly human-disturbed catchments
322 (Hewawasam et al., 2003; Vanacker et al., 2007). Considering the low number of complete annual records
323 on streamflow and sediment discharge, and the absence of sub-daily or depth-integrated measurements of
324 sediment concentrations, we regard the decadal sediment data as a conservative estimate for recent catchment
325 erosion. This was also reported for suspended sediments from other rivers of the western Andes (Vanacker
326 et al., 2020; Carretier et al., 2018). In addition, suspended sediments do not record the effects of chemical
327 weathering on denudation rates. This process seems to be relevant in the CCR: in the absence of spatially
328 resolved data of regolith thickness, single observations suggest thick saprolite layers (at least) locally (Vázquez
329 et al., 2016; Mohr et al., 2012; Krone et al., 2021). Thus, depending on the magnitude of mass loss due to
330 chemical weathering, which ranges between 0 and ~ 240 $\text{T}/\text{km}^2/\text{a}$ in other latitudes of the CCR (Schaller and
331 Ehlers, 2022), total denudation in the short term can be equal or even higher than the long term denudation.
332 Yet, we do not have quantitative estimates of local chemical weathering and soil production rates to test
333 that hypothesis.

334 The Purapel river catchment has been a staging ground for rapid expansion of tree plantations and a
335 number of disturbances during the period of suspended sediment monitoring. This landscape was affected

336 by clear-cuts, two widespread wildfires and one Mw 8.8 earthquake. The expansion of tree plantations was
337 mostly at the expense of poorly vegetated surfaces (Fig. 6). Yet, their management includes extensive
338 logging operations – mostly during wet seasons (Fig. 8) – and the construction and maintaining of forestry
339 roads used by heavy machinery. The distribution and density of a road network by itself means an increase
340 in structural sediment connectivity (Fig. 7). Higher connectivity facilitates the routing of detached soils,
341 even from hilltops, where soil production rate is slower compared to the mid-slope or toe positions across
342 the CCR (Schaller and Ehlers, 2022). Thus, hilltop soils may be more difficult to recover during human time
343 scales. The increase in sediment connectivity is distributed along all the hillslopes and more than the half of
344 the catchment experienced at least 2 disturbance events between 2002 and 2019. Despite the disturbances,
345 mean and high (p95) annual values of suspended sediment discharge (Fig. 5) and mean suspended sediment
346 concentrations during the wet seasons (Fig. 4) decreased and remained low after the 2017 fire. In contrast,
347 only the lower percentiles of suspended sediment discharge increased after 2017 wildfire. Such behavior
348 corresponds to baseflow conditions. Regardless, we emphasize that the connectivity index here may be a
349 minimum estimate as we used a coarser digital terrain model compared to the original study.

350 If the suspended sediment record is representative of the sediment yields on Purapel river, the disturbance
351 regime contrasts with expected responses in sediment mobilization, given observations reported in other
352 landscapes (e.g., Reneau et al., 2007; Brown and Krygier, 1971). Nevertheless, the low values of the AI, i.e.
353 the ratio between annual precipitation and evapotranspiration, indicate increasingly scarce water. A decrease
354 can be also interpreted for the streamflow and the baseflow of the wet seasons, mostly in the Autumn. The
355 sediment detachment and transport may coincide with these negative trends. Sediment mobilization both
356 on hillslopes and streams depends mostly on specific thresholds of rainfall intensity and water discharge,
357 while the unprecedented drought starting in 2010, together with high root water uptake by fast-growing
358 tree plantations resulted in a reduction in water availability. In this scenario, a lack of minimum rainfall
359 intensity required to trigger runoff and soil erosion on hillslopes (Mohr et al., 2013) and/or an increase in
360 the residence time of sediments stored within the valleys is plausible. As rainfall and direct runoff control
361 sediment fluxes at the catchment scale (Andermann et al., 2012; Tolorza et al., 2014), sediment mobilization
362 under the current hydrological regime may stay low despite landscape disturbances. In fact, after the severe
363 and extended 2017 fire (Fig. 6) and after the M_w 8.8 Maule earthquake (Tolorza et al., 2019), sediment
364 discharge remained low at Purapel river. A recent model in post-fire sediment cascades indicates that, even
365 when post-fire erosion may be severe in source areas, a substantial fraction of the detached sediment load
366 may (intermittently) remain stored within valleys with only moderate delivery to the river network (Murphy
367 et al., 2019). Assuming transport limitation under the current drought conditions, prolonged residence times
368 of sediments may be also expected. Indeed, both tree plantations and the drought reduced the recharge of
369 deep soil water reservoirs (Iroumé et al., 2021; Huber et al., 2010). Also the loss of soils due to erosion
370 may further reduce the water-storage capacity (Ratta and Lal, 1998). The long deficit of water due to the
371 drought and the tree plantations may reduce groundwater storage, which is consistent with the observed
372 negative trend in baseflow. Such sharp reduction in water availability may limit the sediment transport in
373 channels. The increase of the sediment transport only for the lower percentiles supports the notion that
374 sediment transport is largely restricted to baseflow conditions during the study period. Hence, we cannot
375 unambiguously quantify the overall effect of landscape disturbances on sediment fluxes. Sediment fluxes are
376 more efficient during periods of high flows which correspond to wetter conditions (e.g., Mohr et al., 2013).
377 Consequently, the sediment stored in the valleys, highly rich in nutrients and carbon, can be re-suspended

378 during higher discharge events, causing temporarily delayed off-site problems for several decades to come.

379 The expansion of tree plantations has been proposed as a tool to mitigate soil erosion (CONAF and
380 MINAGRI, 2016). Recently, plantations have been favored as a better solution to mitigate soil erosion
381 compared to native forests for the same Purapel catchment (Pizarro et al., 2020). A direct comparison
382 between native forest and plantations cannot be done for the period 1986-2018, because the major land
383 cover transition was from poorly vegetated surfaces to tree plantations (Fig. 6). Nevertheless, we can
384 discuss whether the observed land management is a suitable solution for soil erosion mitigation in the CCR.
385 There is abundant evidence of increased soil erosion in Chilean tree plantations, such as truncated soil
386 profiles in an eucalyptus stand at 36°37'S (Banfield et al., 2018), a fourfold increase in net soil loss under
387 pine stands relative to native forest at Talcamavida (37°7'S) and Nacimiento (37°30'S) (Aburto et al., 2020)
388 or changes in nutrient cycles and increased sedimentation rates in coastal lakes, such as Matanza (33°45'S,
389 Fuentealba et al., 2020), Vichuquén (34°S, Fuentealba et al., 2021), San Pedro (36°51', Cisternas et al.,
390 2001), and Lanalhue (37°S, Alaniz et al., 2021). Based on such strong empirical evidence along CCR and
391 our own results (Fig. 2, 6, 7 and 8), we argue that the observed ongoing forest management of tree plantations
392 promotes soil erosion and landscape degradation. In addition, soils in tree plantations are depleted in carbon
393 and nutrients (Soto et al., 2019; Banfield et al., 2018), and inhibit lower invertebrate diversity (Cifuentes-
394 Croquevielle et al., 2020) compared to soils under native forest. As a result, C and N stocks are relatively
395 lower in tree plantations up to deep soil compartments (>120 cm) (Crovo et al., 2021). Soil organic matter
396 is a key component for soil formation (Bernhard et al., 2018). For that reason alone, native forests rather
397 than exotic tree plantations are a more appropriate land cover to regenerate soils and reverse or, at least,
398 decelerate 200 years of intense soil erosion. Indeed, the protection and conservation of natural vegetation
399 has the strongest effect on soil quality after water erosion (Vanacker et al., 2022), and the few empirical
400 restoration examples of native forest in former Eucalyptus plantations has promising increases for water
401 availability (Lara et al., 2021).

402 Conclusion

403 The Purapel catchment, as other similar catchments along the CCR, denudates slowly on scales of 10^3 to 10^4
404 years. The averaged suspended sediment discharge is similar in magnitude, although likely underestimating
405 total denudation. Then, depending on the magnitude of the unmeasured portion of the denudation, decadal
406 lowering of Earth Surface may be equal or even higher than the long-term average.

407 Suspended sediment transport decreases during the wet seasons between 1986 and 2018, which, at first
408 glance, conflicts with the disturbances observed in vegetation, especially the intense and widespread wild-
409 fires. The decrease in several hydroclimatic measures, including baseflow and aridity, coincides with lower
410 suspended sediment loads. We argue that the low range of recent suspended sediment discharge resulted
411 from limitations in the detachment and transport of sediments due to the overall observed water scarcity.
412 Or in other words: The drought offsets the effects of the disturbances and the higher connectivity. With-
413 out sufficient water, residence times of sediments are long, despite the increased sediment connectivity on
414 hillslopes. The contribution of tree plantations to reduce erosion, if any, seems to be more related to their
415 impact in water availability than directly in soil protection.

416 Because the surface lowering in the last 3 decades is similar to or higher than the long-term benchmark
417 and those measures are spread along a specific dry period, we argue it may be considered high for this specific

418 system. That conclusion and the documented effects of tree plantations on SOC and soil biodiversity are
419 indicators of a degrading landscape.

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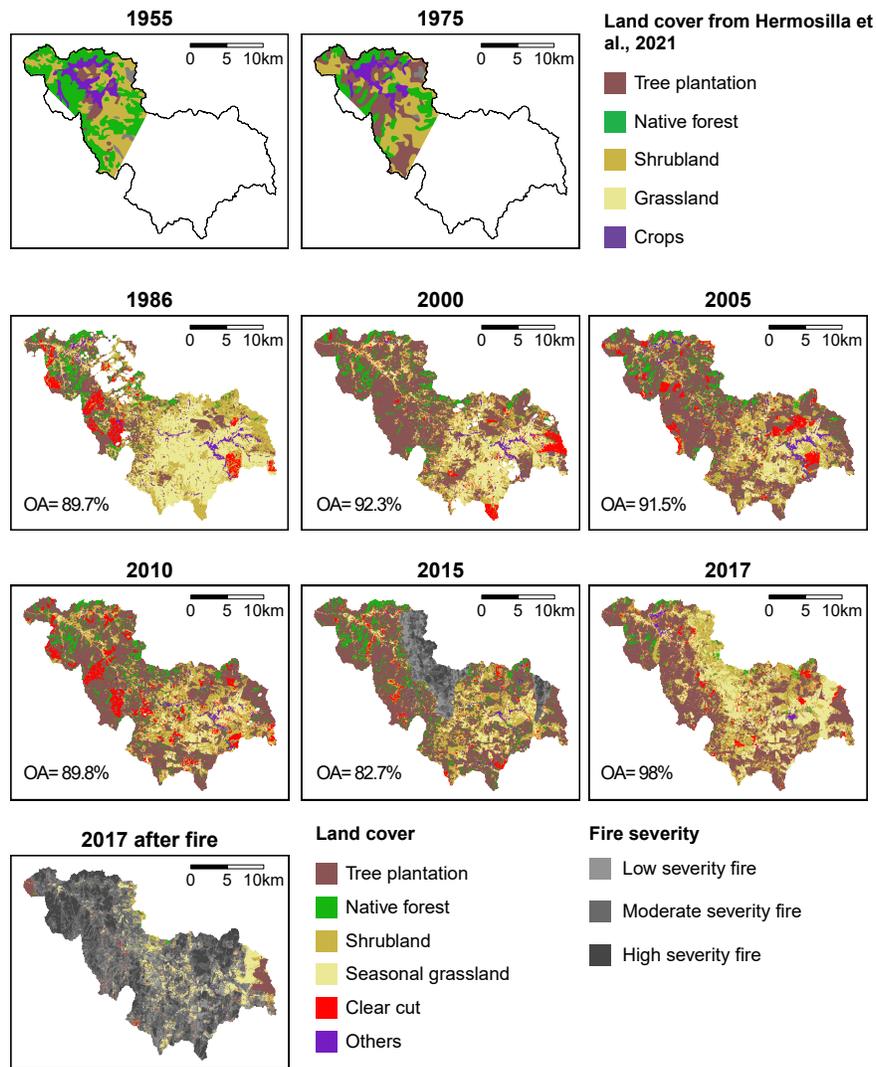
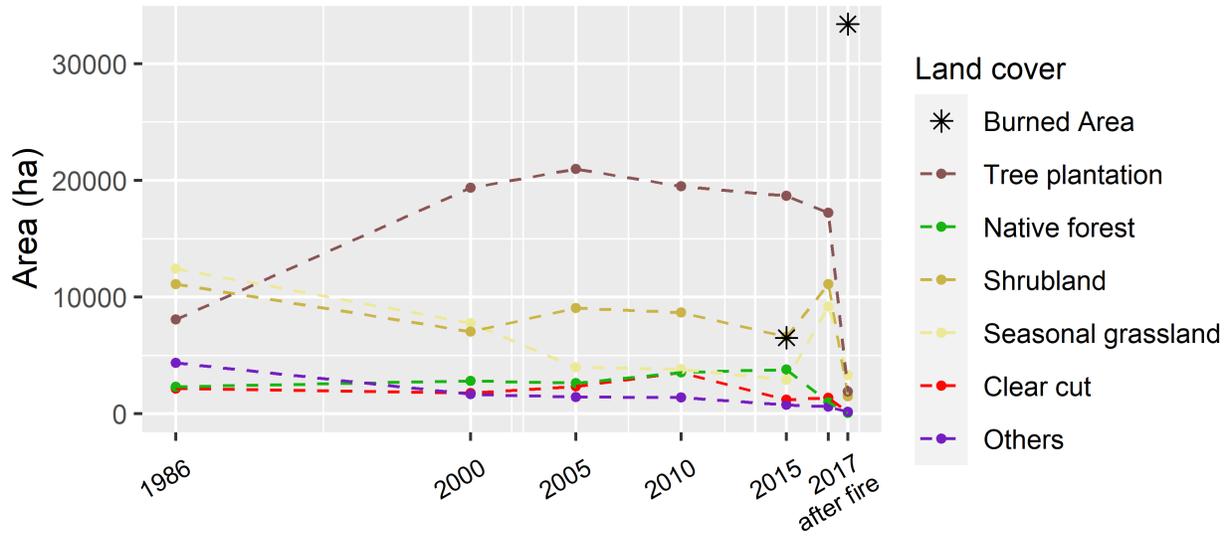


Figure 6: Land cover classification and transitions. Maps of 1955 and 1975 from Hermosilla-Palma et al. (2021), 1986-2015 from this work, and 2017 from Tolorza et al. (2022).

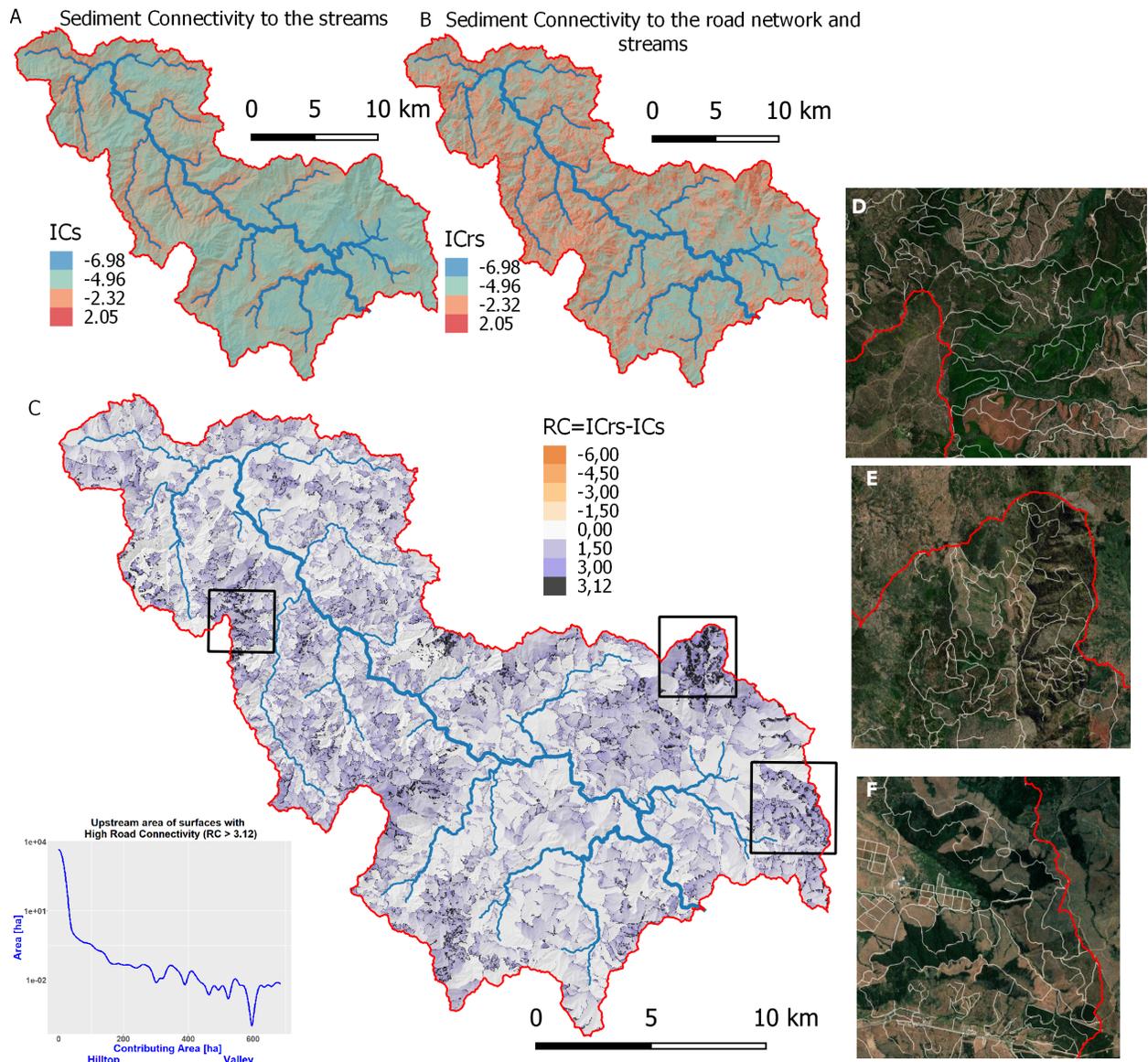


Figure 7: Sediment connectivity index (Cavalli et al., 2013) calculated using (A) the streams and (B) the streams and forest roads as targets. (C) is the difference between both models. (D-F) Details of hilltops with highest values of RC .

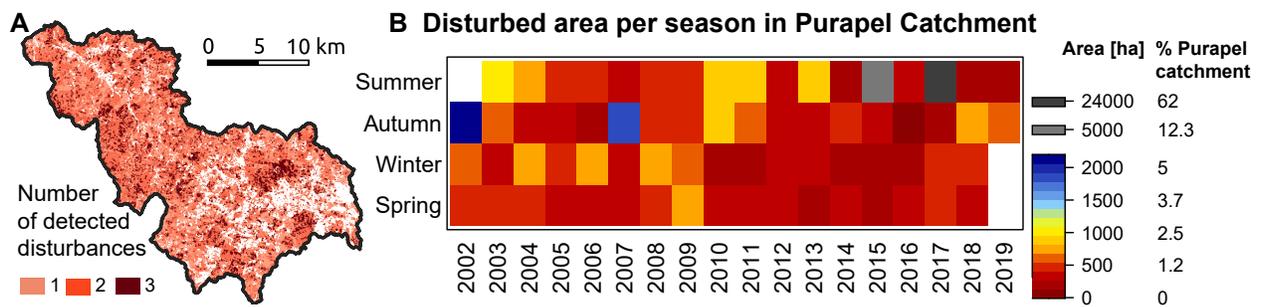


Figure 8: Detected disturbances from BFAST (A) map of the number of disturbances in vegetation detected for the period 2002-2019 (B) Seasonality of disturbance area detected within the Purapel catchment.