SWAT as a decision support tool to regulate impacts of forestry on water quantity in Uruguay

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2025 Jeju, South Korea SWAT Conference

Topic: Forest Hydrology

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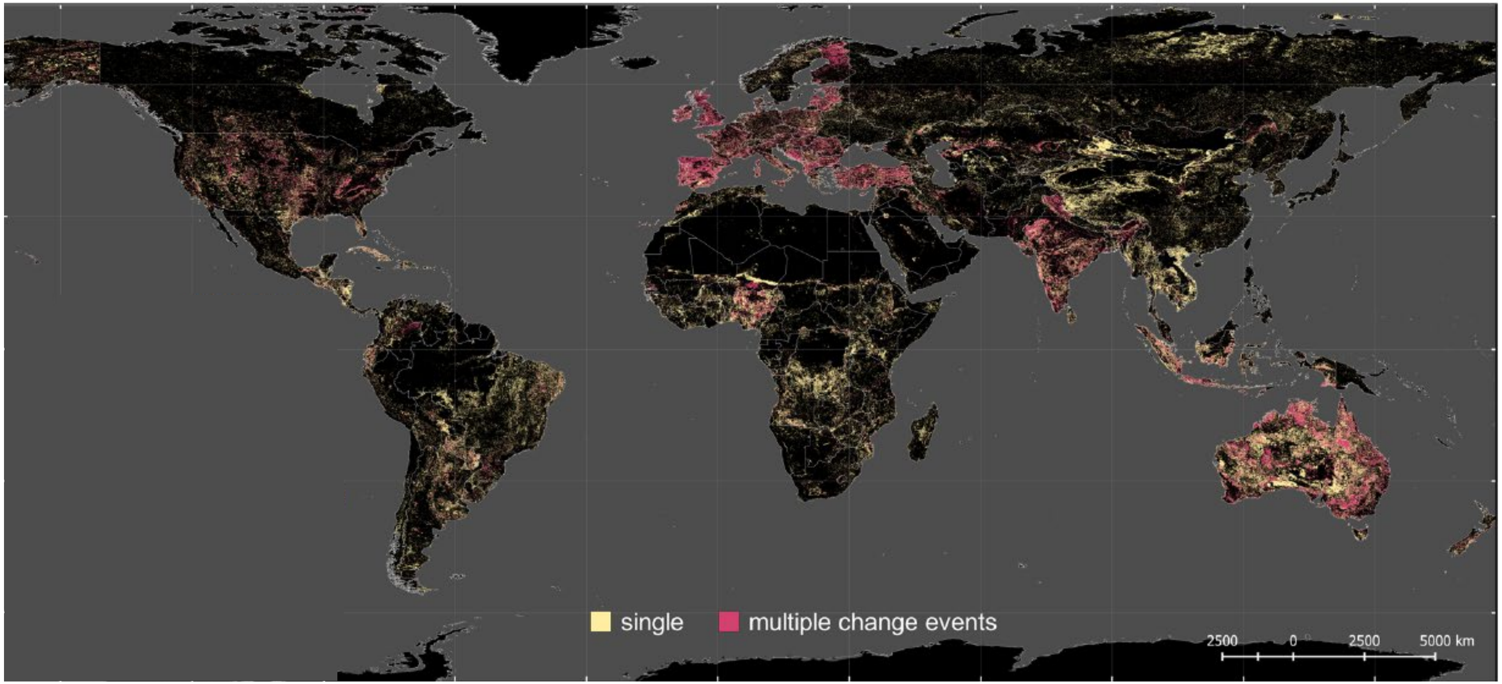
GRUPO DE MODELACIÓN INTEGRADA DE CUENCAS

Land use change impacts soil, biodiversity, water and climate

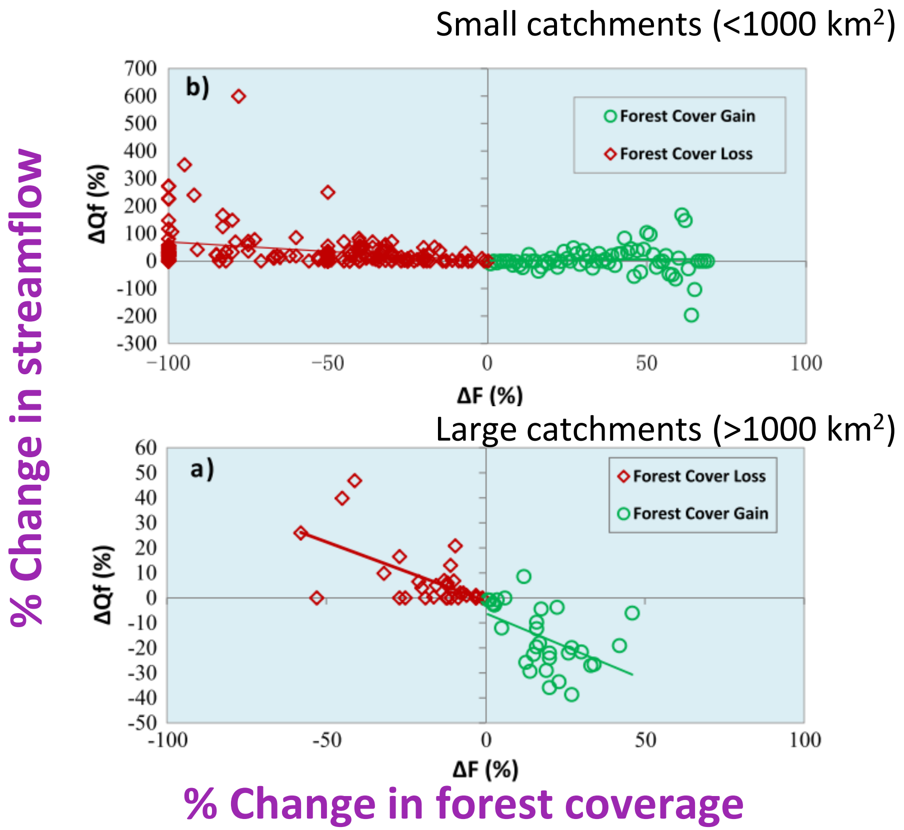
From 1960 to 2019, almost a third of the global land surface (43 million km²) has changed due to human activities (HILDA+ dataset, Winkler et al. 2021)



Global land use/cover change areas from Winkler et. al 2021 in 1960–2019.

New South Wales state in Australia (~800,000 km²) has **changed yearly since 1960.**

The effect of forestry coverage in streamflow at catchment level: it is not that simple



- Small -> Pair Catchment Experiments (PCE) area the leading approach to collecting high-quality data for land use change.
- *Scaling up* from small-scale experiments is problematic (soil, slope, climate, land use).
- How can we advise decisions in land use change for afforestation allocation in large catchments?

Overview of global data analysis from Zhang et al., 2017

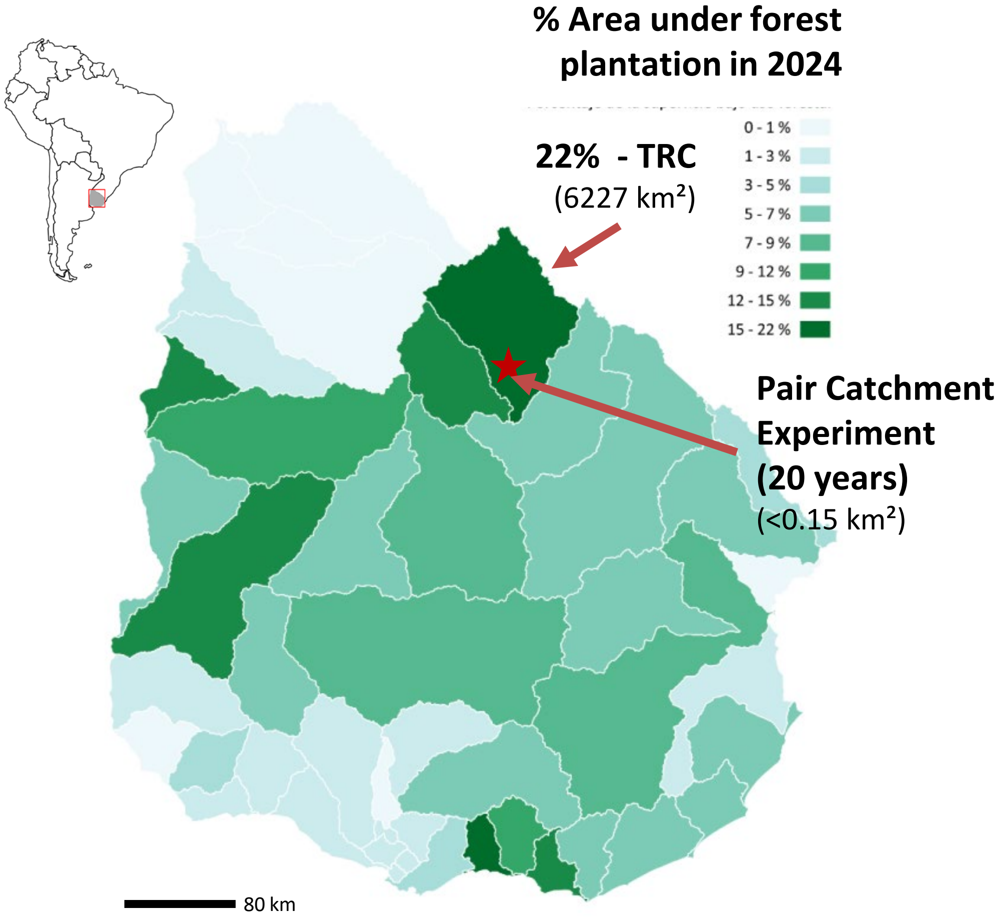
(Jones et al., 2017, Bosch & Hewlett, 1982; Costa et al., 2003; Scanlon et al., 2007)

A decision support tool to regulate impacts of forestry on water quantity

- The National Forest map 2024 shows that forest use in Uruguay reaches 6.6% of the territory, with a 6.9% increase compared to 2021 (MA,2024).

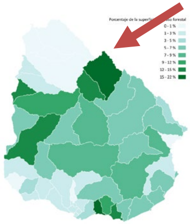
- **Tacuarembó River Catchment (TRC) in Uruguay, South America** has the highest percentage of plantation area of the country.

Forestry =

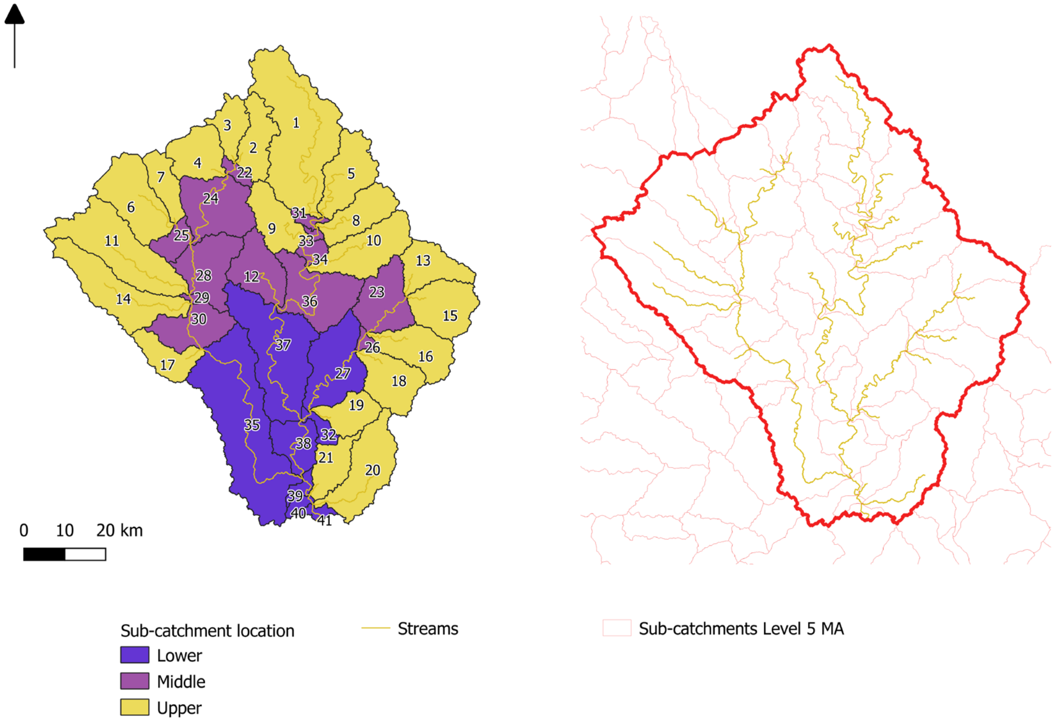


A decision support tool to regulate impacts of forestry on water quantity

TRC
(6227 km²)



- Similar to many other countries, current regulations apply a single allowed maximum fractional area of forestry, **ignoring key landscape and climate variation.**
- Management decisions allow 60% area for each sub catchment level 5 (Decree No. 405/02, December, 2021)
- **Can we use SWAT to advise catchment management regulations in the Tacuarembó River Catchment?**

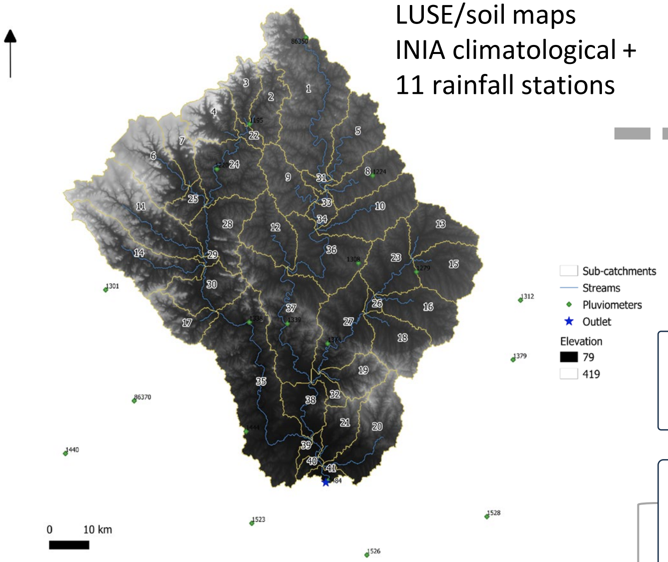


Objective

- To demonstrate how SWAT can provide more support to decision makers, identifying impacts on the whole flow duration curve and reflecting key landscape and climate.

- In particular, the tool should identify the spatial and temporal variation in the impact of forestry development

Experimental design



LUSE/soil maps
INIA climatological +
11 rainfall stations

SWAT Soil & Water Assessment Tool

SWAT 2012

60 sensitive parameters (LAI,ET,Flow)

Step-wise calibration with PCE prior information (2002-2015)
SUFI-2 (Abbaspour 2015) in R

Validation (2016-2020)

LUSE change scenarios (2003-2020)
Natural grasslads -> plantation

Monthly timestep

- Streamflow (cms)
- Observed ET (mm) from MODIS (MOD16A2GF.061)

Scaling of calibrated parameter ranges for LAI and ET from La Corona PCE, ***Pinus taeda*** plantation vs natural grasslands **2003-2020**

Step 1 – ET calibration in 41 subbasins, OF=mean(KGE_{ET})
(3 iterations, 1500 runs)

13:50 - 14:10 Byeongwon Lee

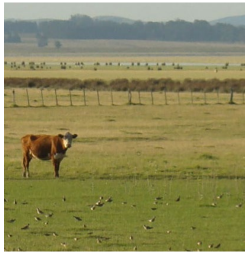
Step 2 – Flow calibration at outlet (Sub 41), OF=(KGE_{Flow})
(2 iterations, 1000 runs)

https://github.com/enervifa/SUFI2_R

Experimental design: potential plantation areas

Transition code	Landuse
PINE	Pines
EUCA	Eucalyptus
GRAS	Natural grasslands
OTRO	Other areas not suitable for forest plantation
FORN	Native forest
ESC	Scenario
AGRI	Agriculture
FORC	Forest conversion (change in forest plantations)
FORD	Forest plantation up to 2018
FORQ	Forest plantation up to 2015
FONP	Native forest to forest plantation (FORN to FORP)
FODV	Forest plantation from 2018

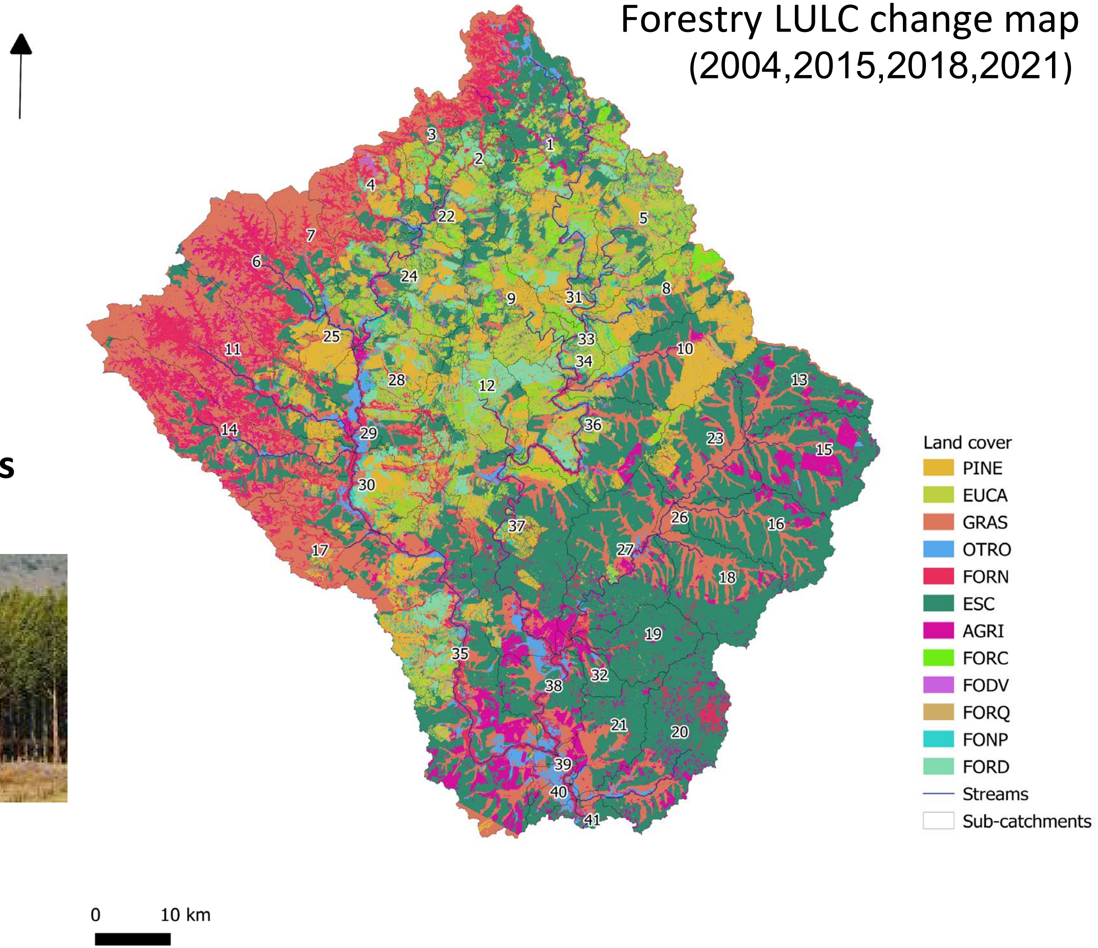
Baseiline ESC =



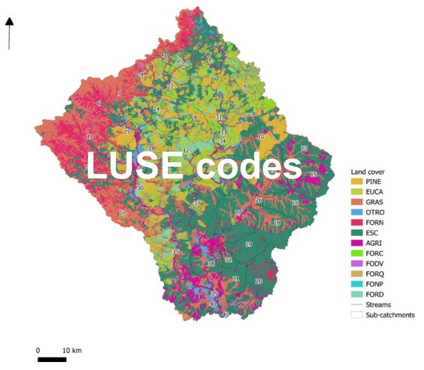
Scenarios ESC =

Forestry priority areas
(Decree No. 405/02)

Forestry LULC change map
(2004,2015,2018,2021)



Dynamic land use change in mgt tables for QSWAT 2012



A. Loop .mgt files of each HRU and sample **new management**

1.Random selection:
- target years for planting
- target agriculture management (AG1,AG2,AG3)

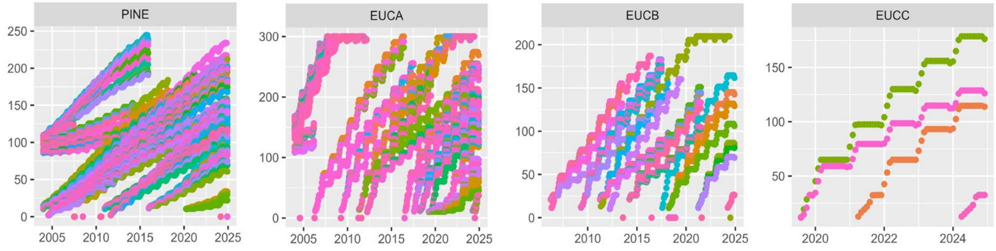
2.Update schedule + adjust BIO_INIT

B. Loop to shift planting dates and plant cover %

1. Randomly select initial plantation years (0,5, 10, 8, 11)
2. .Shift planting operations accordingly in 25 years rotation

3.Change IGRO condition, update schedule + adjust BIO_INIT

4.Adjust % tree species representation using baseline map

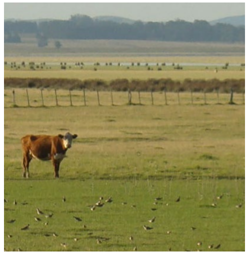


Pinus taeda
Eucalyptus grandis
Eucalyptus globulus

Experimental design:
> afforestation scenarios

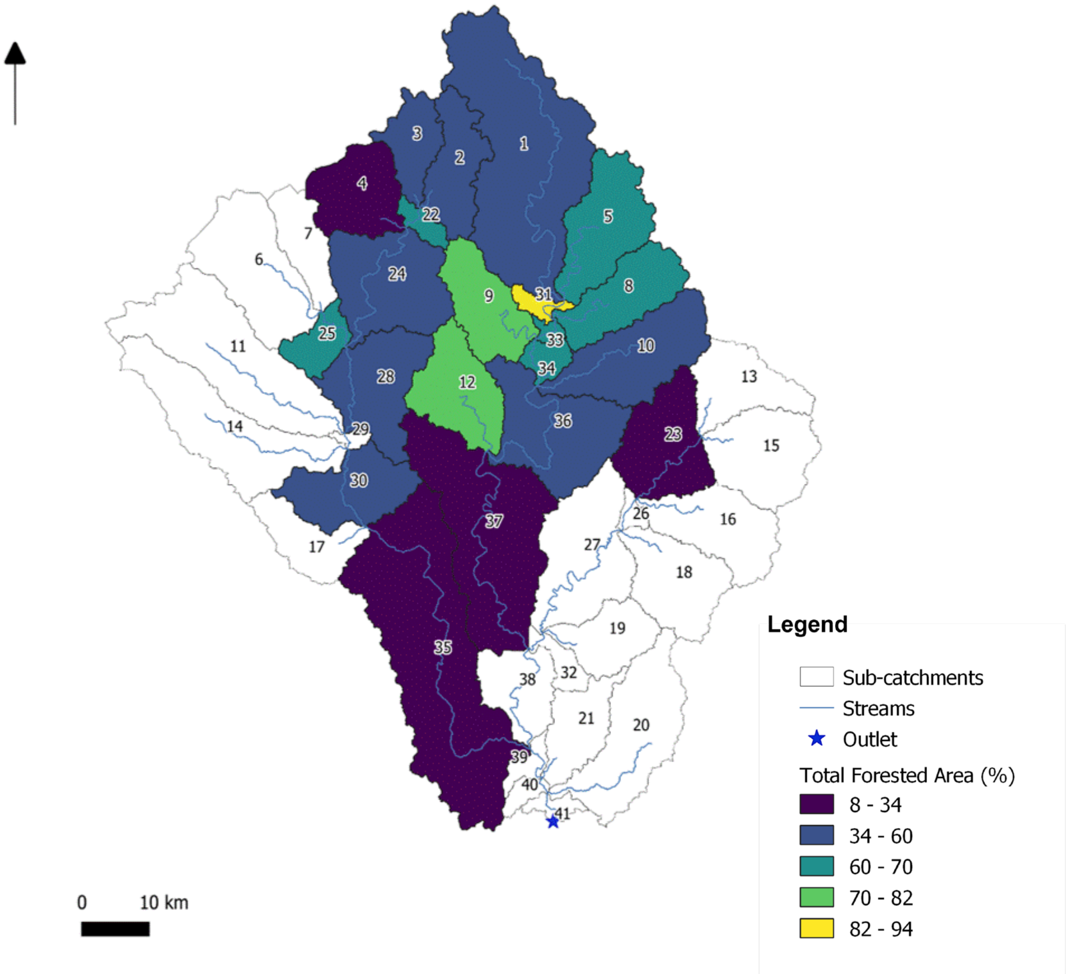
Scenarios A1-A10
25%, 50%, 100% Scenario land use HRUs

→from pasture to pine
→ from pasture to eucalyptus



→

Baseline (26%)

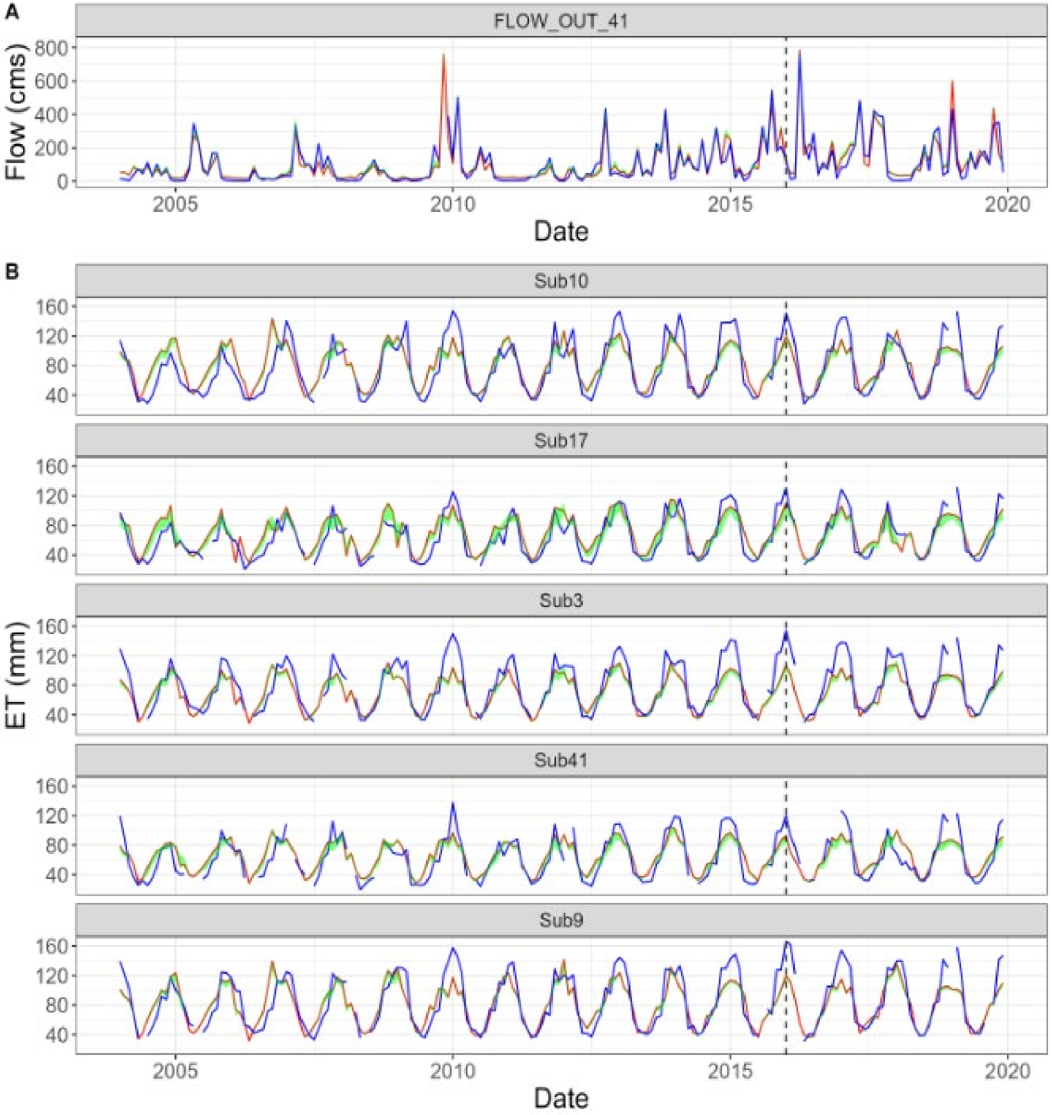


Calibration and validation

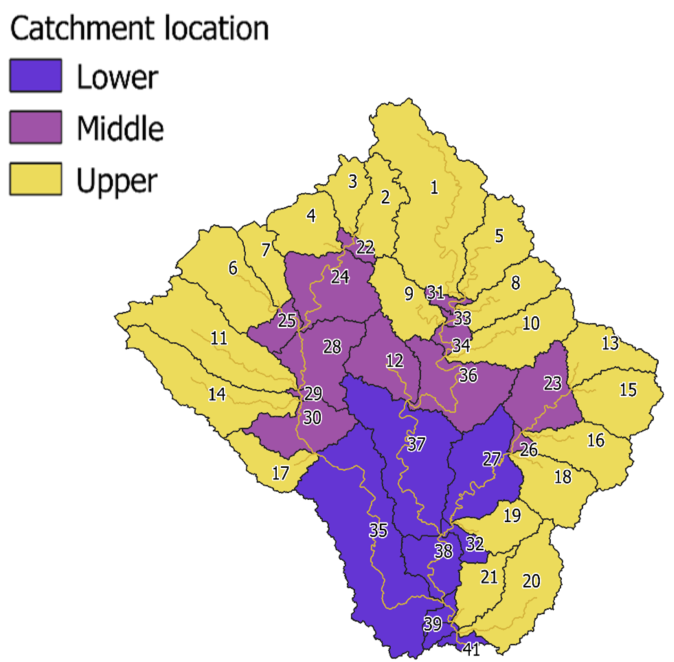
Period	Catchment	NSE	KGE	R^2	PBIAS (%)	Vol_frac
Calibration (2004-2015)	FLOW_OUT_41	0.88	0.92	0.88	0.95	0.95
	Subs1:41	0.57	0.52	0.69	1.07	1.00
Validation (2016-2019)	FLOW_OUT_41	0.86	0.87	0.87	-11.78	0.89
	Subs1:41	0.51	0.36	0.77	8.88	0.47

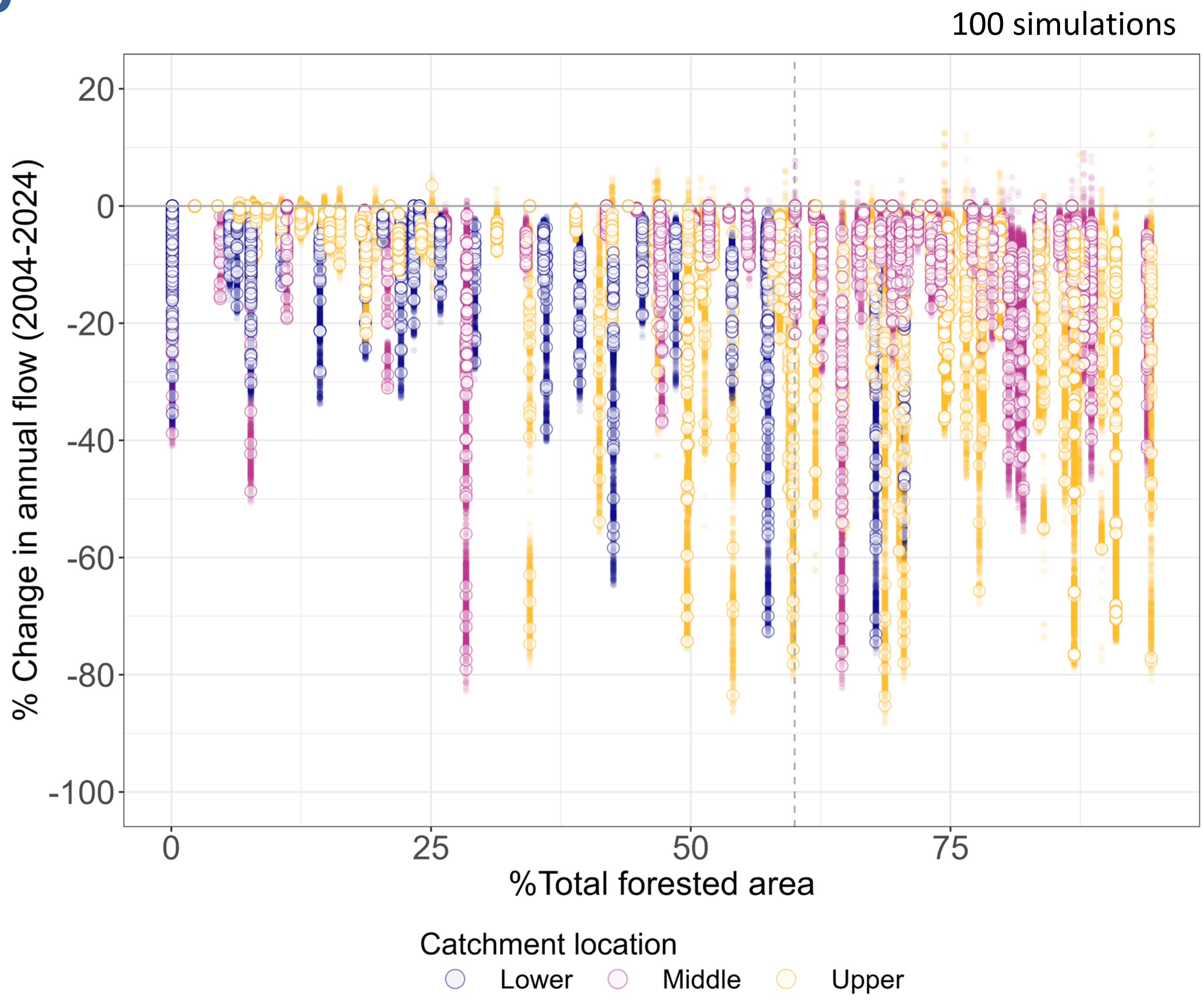
- Streamflow gave only slightly reduced performance in the prediction of streamflow at the outlet

- The model performance for ET was not as good as for streamflow



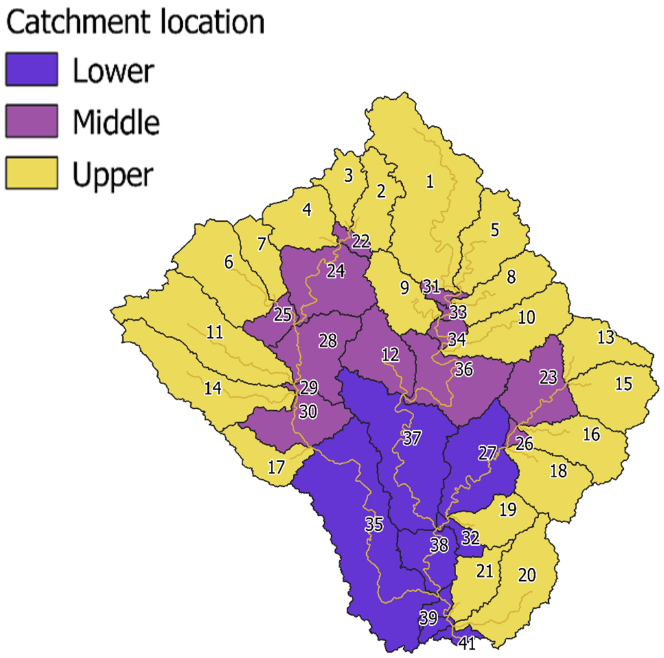
Forest expansion scenario simulations in the TRC

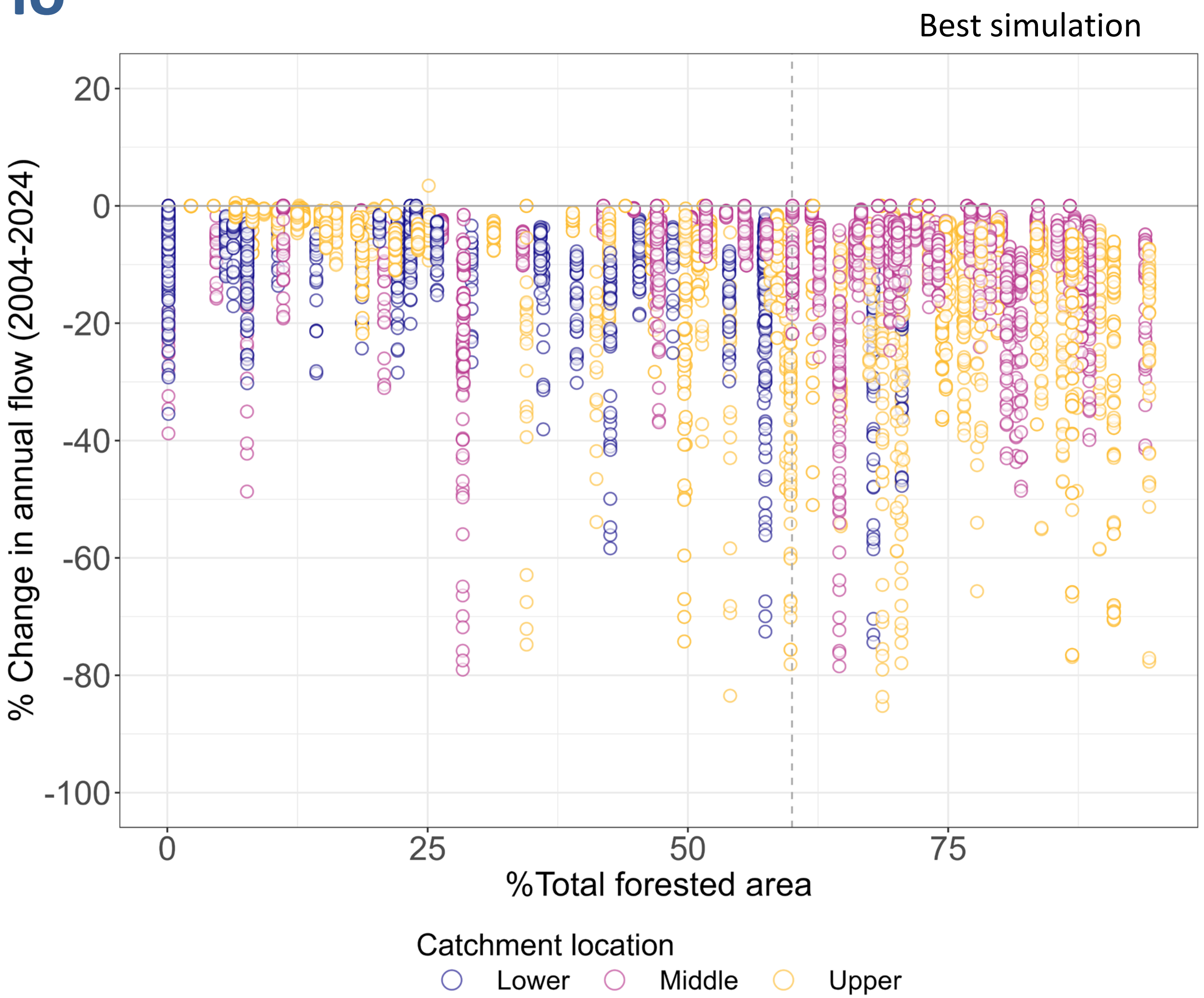




- Model simulations across the parameter distribution **indicate high variability**

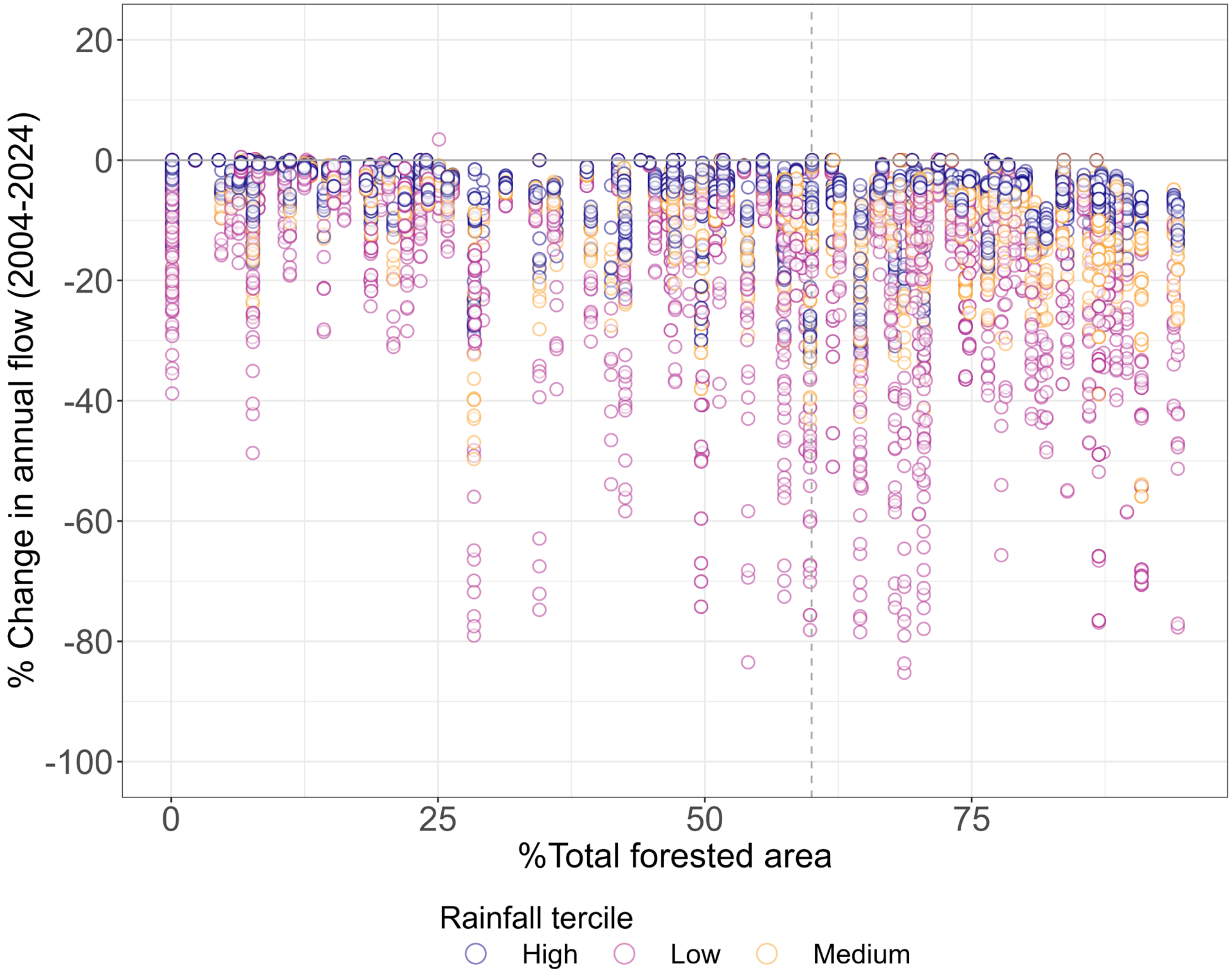
Forest expansion scenario simulation in the TRC





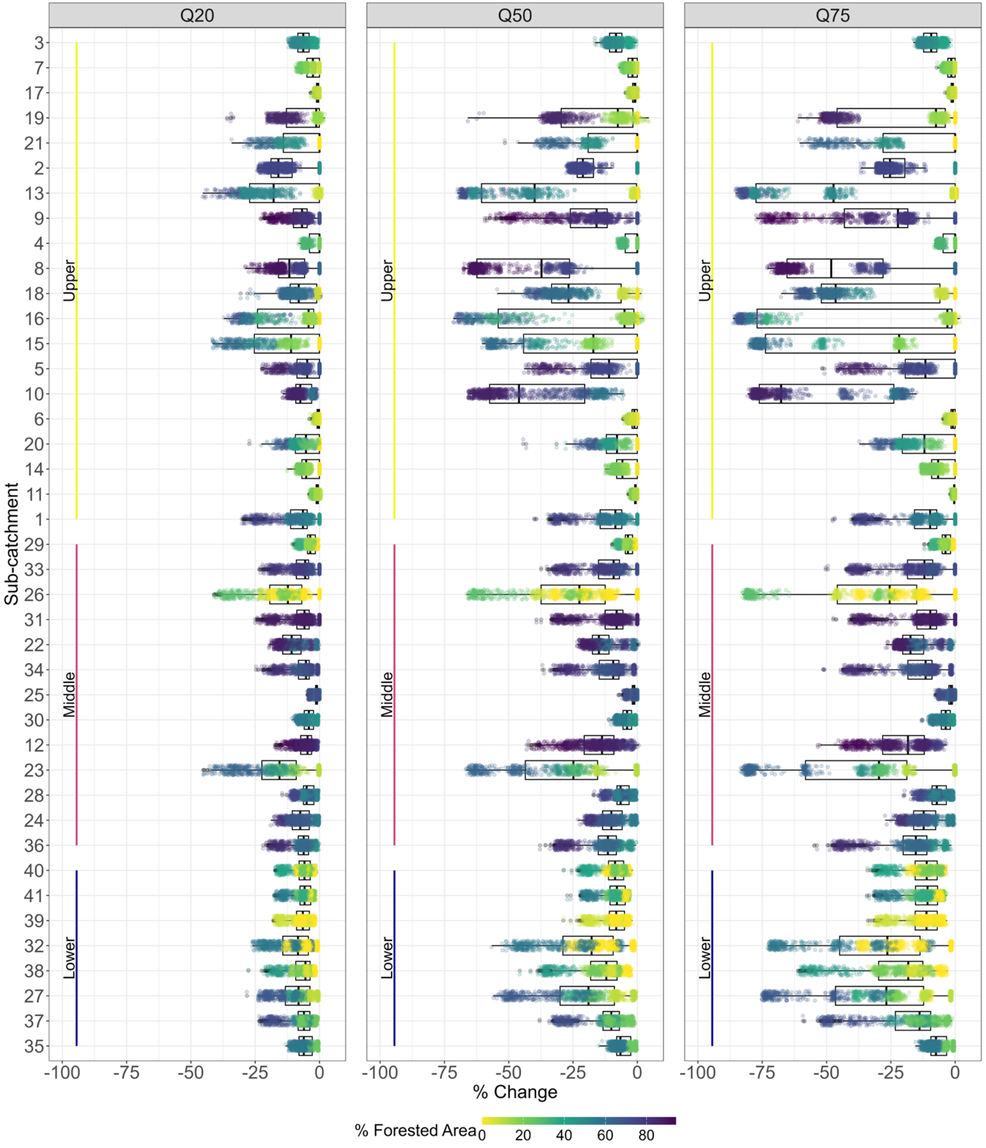
- Upper catchments are more sensitive to water yield changes due to afforestation
- Effect of catchment features (Cornish and Vartessy, 2001)

Forest expansion scenario simulation in the TRC



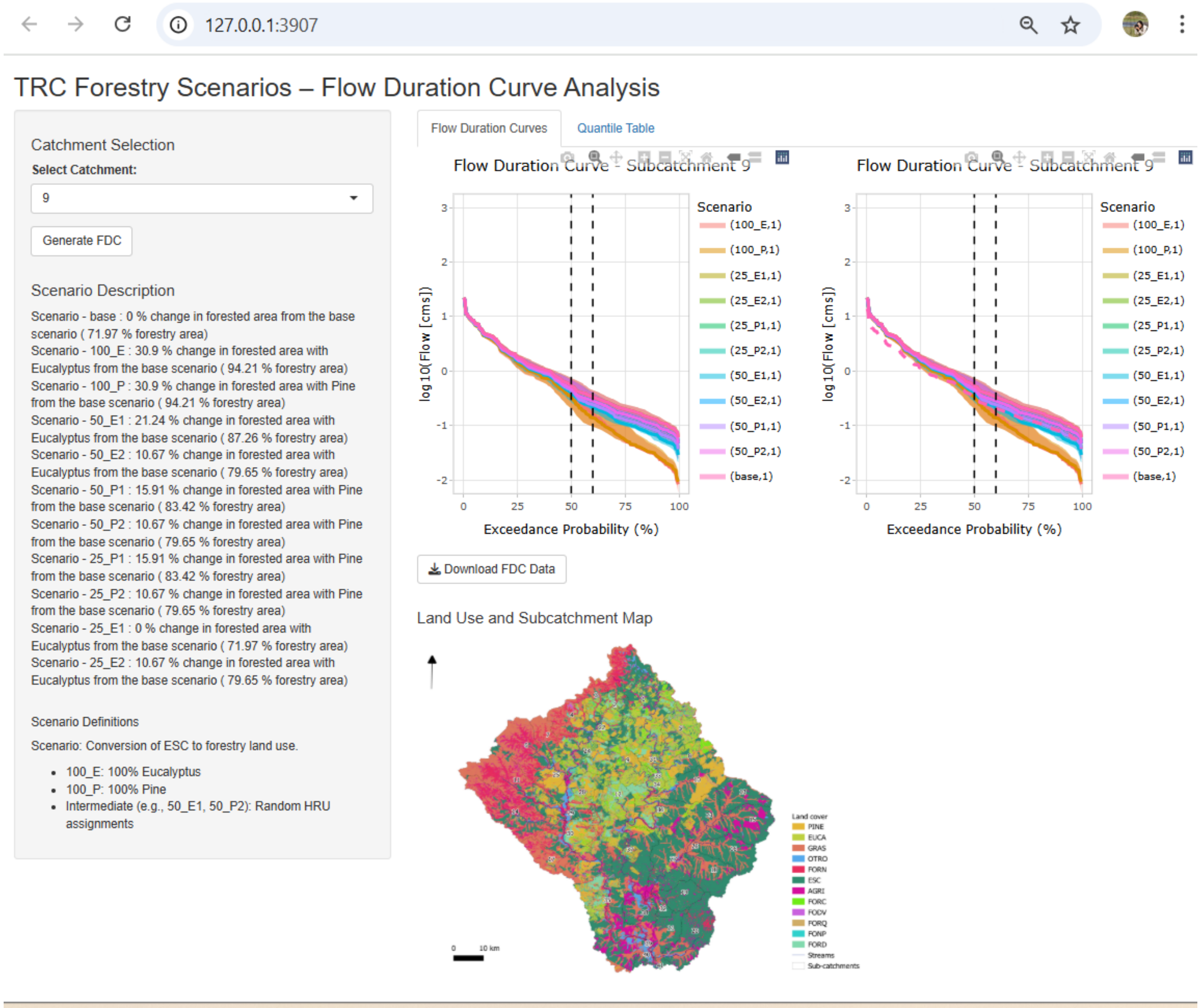
- Rainfall variability consistently masks many other changes in the catchment.
- In drier conditions, runoff is more sensitive to the increase in forest area (Zhang et al. 2001)
- Climate in Uruguay is strongly influenced by ENSO events (De Vera and Terra (2018), Baethgen (2010).

How could forest change flow quantiles?



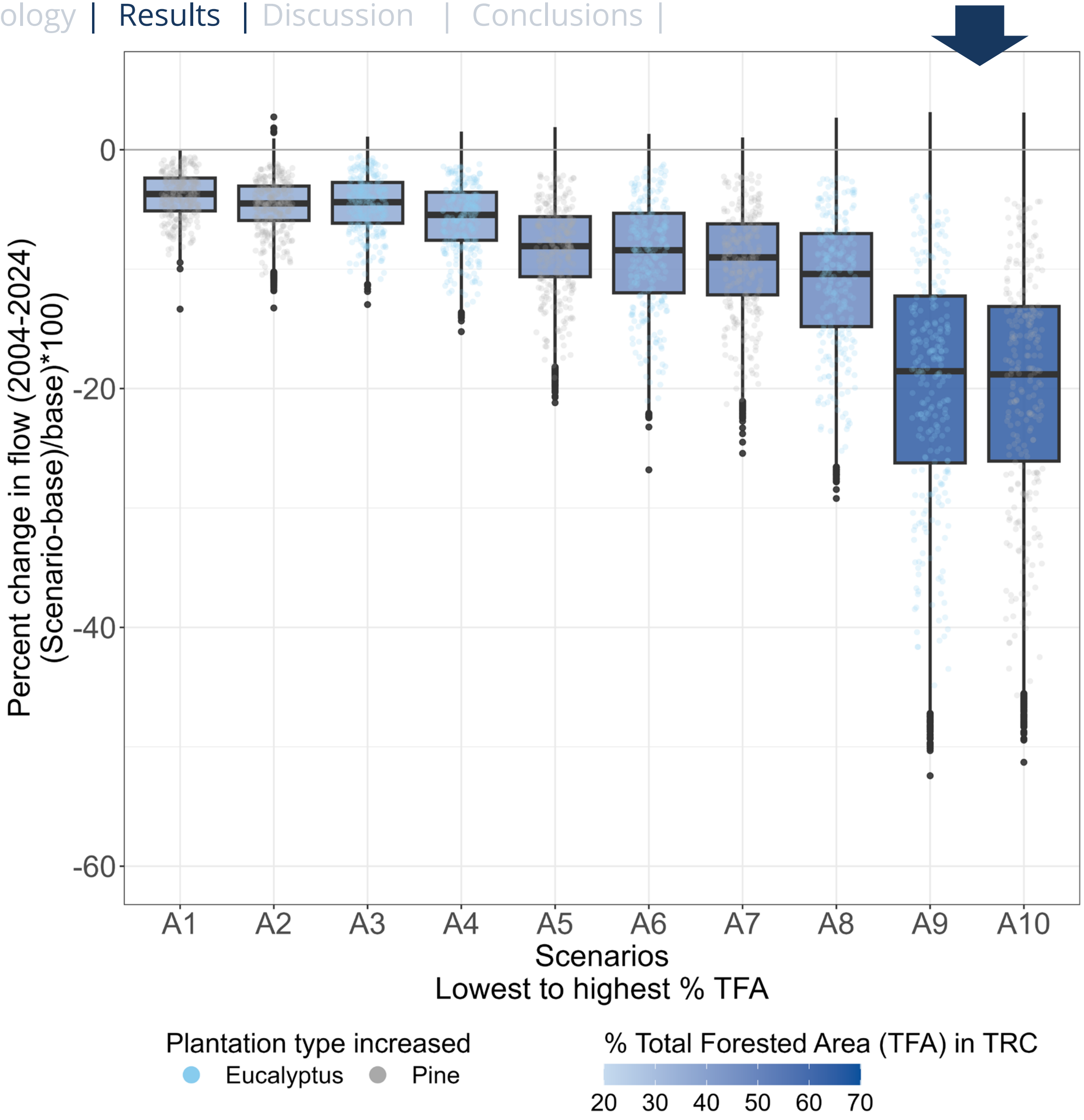
Key points to take home

- The impact of forestry on streamflow **varies significantly (location, features).** Still, the main variable affecting water availability and the level of year-to-year afforestation impact is **rainfall.**
- If the simulations aim to develop relevant **landscape level scenarios**, then this has to come with the recognition that landuse activities are not static and interact with climate.
- Policies should include room for adjustment to consider **uncertainties** if new evidence emerges.
- Using a single threshold for evaluating forestry impact may lead to **an underestimation of the true environmental impact** in some areas and a loss of opportunity for sustainable forestry development.


127.0.0.1:3907
TRC Forestry Scenarios – Flow Duration Curve Analysis
Catchment Selection
Select Catchment:
9
Generate FDC
Scenario Description
Scenario - base : 0 % change in forested area from the base scenario (71.97 % forestry area)
Scenario - 100_E : 30.9 % change in forested area with Eucalyptus from the base scenario (94.21 % forestry area)
Scenario - 100_P : 30.9 % change in forested area with Pine from the base scenario (94.21 % forestry area)
Scenario - 50_E1 : 21.24 % change in forested area with Eucalyptus from the base scenario (87.26 % forestry area)
Scenario - 50_E2 : 10.67 % change in forested area with Eucalyptus from the base scenario (79.65 % forestry area)
Scenario - 50_P1 : 15.91 % change in forested area with Pine from the base scenario (83.42 % forestry area)
Scenario - 50_P2 : 10.67 % change in forested area with Pine from the base scenario (79.65 % forestry area)
Scenario - 25_P1 : 15.91 % change in forested area with Pine from the base scenario (83.42 % forestry area)
Scenario - 25_P2 : 10.67 % change in forested area with Pine from the base scenario (79.65 % forestry area)
Scenario - 25_E1 : 0 % change in forested area with Eucalyptus from the base scenario (71.97 % forestry area)
Scenario - 25_E2 : 10.67 % change in forested area with Eucalyptus from the base scenario (79.65 % forestry area)
Scenario Definitions
Scenario: Conversion of ESC to forestry land use.
• 100_E: 100% Eucalyptus
• 100_P: 100% Pine
• Intermediate (e.g., 50_E1, 50_P2): Random HRU assignments
Flow Duration Curves
Quantile Table
Flow Duration Curve - Subcatchment 9
Scenario
(100_E,1)
(100_P,1)
(25_E1,1)
(25_E2,1)
(25_P1,1)
(25_P2,1)
(50_E1,1)
(50_E2,1)
(50_P1,1)
(50_P2,1)
(base,1)
log10(Flow [cms])
Exceedance Probability (%)
Flow Duration Curve - Subcatchment 9
Scenario
(100_E,1)
(100_P,1)
(25_E1,1)
(25_E2,1)
(25_P1,1)
(25_P2,1)
(50_E1,1)
(50_E2,1)
(50_P1,1)
(50_P2,1)
(base,1)
log10(Flow [cms])
Exceedance Probability (%)
Download FDC Data
Land Use and Subcatchment Map
Land cover
PINE
EUCA
GRAS
OTRO
FORN
ESC
AGRI
FORC
FODV
FORQ
FONP
FORD
Streams
Sub-catchments
0 10 km

Forest expansion scenario simulation in the TRC

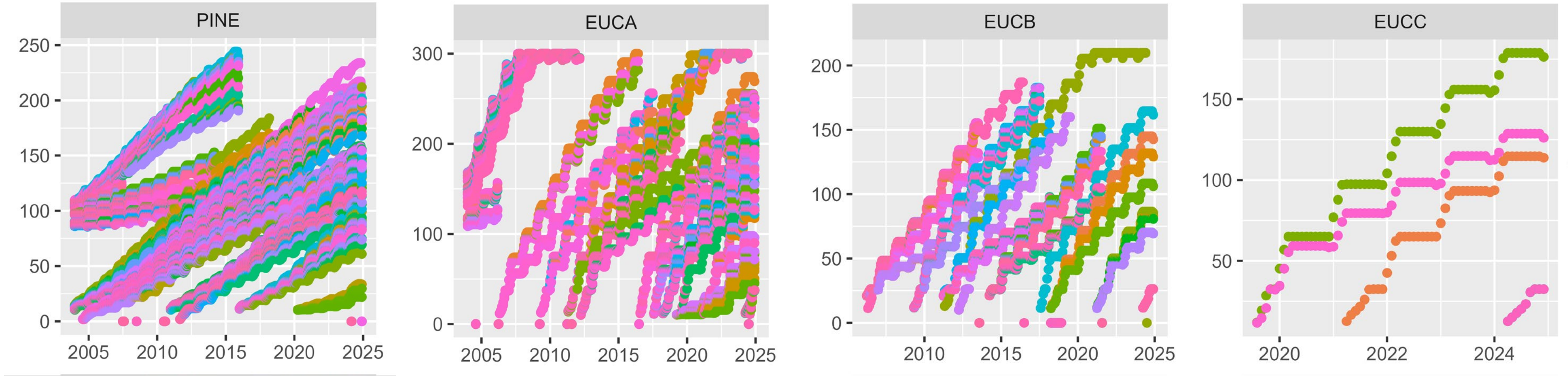
- Conversion of the total potential area in the TRC to forest resulted in a mean change in monthly flow of 28%



Limitations and policy implications from SWAT scenarios

- Future changes in climate, landuse or forest operations can change these results.
- Policies should include room for adjustment to consider uncertainties if new evidence emerges.
- Despite the efforts to capture the vegetation-water interactions in the model more work is needed to refine plant parameters (ET underprediction in small sub-catchments with mixed land uses).

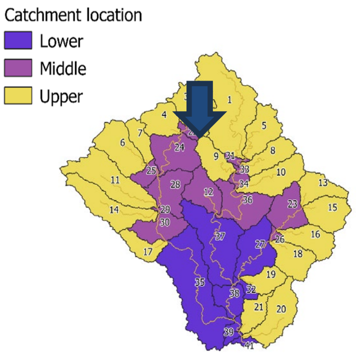
HRUs simulated biomass

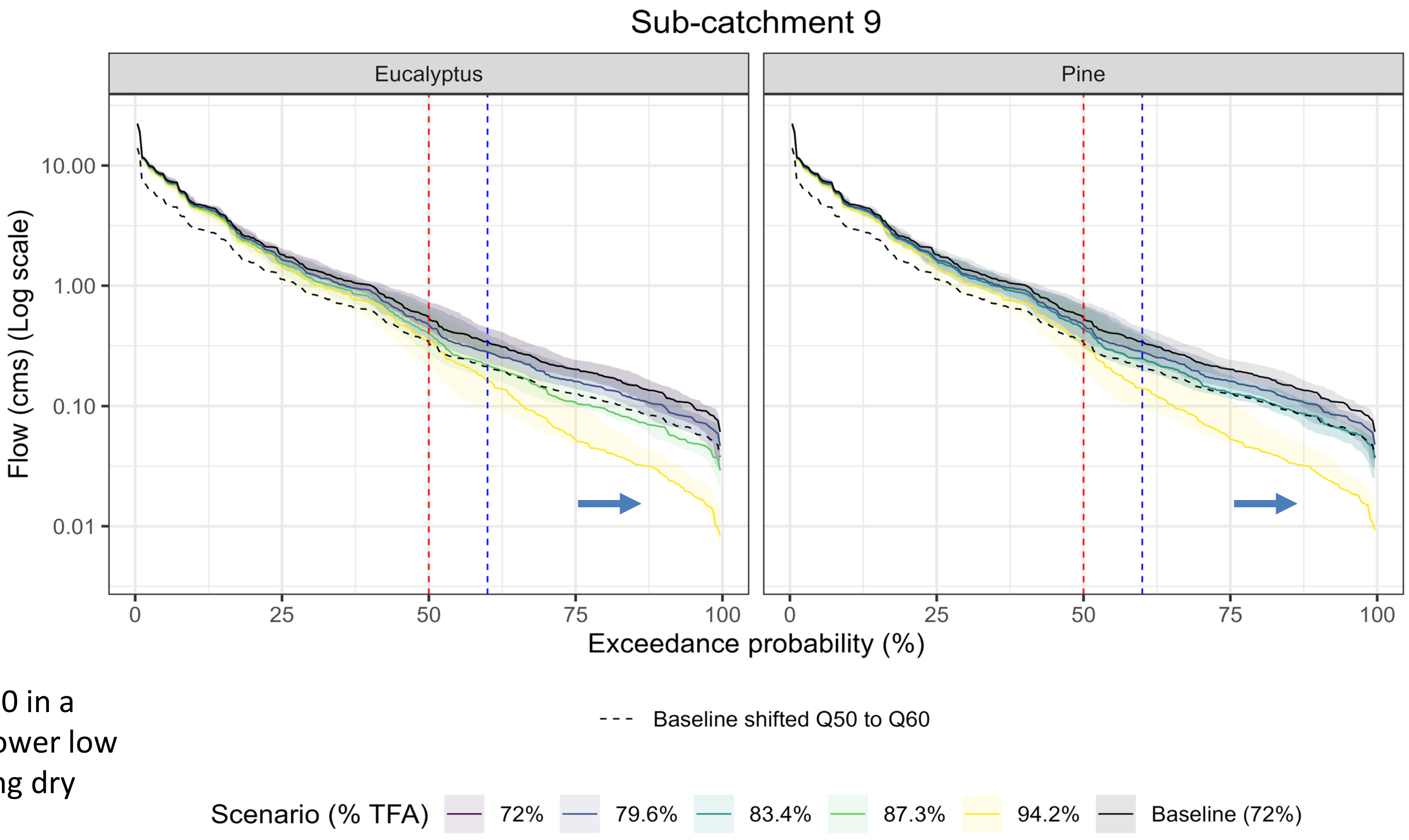


Pinus taeda *Eucalyptus grandis* *Eucalyptus globulus* *Other eucalyptus*

- Different planting and clearing dates for the 25 year rotations on forestry-priority soils
- Representation of the change of forestry area 2004-2024 in the baseline

How could forest expansion affect flow quantiles?



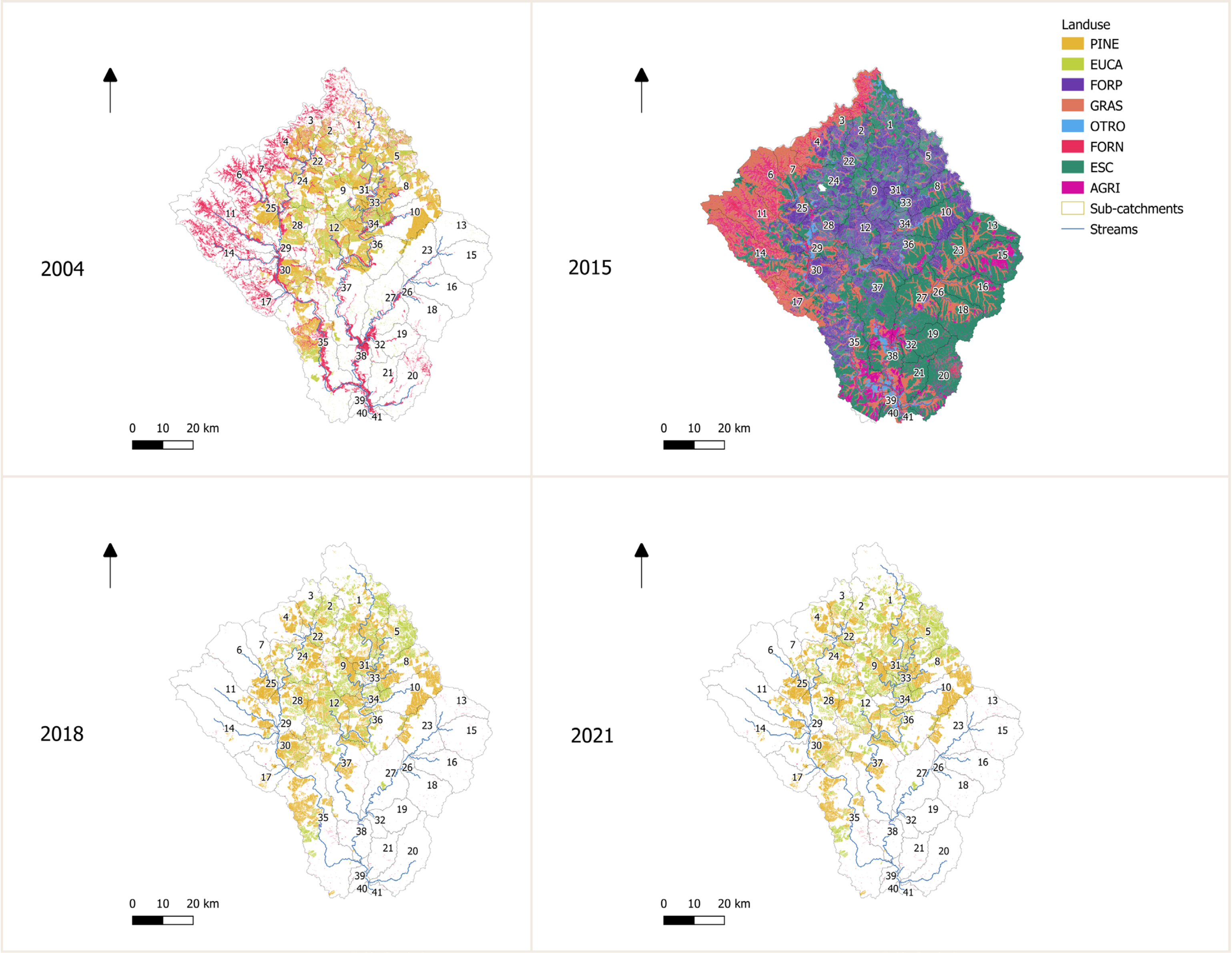


- A change from Q60 to Q50 in a catchment can result in lower low flows at Q75 or Q90 during dry years.

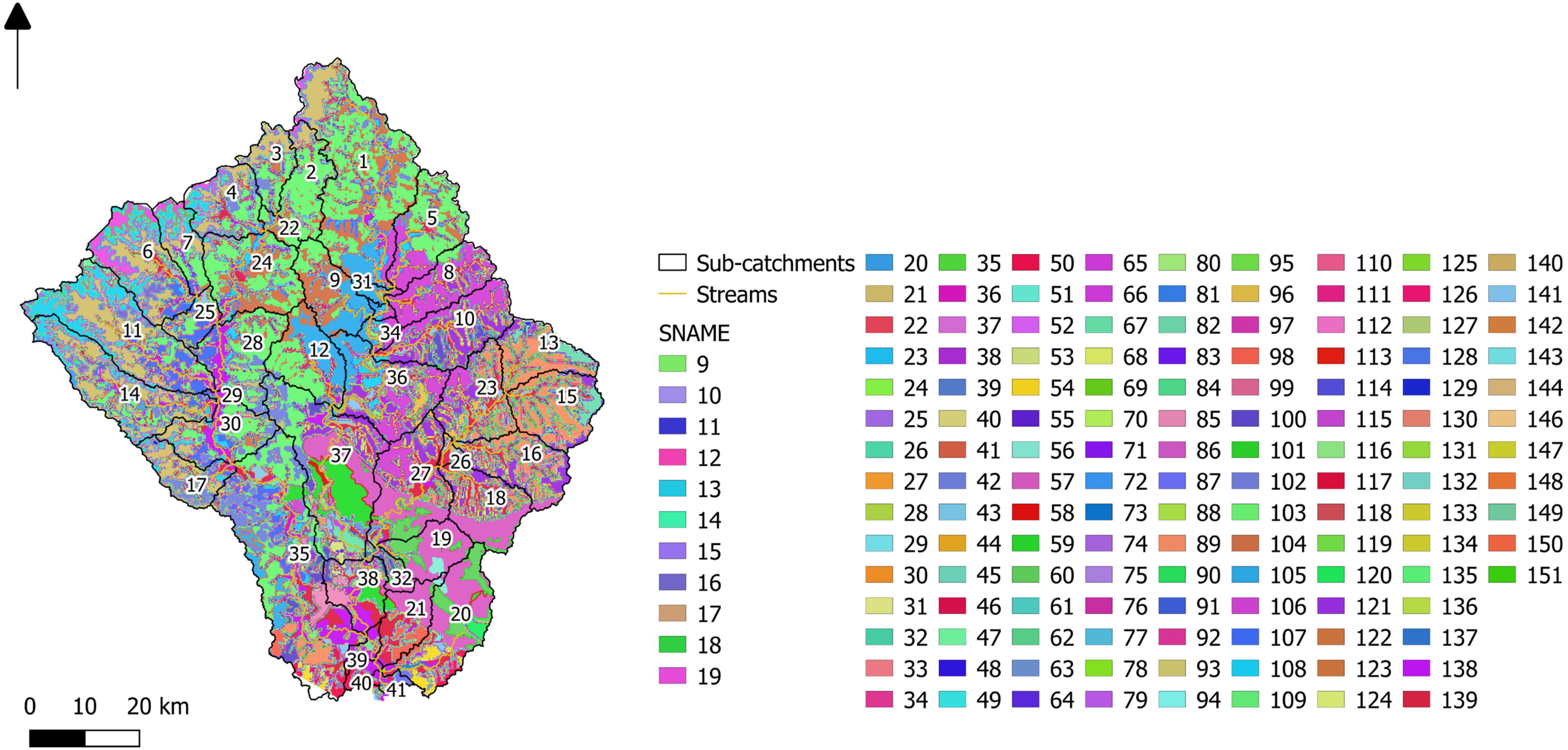
Table 7 Parameters used in model calibration

Method	Min	Max	Parameter	References	Calibrated
v	0.1	0.50	CANMX.hru_GRAS,ESC	N. O. von Stackelberg et al. (2007)	0.53
v	2.00	12.00	CANMX.hru_PINE	Haas et al. (2021); N. O. von Stackelberg et al. (2007)	5.04
v	10.00	22.00	CANMX.hru_EUCA	(Alonso, 2021)	15.95
v	2.00	22.00	CANMX.hru_FORC,FONP, FORD,FORQ,FODV	(Alonso, 2021)	8.11
v	3.92	4.22	BLAI{94}.plant.dat_	LC	4.11
v	1.84	1.92	BLAI{12}.plant.dat_	LC	1.87
v	0.99	1.00	DLAI{94}.plant.dat_	LC	0.99
v	1.00	1.00	DLAI{12}.plant.dat_	LC	0.99
a	-2.28	-1.89	T_BASE{94}.plant.dat_	LC	-2.00
a	15.65	16.71	T_OPT{94}.plant.dat_	LC	16.40
a	0.65	0.98	T_BASE{12}.plant.dat_	LC	0.85
a	8.13	9.75	T_OPT{12}.plant.dat_	LC	8.92
v	0.89	0.91	ALAI_MIN{94}.plant.dat_	LC	0.90
v	2.28	2.44	ALAI_MIN{12}.plant.dat_	LC	2.43
v	0.64	0.70	LAIMX1{94}.plant.dat_	LC	0.66
v	0.62	0.67	LAIMX2{94}.plant.dat_	LC	0.64
v	0.50	0.61	FRGRW1{94}.plant.dat_	LC	0.62
v	0.07	0.13	FRGRW2{94}.plant.dat_	LC	0.09
v	0.24	0.25	LAIMX1{12}.plant.dat_	LC	0.24
v	0.90	0.90	LAIMX2{12}.plant.dat_	LC	0.89
v	0.08	0.09	FRGRW1{12}.plant.dat_	LC	0.85
v	0.41	0.44	FRGRW2{12}.plant.dat_	LC	0.42
v	877.00	1271.00	REVAPMN.gw_PINE	LC	1854.00
v	302.00	556.00	REVAPMN.gw_GRAS,ESC	LC	414.00
v	877.00	1271.00	REVAPMN.gw_EUCA	LC	1518.00
v	877.00	1271.00	REVAPMN.gw_FORC,FONP, FORD,FORQ,FODV	LC	975.00
v	0.06	0.12	GW_REVAP.gw_PINE	LC	0.17
v	0.02	0.02	GW_REVAP.gw_GRAS,ESC	LC	0.01
v	0.06	0.12	GW_REVAP.gw_EUCA	LC	0.19
v	0.06	0.12	GW_REVAP.gw_FORC,FONP, FORD,FORQ,FODV	LC	0.14
v	0.012	0.019	GSI{94}.plant.dat_	LC	0.19
v	0.006	0.01	GSI{12}.plant.dat_	LC	0.009
v	0.004	0.009	GSI{119,184,183,185}.plant.dat_	(Alonso, 2021)	0.009
v	6.00	10.50	MAT_YRS{94}.plant.dat_	LC	4.00
v	7.00	9.00	MAT_YRS{119,184,183,185}.plant.dat_	(Alonso, 2021)	6.00
v	1.064	1.788	VPDFR{94}.plant.dat_	LC	1.47
v	1.57	2.539	VPDFR{12}.plant.dat_	(Alonso, 2021)	2.05
v	1.064	1.788	VPDFR{119,184,183,185}.plant.dat_	(Alonso, 2021)	1.56
v	0.133	0.428	ESCO.hru_EUCA	LC	0.22
v	0.133	0.428	ESCO.hru_FORC,FONP, FORD,FORQ,FODV	LC	0.18
v	0.133	0.428	ESCO.hru_PINE	LC	0.36
v	0.001	0.17	ESCO.hru_GRAS,ESC	LC	0.02
v	0.645	0.9	EPCO.hru_PINE	LC	0.71
v	0.0.645	0.9	EPCO.hru_EUCA	LC	0.89
v	0.645	0.9	EPCO.hru_FORC,FONP, FORD,FORQ,FODV	LC	0.92
v	0.63	0.877	EPCO.hru_GRAS,ESC	LC	0.68
v	0.00	1.00	ALPHA_BF.gw	SWAT manual (Arnold et al., 2012)	0.65
r	-0.30	-0.01	CN2.mgt_PINE	LC	-0.32
r	-0.08	0.10	CN2.mgt_GRAS,ESC	LC	-0.13
r	-0.50	0.50	CN2.mgt_EUCA	SWAT manual(Arnold et al., 2012)	-0.33
r	-0.50	0.50	CN2.mgt_FORC,FONP, FORD,FORQ,FODV	SWAT manual (Arnold et al., 2012)	-0.30
r	-0.50	0.50	CN2.mgt_AGRI	SWAT manual (Arnold et al., 2012)	-0.22
v	200.00	7000.00	GWQMN.gw_EUCA,FORC, FORP,FORD,FORQ,FODV,PINE	SWAT manual (Arnold et al., 2012)	6632
v	0.18	0.22	OV_N.hru_GRAS,ESC	SWAT manual (Arnold et al., 2012)	0.20
v	0.00	500.00	GW_DELAY.gw_GRAS,ESC	SWAT manual (Arnold et al., 2012)	421.00
v	0.00	500.00	GW_DELAY.gw_EUCA,PINE	SWAT manual (Arnold et al., 2012)	467.00
v	0.00	500	GW_DELAY.gw_FORC,FONP, FORD,FORQ,FODV	SWAT manual (Arnold et al., 2012)	360.00

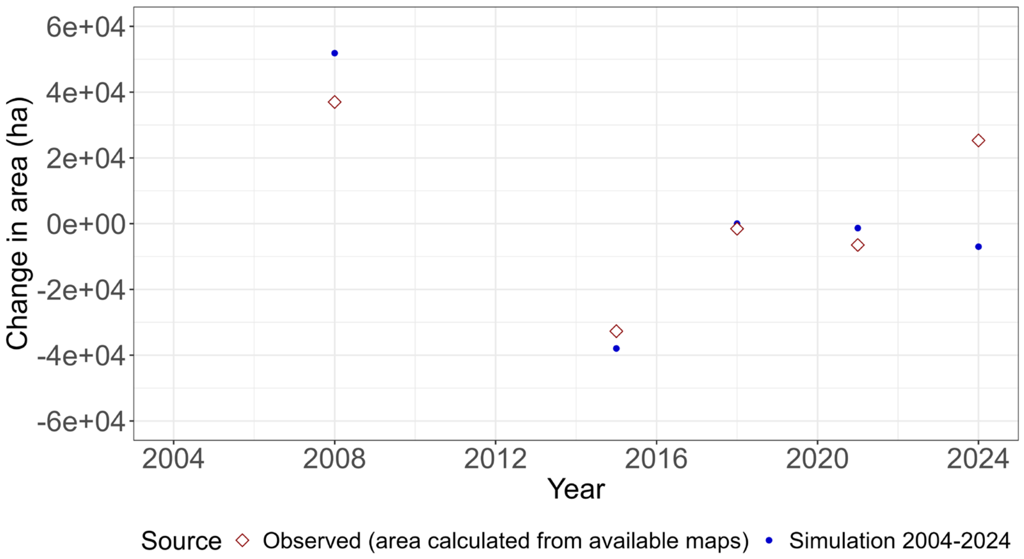
Land use maps



Soil map


Sub-catchments
Streams
SNAME
9 10 11 12 13 14 15 16 17 18 19
20 21 22 23 24 25 26 27 28 29 30 31 32 33 34
35 36 37 38 39 40 41 42 43 44 45 46 47 48 49
50 51 52 53 54 55 56 57 58 59 60 61 62 63 64
65 66 67 68 69 70 71 72 73 74 75 76 77 78 79
80 81 82 83 84 85 86 87 88 89 90 91 92 93 94
95 96 97 98 99 100 101 102 103 104 105 106 107 108 109
110 111 112 113 114 115 116 117 118 119 120 121 122 123 124
125 126 127 128 129 130 131 132 133 134 135 136 137 138 139
140 141 142 143 144 146 147 148 149 150 151
0 10 20 km

Change in forested area 2004-2024



Pine biomass growth and LC data

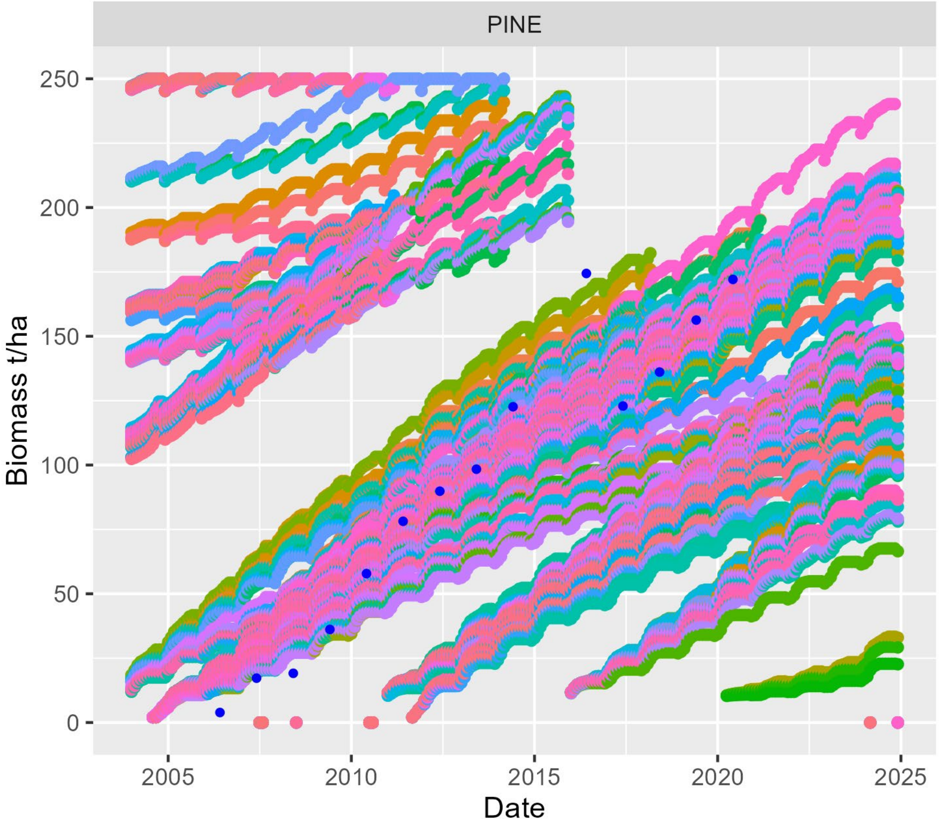
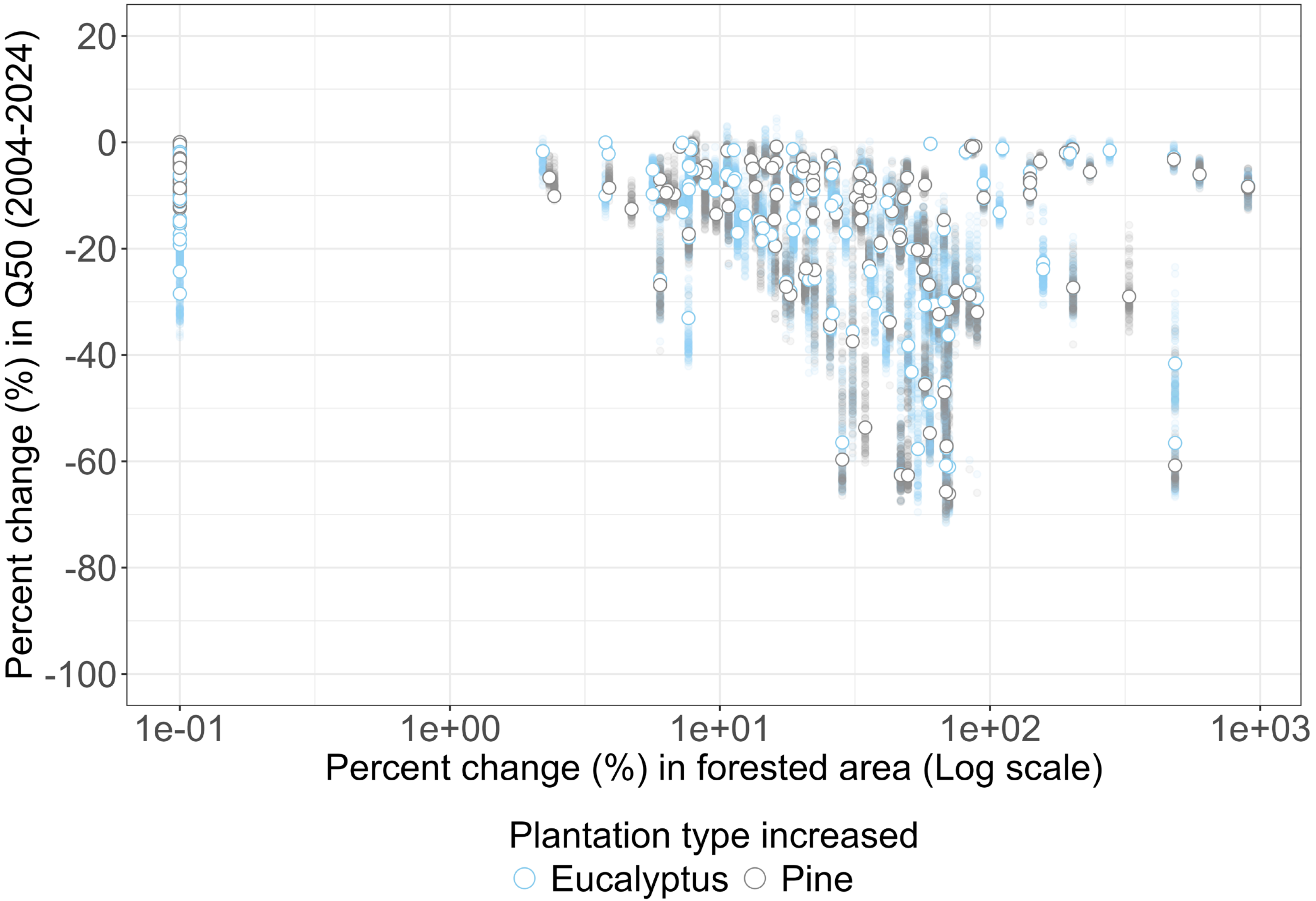


Table 1 Input data for SWAT model implementation in the Borracho catchment.

Data	Source	Details	Reference
Digital Terrain Model	Electronic Government and Information and Knowledge Society Agency (IDEUY-AGESIC)	Resolution of 0.32 m/pixel resized to 120 m/pixel	https://visualizador.ide.uy/geonetwork/
Weather data	12 rain gauges from UTE (Uruguayan Electricity Company) and 1 climatological station from the National Agricultural Research Institute (INIA)	Daily rainfall from UTE (stations ID: 1195, 1220, 1224, 1279, 1301, 1308, 1338, 1339, 1374, 1444, 1484). INIA Tacuarembó climatological station: Daily rainfall, daily ET (Penman), solar radiation, temperature, wind velocity (2000–2019). Weather data was converted to a monthly time step.	Agroclimatic station INIA Tacuarembó (INIA, 2021) and UTE (https://portal.ute.com.uy/)
Soil map	MGAP	The soil map was adapted from (Hastings et al., 2022) developed using the 1:40,000 soil map from MGAP-RENARE (2016), with representative profiles for the Río Negro watershed	(Hastings et al., 2022)
Land-use map	MGAP	The vegetation map for the purpose of this study was generated using the Union tool in QGIS 3.4.1 QGIS Development Team (2018) applied to the landuse cover map from 2015 and the afforestation maps from 2004, 2015, 2018 and 2012.	Land cover maps from OAN-MA (Observatorio Ambiental Nacional, Ministerio de Ambiente, 2000) and afforestation maps from MGAP (Ministerio de Ganadería, Agricultura y Pesca (MGAP), 2022)


Percent change (%) in Q50 (2004-2024)
20
0
-20
-40
-60
-80
-100
1e-01
1e+00
1e+01
1e+02
1e+03
Percent change (%) in forested area (Log scale)
Plantation type increased
Eucalyptus
Pine