Natural revegetation and afforestation in abandoned cropland areas: Hydrological trends and changes in Mediterranean mountains

Makki Khorchani1 | Estela Nadal-Romero1 | Teodoro Lasanta1 | Christina Tague2

1Instituto Pirenaico de Ecología, Procesos Geoambientales y Cambio Global, IPE-CSIC, Zaragoza, Spain
2Bren School of Environmental Science and Management, University of California at Santa Barbara, Santa Barbara, California, USA

Abstract

Water resources availability is one of the main concerns for policy makers around the world in present and future management plans. In the Mediterranean basin, this concern is increased given the extreme variability in climate and the intrinsic aridity conditions. Water resources in the Mediterranean region depend mainly on surface and subsurface supply from mountain areas. Because evapotranspiration comprises a substantial portion of the water budget, recent land cover changes due to cropland abandonment may change transpiration (TRANS) and water supply. Therefore, land management plans must account for these potential hydrologic changes to guarantee water availability in the upcoming decades. Short-term changes to water yield have been shown to follow afforestation or natural revegetation, the main management strategies in abandoned cropland areas. Studies comparing long-term trends of these management practices, however, are scarce due to the lack of long-term hydrological data. In this study, we use the regional hydro-ecological simulation system (RHESSys), to analyse long-term changes and annual and seasonal trends in streamflow (STR) and transpiration following management of abandoned cropland areas. Annual mean values show significant differences between the three management scenarios for both streamflow and transpiration, while differences between climate scenarios are not significant. The Mann Kendall trend analysis shows significant changes to water availability compared to the situation before management. Depending on the total afforested area, afforestation could significantly decrease annual streamflow between 2.3% decade$^{-1}$ and 5.9% decade$^{-1}$ and increase annual transpiration between 1.1% decade$^{-1}$ and 3.5% decade$^{-1}$. These trends are attributed to changes during the first 30 years after management, while during the fourth and fifth decade, changes to water yield tend to stabilize or decrease. These results are substantial to optimize land management plans, ensuring sustainable hydrological and ecological ecosystem services.
1 INTRODUCTION

The availability of water resources and their quality constitutes, possibly, the most important environmental problem in many countries around the world, including those of the Mediterranean basin (García-Ruiz et al., 2011). In fact, the Mediterranean basin is considered a ‘hot spot’ on a global scale due to: (a) the scarcity of water resources (Giorgi, 2006); (b) climate change (increased temperatures, less snow accumulation and greater atmospheric evaporative demand; Gonzalez-Hidalgo et al., 2016; López-Moreno et al., 2008; Polade et al., 2017; Vicente-Serrano et al., 2014); and (c) the significant expansion of the vegetation cover during the last century (Chauhard et al., 2007; García-Ruiz & Lana-Renault, 2011; Sitzia et al., 2010; Vicente-Serrano et al., 2020; Vicente-Serrano & Heredia-Lacastura, 2004). Water resources are a limitation for economic development in the Mediterranean basin and are an essential factor to satisfy the increasing needs of society, as a consequence of the increase in population, urbanization and living standards (García-Ruiz et al., 2011), the development of irrigated agriculture (Iglesias et al., 2011; Jlassi et al., 2016) and industrial and tourist activities (Morote et al., 2016; Rico-Amoros et al., 2009).

Water resources in Mediterranean regions depend mainly on mountain areas, which act as ‘moisture islands’ in the middle of drier areas (de Jong et al., 2009; Immerzeel et al., 2020; Viviroli et al., 2011; Viviroli & Weingartner, 2004). However, during the last century, Mediterranean mountains, especially those in Europe, have experienced important changes in land use and cover due to depopulation and the collapse of primary activities (García-Ruiz & Lasanta-Martínez, 1990; Price, 2004). From a hydrological perspective, the abandonment of agricultural lands and pastures is one of the most important features of these changes (García-Ruiz et al., 2020; Lasanta, 1988; Macdonald et al., 2000), which triggered important revegetation processes on the slopes (García-Ruiz & Lana-Renault, 2011; Poyatos et al., 2003; Sanjuán et al., 2018).

On the other hand, active afforestation carried out by land administrations also constituted a major feature of land cover changes during the last century. In Spain, for example, in 1939 an important afforestation plan (Plan de Repoblación Forestal de España) proposed the afforestation of 6 million hectares in 100 years (Ortízos Izquierdo, 1991). Afforestation pursued two objectives: (a) economic: increasing forest production to meet the growing industrial demand, and (b) environmental: reducing soil erosion and regulating the hydrology of slopes (Ortízos Izquierdo, 1991; Vallejo et al., 2006). This plan had already reached 5 million hectares by 2006 (Lasanta et al., 2015).

The combination of natural revegetation and active afforestation has led to a substantial increase in forest cover in Spain during the last decades. In fact, the forest area increased by 130 000 km² in 45 years (MAPA, 2020). At present, more than 55% of the national territory is covered by trees and shrubs, concentrated particularly in mountain areas (Vicente-Serrano et al., 2020). Several studies relate the progressive decrease in river flows, particularly in mountain areas, to this increase in vegetation and its impact on interception, infiltration, runoff and river-slopes connectivity processes (Beguería et al., 2003; Germer et al., 2010; Muzylko et al., 2012). At the same time, climate change has had significant impacts on water resources in Mediterranean mountains (García-Ruiz et al., 2011) through changing precipitation patterns and atmospheric energy demand (Trenberth, 2011). These environmental changes can combine to lead to significant decrease in river flows and runoff coefficients (López-Moreno et al., 2008; Martínez-Fernández et al., 2013; Morán-Tejeda et al., 2014; Polade et al., 2017), and have already forced the adaptation of reservoir management, limiting water discharge and using multi-year impoundment cycles (López-Moreno et al., 2008; Zabalza-Martínez et al., 2018). These changes are expected to intensify in the coming decades. López-Moreno et al. (2014) for instance, projected that annual flows from Pyrenean rivers will decrease by 2050 between 13 and 23%, depending on location and forest regeneration patterns. In spite of the impacts to water resources, there is science-based support for natural revegetation process that highlight the important benefits of forest regeneration for biodiversity and ecosystem services (Perino et al., 2019). This support underlines promoting natural succession or passive revegetation (rewilding; Navarro & Pereira, 2012) and active revegetation in abandoned cropland areas (Rey Benayas & Bullock, 2012).

Future water management plans in these regions must take into account not only water demand, but also how climate and revegetation may change available water. Interactions between land use and climate change and their combined impacts on water resources are of valuable interest to hydrological decision makers, particularly in rapidly changing Mediterranean environments (Beniston, 2003; Nogués-Bravo et al., 2008; Vivirol & Weingartner, 2011). Deepening knowledge on these interactions can also enhance land management planning to ensure the sustainability of water resources. In this sense, a very important unresolved question is: what is the long-term (next few decades) impact of passive and active revegetation of abandoned lands on vegetation water use and surface water supply? To answer this question, this study uses a well-established ecohydrologic model RHESSys (Tague & Band, 2004), to estimate long term annual and seasonal trends and changes to streamflow (STR) and transpiration (TRANS) following management of abandoned cropland areas under both historic and a warming climate scenario. To parametrize RHESSys, we used data from the monitoring of a small catchment in the Central Spanish Pyrenees (Arns) representative of the process of cropland abandonment.
2 | MATERIALS AND METHODS

2.1 | Study area

Arnás is a small catchment (0.284 km²) of the upper Aragón river located in the Central Spanish Pyrenees (Figure 1). The lithology is Eocene Flysch with sandstones and marl layers alternating and sloping northward (Lana-Renault et al., 2007). The ravine, with a west-east orientation, separates a strongly contrasted north-facing and south-facing slopes. Poor eroded soils characterize the steep south-facing slopes. While, soils in the gentler north-facing slopes are deep and well developed (Navas et al., 2005; Seeger et al., 2005).

The Arnás catchment is a good example of the process of cropland abandonment in Mediterranean mountains. After being highly cultivated with non-irrigated cereals in the 19th century including the steep slopes, Arnás has been progressively abandoned during the first half of the 20th century. Following abandonment, a process of secondary succession of shrubs followed by trees (approximately 100 years following abandonment) took place and a natural vegetation cover colonized most of the catchment. Since abandonment, no active management plans have been adopted in the catchment. Consequently, the present vegetation cover is the result of the natural revegetation process. Present vegetation cover consists mainly of *Pinus sylvestris* and *Quercus faginea* trees (particularly in the north-facing slopes in the first abandoned fields) and *Genista scorpius, Buxus sempervirens, Rosa gr. canina, Juniperus communis* and *Echinospartum horridum* covering most of the catchment. Since 1996, the Pyrenean Institute of Ecology (IPE-CSIC) is monitoring Arnás through the installation of a meteorological station, a gauging outlet and three pluviometers in the catchment (Figure 1).

2.2 | Management of abandoned cropland areas and study scenarios

We develop three land management scenarios that are used to parameterize our ecohydrologic model. All scenarios begin from an initial scenario that follows the historic land abandonment prior to 1960 (Lasanta, 1988). To define this initial state, we used an aerial photography of the catchment from 1957 and developed a land cover map.

We then defined the three simulated scenarios (Figure 2, Table 1). These three scenarios represent three theoretical management trajectories of Arnás catchment following abandonment.

*Scenario 1 (PM and PM.W)*: representing early successional passive management allowing a natural revegetation by shrubs of the catchment following abandonment. Scenario 1 is a representation of the...
The colonization process by shrub species (G. Scorpius, B. sempervirens, E. horridum...) before the entry of a secondary forest. We note that the actual Arnás was abandoned in stages so a transition from shrub to forest occurred at different times in different parts of the catchment. To simplify here we use this to represent a shrub scenario to compare with afforestation catchments where trees are actively introduced.

**Scenario 1**: Passive management through shrub expansion in most of the study area.

**Scenario 2 (AFF1 and AFF1.W)**: representing active management through afforestation of areas of high erosion risk (>30% of slope) in the south-facing slopes.

**Scenario 3**: Active management scenario through afforestation of areas of high erosion risk in both north-facing and south-facing slopes.

**Table 1**: Vegetation cover under the different management scenarios

| Scenario 1 (%) | Scenario 2 (%) | Scenario 3 (%) |
|----------------|----------------|----------------|
| Target areas for afforestation | - | 30.1 | 61.1 |
| Forest land | 3.2 | 3.2 | 3.2 |
| Shrub land | 90.7 | 61 | 30.5 |
| Grass land | 6.1 | 5.7 | 5.2 |
without management around 100 years after abandonment (Gibon et al., 2010; Pueyo & Begueria, 2007). 

Scenario 3 (AFF2 and AFF2.W): Also representing active management, but in this case, all areas of high erosion risk in the study area are afforested. While the rest of the catchment is left to natural revegetation by shrubs. The target areas for management in this scenario represent 60% of the study area (Table 1).

To study the effect of climate change on the trends of STR and TRANS, we coupled these three scenarios with a warming scenario. The European Environmental Agency (EEA, 2020) and the Pyrenean Climate Change Observatory (OPCC, 2018) predicted an increase in temperature between 1–2°C by 2030 and 2.5–5°C by the end of this century in the Pyrenees with respect to the 1961–1990 and 1971–2000 reference periods respectively. Nevertheless, projections for the precipitation are found to be non-significant during the 21st century given that the number of models predicting an increase in precipitations is similar to those predicting a decrease (OPCC, 2018). To translate these climate projections in our climate warming scenario, we considered an increase of 3°C (as a midpoint between the lowest and the highest projections) in maximum and minimum temperature. Whereas, due to the uncertainty in projections, no precipitation change was applied to the climate warming scenario to avoid altering model results.

2.3 | RHESSys model

The RHESSys model (Tague & Band, 2004) was used to simulate the different management scenarios. RHESSys is a dynamic process-based model that calculates carbon, nitrogen and water fluxes over variable terrain from local to regional spatial scale. It was developed to study the effects of land cover and climate changes on the hydrological and ecological processes (Tague & Band, 2004). RHESSys uses a hierarchical representation of the landscape that subdivides ecohydrological processes into different spatial units. The hierarchical representation of the landscape enhances the ability of the model to represent both plot scale processes (at patch level) and hillslopes spatial heterogeneity, accounting for interactions between the smallest spatial units through downslope redistribution. Merging local process and landscape spatial heterogeneity enhances the sensitivity of the model to changes in ecohydrological processes due to climate and land cover changes.

RHESSys partitions precipitation to snow and rain based on air temperature. Total evapotranspiration fluxes, including evaporation of intercepted water by the vegetation and transpiration from canopy layers, are modelled using the Penman–Monteith equation (Monteith, 1965). The intercepted water by the vegetation is modelled as a function of the size and the type of the vegetation. Surface and subsurface hydrological processes include vertical and lateral moisture fluxes. Vertical fluxes include the infiltration of water to soil and its drainage through rooting and unsaturated soil layers. Lateral fluxes may drain saturated water to reach the main stream via surface and subsurface water flow or groundwater flow. Vertical and lateral water fluxes are controlled by the vertical hydraulic conductivity profile. In RHESSys, the saturated hydraulic conductivity is computed as:

$$K_{sat}(z) = K_{sat0}e^{-rac{z}{m}}$$

Where $z$ is soil depth, $K_{sat0}$ is hydraulic conductivity at the surface and $m$ represents the decay of conductivity with soil depth.

RHESSys model vegetation growth and mortality through a carbon cycling model that includes estimates of photosynthesis, respiration and carbon allocations to leaves, stems and roots. Details on the modelled processes in RHESSys model can be found in (Tague & Band, 2004).

The calibration and validation of RHESSys have been performed using data records from meteorological and gauging stations installed in the Arnás catchment since 1996 by the Pyrenean Institute of Ecology (IPE-CSIC). For details on the calibration and validation process see Khorchani et al. (2020). Information and guidelines on RHESSys model can be found in https://github.com/RHESSys/RHESSys/wiki/Parameter-Definition-Files.

We parameterized the vegetation in this study as standard classes of conifers, shrubs and grasses using the 1957 land cover map. Parameters of these standard vegetation classes can be found in https://github.com/RHESSys/RHESSys/wiki/Parameter-Definition-Files. Before simulating management scenarios, a first 100-year spin-up simulation followed by vegetation stores removal, was conducted to initialize soils carbon and nitrogen stores. All the simulations are run with RHESSys model in dynamic mode, which simulates vegetation growth throughout time.

2.4 | Climate record and analysed variables

The climate record from the Arnás monitoring station barely covers 20 years due to high data gaps and instrument problems. To generate a long term data record, for a better analysis of the hydrological trends, several meteorological stations from the Spanish Meteorological Agency (AEMET) and the Pyrenean Institute of Ecology (IPE-CSIC) in a radium of 10 km from the Arnás catchment and at a similar altitude, were used. We followed Vicente-Serrano et al. (2010) and El Kenawy et al. (2012) for the homogenization and gap filling processes. Fifty years of daily precipitation, maximum and minimum air temperature were used for the simulations.

To address the effects of management and climate scenarios on the trends of STR and TRANS and reduce the effect of annual and seasonal precipitation variability on the interpretation of results, the trend analysis used normalized STR and TRANS by total precipitation. STR and TRANS are calculated as follows:

$$\text{Normalized STR}_{\text{Annual,Seasonal}} = \frac{\text{STR}_{\text{Annual,Seasonal}}}{\text{Precipitation}_{\text{Annual,Seasonal}}}$$

$$\text{Normalized TRANS}_{\text{Annual,Seasonal}} = \frac{\text{TRANS}_{\text{Annual,Seasonal}}}{\text{Precipitation}_{\text{Annual,Seasonal}}}$$

Changes to vegetation biomass, Leaf Area Index (LAI) and rooting depth were also analysed to study potential effects on waters fluxes trends.

2.5 | Statistical analysis

In this study, we analyse 50 year trends in STR and TRANS for annual, wet and dry seasons – across three management scenarios with both
historic and warmer climates for a total of six scenarios (3 * 2). For each scenario, we compute annual averages and trends.

The Tukey’s Honestly Significant Difference test (TukeyHSD; Tukey, 1949) was implemented to compare differences between mean annual STR and TRANS under the different management and climate scenarios.

The non-parametric Mann Kendall trend test (Kendall, 1975; Mann, 1945) was used to test the significance of the trends in STR and TRANS. Being a non-parametric test enhances the robustness of the Mann Kendall test, since it is not sensitive to outliers and no prior distribution of the data is assumed (Lanzante, 1996). The significance of the trends in this study was assessed at a 95% of confidence level. The non-parametric Sen’s slope (Sen, 1968) estimator was used to calculate the magnitude of change relative to each management and climate scenario.

Trends and magnitude of change were computed at annual and seasonal scales. Lana-Renault et al. (2007), using water-table data, classified seasonal hydrologic regimes in the Arnäs catchment as follows: a wet period during winter and spring seasons and a dry period during summer months while a strong variability characterizes the transition between wet and dry conditions. STR data in the Arnäs catchment similarly shows a strong seasonality with a wet winter and summer dry period (Figure S1). Based on these definitions and to simplify the results, we defined two seasonal scales: a ‘wet period’ from December to May (winter and spring) and a ‘dry period’ from June to November (summer and autumn). These two periods were used to study the seasonal changes of water regimes due to management and climate scenarios.

We also computed a 30-year moving trend to study the stabilization of the trends under the different management and climate scenarios. Based on the age of management, three phases were defined: 0–30, 10–40 and 20–50 years of management.

3 | RESULTS

3.1 | Annual streamflow and transpiration under management and climate scenarios

At annual scale, the results show high inter-annual variability particularly for STR with a coefficient of variation >37% (Figure 3, Table 2). Significant differences between the three management scenarios are found for annual STR and annual TRANS. However, no significant differences between the climate scenarios (warming vs. no warming) are found for either STR or TRANS (Table S1).

For STR, annual averages over the climate record (50 years), decrease drastically with afforestation scenarios (AFF1 and AFF2) compared to the control scenario (PM). Results show a decline in annual STR by 27 and 50% under AFF1 and AFF2 respectively compared to PM (Figure 3, Table 2). Whereas, under the warming scenario, the decrease in annual STR, compared to PM, is slightly higher under AFF1.W (28%) and AFF2.W (53%; Figure 3, Table 2). Differences between historic and warming climate scenarios show a slight decrease in annual STR due to temperature increase nevertheless these differences are non-significant (Table 2, Table S1).
For annual TRANS, due to the lower inter-annual variability (less than 23%, Table 2), differences between the three management scenarios are clearer than STR (Figure 3). Significant differences are found between the three management scenarios, while differences between climate scenarios are non-significant (Table 2, Table S1). Afforestation strongly increased annual TRANS with 40 and 89% higher values under both AFF1 and AFF2 respectively compared to PM. These differences are higher under the warming scenario (41 and 93%; Table 2, Table S1).

Table 3 shows three structural vegetation variables that directly affect the hydrological fluxes (vegetation biomass, LAI, rooting depth). All of these variables are computed by RHESSys, evolving over time and respond to available energy and moisture. Comparing these three variables under the different scenarios helps to explain the difference in hydrological fluxes across scenarios. Compared to PM, afforestation scenarios presented a higher vegetation biomass (up to 127%), a more developed LAI (up to 99%) and a deeper rooting depth (up to 27%), though differences are not significant in this case; Table 3, Table S2). These differences between management scenarios contribute to greater TRANS (and correspondingly lower STR). However, vegetation structural variables do not show significant differences between historic and warmer climate scenarios (Table S2). At seasonal scale, AFF3 and AFF3.W presented higher differences in LAI between historic and warming climate scenario compared to PM and AFF1 scenarios. However, the duration of the growing season was not changed by the increase of temperature, reflecting the dominance of water availability as the main control on growing season length (Figure 4).

### 3.2 Annual and seasonal trends of normalized streamflow and transpiration under management and climate scenarios

#### 3.2.1 Effect of climate variability and trends

To make sure the effect of trends in the climate record on our results are minimum, we calculated trends and changes in precipitation, maximum, minimum and average temperature to study if the climate record already presented significant trends. Results show non-significant trends in precipitation in both annual and seasonal scales (Figure S2). This confirms that recent trends in precipitation would not have significant impacts on STR. However, we note that future trends in precipitation may be more substantial and potentially accelerate declines. Maximum temperature showed significant decrease by $0.26 \, ^\circ \text{C}\, \text{decade}^{-1}$ during the dry period, while during the wet period and at annual scale the trends are non-significant. Minimum temperature showed significant increase at annual and seasonal scale ($0.2 \, ^\circ \text{C}\, \text{decade}^{-1}$ at annual scale and $0.19 \, ^\circ \text{C}\, \text{decade}^{-1}$ during the dry period; Figure S2). Nevertheless, trends are not significant for average...
temperature, which reduces the likelihood of substantial effects on the trends in STR and TRANS at annual and seasonal scales.

### 3.2.2 Annual trends and magnitude of change

At annual scale, the trend analysis of the different management and climate scenarios show significant changes to normalized STR and TRANS. For PM scenario, STR significantly decreases by 2.4% decade\(^{-1}\) and 2.3% decade\(^{-1}\) under historic and warming climates respectively. However, though trends are non-significant, TRANS decrease by around 1% under both climate scenarios (Figure 5, scenario 1).

Under AFF1 scenario, significant trends in STR and TRANS are found for both climate scenarios. For STR, the decrease is of 4.5% decade\(^{-1}\), under no warming effect, and of 4.2% decade\(^{-1}\) under warming. TRANS shows an increase of 2.2% decade\(^{-1}\) and 2.3% decade\(^{-1}\) without and with warming effect respectively (Figure 5, scenario 2).

The highest changes to STR and TRANS are found under AFF2 scenario. Results shows a strong significant decrease in STR by 5.9% decade\(^{-1}\) under no climate change effect and by 5.4% decade\(^{-1}\) under a 3°C increase in air temperature. While TRANS presented a significant increase by 3.5% decade\(^{-1}\) under no warming effect and 3.4% decade\(^{-1}\) under warming (Figure 5, scenario 3).

The significant annual trends are attributed mainly to changes occurring during the first phase of the study period (first 30 years of management; see Figures 6 and 7). In fact, analysing a 30-year moving trend of the normalized STR and TRANS in three management phases revealed only significant trends during the first phase while during the second and the third phases all the trends are non-significant for both variables under the different scenarios (see Figures 6 and 7). During phase 1, STR presented significant negative trends all management and climate scenarios. The magnitude of change in the significant trends oscillates between \(-5.9\%\) decade\(^{-1}\) to \(-12.6\%\) decade\(^{-1}\) (Figure 6).

Similarly to STR, significant trends in TRANS are only found during phase 1. Under the different management and climate scenarios, TRANS shows significant positive trends. The magnitude of change in TRANS ranges between \(3\%\) decade\(^{-1}\) to \(6.6\%\) decade\(^{-1}\) (Figure 7). During phase 3, although the trends are non-significant, a clear increase in water yield is observed, marked by higher STR and lower TRANS values (Figures 6 and 7).

These trends are highly related to changes in vegetation structural variables. Figure 8 shows the year-to-year change in vegetation biomass, LAI and rooting depth. Results show a clear increase during first years of management corresponding with a growing vegetation cover. Annual changes to vegetation variables reach a maximum and start decreasing until relatively stabilizing around 10 years after management (Figure 8). These changes are reflected in vegetation water use marked by significant changes to water fluxes during first years of management.

### 3.2.3 Seasonal trends (dry period and wet period) and magnitude of change

At seasonal scale, results show high inter-annual variability in both STR and TRANS under the different management and climate scenarios (Figures S3 and S4). For PM scenario, STR and TRANS presents
non-significant trends during both seasonal periods and climate scenarios (Tables 4 and 5, scenario 1).

For AFF1, under no warming, STR only shows a significant decrease during the wet period by 4.4%/decade. While results of the warming scenario AFF1.W show a significant decrease of STR by 2.7%/decade and 4%/decade during dry and wet periods respectively (Table 4). Trends in TRANS, are significant only during the wet period with increases of up to 2.4%/decade. While, during the dry period, the trends are non-significant (Table 5).

The highest changes to STR and TRANS are found during the wet period under AFF2 scenario. STR significantly decline during the wet period by 5.7%/decade and 4.3%/decade for historic and warming climates respectively (Table 4, scenario 3). However,
during the dry period, low significant decreases are found (Table 4). TRANS trends on the other hand are only significant during the wet period with increases of 3.5% decade$^{-1}$ and 3.9% decade$^{-1}$ for historic and warming climates respectively (Table 5, scenario 3). Figure 9 presents a summary of the obtained results under the different management and climate scenarios for STR and TRANS.

4 | DISCUSSION

This study compares several management and climate scenarios in a small catchment representative of the process of land abandonment in the Central Spanish Pyrenees. Three scenarios of management are compared: (a) a passive management (first 50 years of natural shrub revegetation) and a low and an intense active management scenario through
afforestation (first 50 years after afforestation). Simulations are computed with historical climate data and a warming scenario where 3°C was added to historic record to test climate change effects.

4.1 | Changes to water yield following management

Comparing mean values between the different scenarios revealed significant differences to annual STR and TRANS in Mediterranean mountain areas. Annual STR was lower (27–53%) and TRANS significantly higher (40–93%) under afforestation scenarios when compared to the control scenario PM. These results are consistent with other studies that generally associate afforestation with significant decreases in water yield (Buendia et al., 2016; Jackson et al., 2007; Piao et al., 2007). For instance, in a global analysis of 504 catchment observation, (Farley et al., 2005) estimated a decrease by 44 and 31% of annual STR after afforesting grasslands and shrublands respectively. Silveira and Alonso (2009), pointed out that afforestation of 26% of the watershed with pines and eucalyptus species reduces
annual STR by between 8.2 and 36.5%, depending on annual precipitation. Guzha et al. (2018), revealed that an increase in forest cover decreases surface STR by 25%.

The trend analysis of annual and seasonal STR and TRANS shows how these declines in STR and corresponding increases in TRANS evolve over time. Here again, results for the Arná catchment are consistent with previous studies on STR trends during the past decades that generally point to a significant decrease in annual flows in most of the sub-basins in northern Spain (García-Ruiz et al., 2011; Lorenzo-Lacruz et al., 2012; Vicente-Serrano et al., 2019). In these studies, authors attributed the decrease in annual STR to the expansion of a dense vegetation cover due to the management of abandoned areas. Our modelling study for the Arná catchment confirms that the increase in canopy structural variables (including biomass, LAI, rooting depth) associated with a developing forest corresponds with these hydrologic changes, while climate trends are generally negligible.

It is generally accepted that water consumption of forest is larger than that of shorter vegetation such as shrubs and grasses in

FIGURE 8 Annual change in vegetation biomass (kg C m⁻² year⁻¹), Leaf Area Index and rooting depth (mm year⁻¹) under the different management and climate scenarios. Scenario 1 (PM and PM.W: Passive management), scenario 2 (AFF1 and AFF1.W: Active management), scenario 3 (AFF2 and AFF2.W: Active management). Blue and red colours correspond to the no warming and warming scenarios respectively.
hydrological studies (Bosch & Hewlett, 1982; Brown et al., 2005; Farley et al., 2005; Peel, 2009; Sahin & Hall, 1996). Water consumption by vegetation is mainly related to its morphological attributes (Zhou et al., 2016) and in particular its LAI (Wang et al., 2014). TRANS is strongly linked to canopy conductance, which is directly related to LAI and height (Good et al., 2014; Wang et al., 2014). Although, TRANS is the main component of vegetation-evapotranspiration, interception and soil-evaporation contributes substantially in altering water yield in forest, particularly in coniferous plantation (Cannell, 1999). Trees tend to have higher TRANS, interception and evaporation rates than shrubs, which leads to higher losses of water to the atmosphere as TRANS (Seneviratne et al., 2010).

The significant trends found at annual scale are mainly related to trends during the first 30 years of management. The moving trend analysis shows that changes to STR and TRANS are only significant during the first 30 years. This is in part consistent with some studies that identified significant effects during the first decades following management (Farley et al., 2005; Peel, 2009), nevertheless, long-term trends to water yield are less certain (Peel, 2009). Significant trends during the first 30 years corresponds to a high increase in vegetation structural variables (biomass, LAI and rooting depth) during first years of management. van Dijk and Keenan (2007) suggested that most afforestation species (as conifers) show rapid growth rates with previous studies highlighting a decrease in evapotranspiration rates following the first 10 years of management. This is consistent with studies highlighting a decrease in evapotranspiration with vegetation age (van Dijk & Keenan, 2007). Scott and Prinsloo (2008) related the stabilization of the effects to water yield to vegetation maturity and pointed out a recovery of pre-afforestation

### TABLE 4 Trends and magnitude of change in annual normalized streamflow under the different management and climate scenarios during dry and wet periods

| Scenario | PM | PM.W | AFF1 | AFF1.W | AFF2 | AFF2.W |
|----------|----|------|------|--------|------|--------|
| Dry-period | p-Value | Change (% decade⁻¹) | p-Value | Change (% decade⁻¹) |
| 0.08 | −2.3 | 0.32 | −1.4 |
| 0.09 | −2.4 | 0.32 | −1.3 |
| 0.06 | −2.8 | <0.05 | −4.4 |
| <0.05 | −2.7 | <0.05 | −4 |
| <0.05 | −1.7 | <0.05 | −5.7 |
| <0.05 | −1.8 | <0.05 | −4.3 |

Note: 95% level is used for the significance of the p-value of the Mann Kendall test. Scenario 1 (PM and PM.W: Passive management), scenario 2 (AFF1 and AFF1.W: Active management), scenario 3 (AFF2 and AFF2.W: Active management). PM.W, AFF1.W and AFF2.W represent warming climate scenarios.

### TABLE 5 Trends and magnitude of change in annual normalized transpiration under the different management and climate scenarios during dry and wet periods

| Scenario | PM | PM.W | AFF1 | AFF1.W | AFF2 | AFF2.W |
|----------|----|------|------|--------|------|--------|
| Dry-period | p-Value | Change (% decade⁻¹) | p-Value | Change (% decade⁻¹) |
| 0.37 | 0.9 | 0.07 | 1.2 |
| 0.26 | 1 | 0.07 | 1.3 |
| 0.11 | 2.1 | <0.05 | 2.2 |
| 0.12 | 1.7 | <0.05 | 2.4 |
| 0.08 | 3.1 | <0.05 | 3.5 |
| 0.11 | 2.5 | <0.05 | 3.9 |

Note: 95% level is used for the significance of the p-value of the Mann Kendall test. Scenario 1 (PM and PM.W: Passive management), scenario 2 (AFF1 and AFF1.W: Active management), scenario 3 (AFF2 and AFF2.W: Active management). PM.W, AFF1.W and AFF2.W represent warming climate scenarios.
levels depending on the planted trees (30 years in the case of pine plantation). The age of the vegetation therefore, could be of a great interest to better predict changes to water yield after management.

The analysis of trends at seasonal scale show that significant trends to STR and TRANS are mainly concentrated during the wet period (December–May), which makes sense as this is when plants are most active during the year. During the dry period, STR does decline and these declines are significant for afforestation scenarios while trends in dry season TRANS are non-significant. The declines in dry season STR likely reflect carryover of the effects of higher wet season TRANS, which reduces groundwater levels that subsequently support summer dry season flows.

### 4.2 Land management consideration

Land abandonment and afforestation is widespread in parts of the Mediterranean and particularly in Spain (Vicente-Serrano et al., 2020), and there are large abandoned areas in which the process of plant succession has not ended yet (Lasanta et al., 2017; Lasanta et al., 2021). Results from this study suggest that this type of afforestation can accelerate hydrologic change, leading to significant declines in STR that intensify for several decades. If these hydrologic changes occur over a large area, the STR declines would have important repercussions for water resource management, as highlighted García-Ruiz et al. (2011) and Vicente-Serrano et al. (2017), among others. Under these circumstances, water resource management become a delicate matter if it must guarantee the availability of water resources.

In addition to hydrological implications, the increase in the vegetation cover resulting from afforestation and even natural regrowth strategies could strongly affect the sustainability of ecosystem services in these areas. For instance, the expansion of forest cover could strongly increase fire risks and limit the availability of pasture lands (Lasanta et al., 2018). We caution, however, that there are benefits from afforestation including reduced soil erosion (Huang et al., 2017; Porto et al., 2009), increased infiltration rates (Listedt et al., 2007) and increased biodiversity (Buscardo et al., 2008). Adoption of afforestation plans in abandoned areas, however, should balance these benefits with potential hydrologic impacts and consider alternative land management strategies. In areas where water supply is a critical issue, natural revegetation combined with shrub clearing could be an effective management strategy to ensure lower fire risks (Lasanta et al., 2018) and higher water availability (Khorchani et al., 2020). On the other hand, afforestation plans could be an effective strategy in areas with

| Trend scale | Scenario 1 | Scenario 2 | Scenario 3 | Variable |
|-------------|------------|------------|------------|----------|
|             | No warming | Warming    | No warming | Warming  | No warming | Warming  |
| Yearly      |            |            |            | STR      | TRANS     |
| Phase 1     |            |            |            | STR      | TRANS     |
| Phase 2     |            |            |            | STR      |TRANS     |
| Phase 3     |            |            |            | STR      | TRANS     |
| Wet Period  |            |            |            | STR      | TRANS     |
| Dry Period  |            |            |            | STR      | TRANS     |

**Legend**

- Significant negative
- Non-significant negative
- Non-significant positive
- Significant positive

### FIGURE 9

Summary of the obtained trends under the different management and climate scenarios for normalized streamflow (STR) and transpiration (TRANS) in annual and seasonal scales. Phase 1: From year 1 to 30 of management, phase 2: From year 10 to 40 of management, and phase 3: From 20 to 50 years of management. Wet period: December to May, dry period: June to November.
sufficient annual precipitations to sustain the high water use of trees. In the Central Spanish Pyrenees, as a transitional region between humid high elevations and drier low elevation areas, tailoring management practices to the local setting will be important. In some areas, combining afforestation with natural revegetation and shrub clearing could enhance the hydrological and ecological processes in these areas and guarantee the availability of water resources for lowland areas. Optimizing hydrological and ecological benefits of active and passive management plans therefore, could be a promising objective for future studies in Mediterranean mountains.

5 | CONCLUSIONS

In this study, we aim to gain more insight on the changes to water regimes in abandoned cropland areas due to management and climate change. We used an ecohydrologic model to show that afforestation in abandoned areas would significantly decrease annual STR between 2.3%·decade\(^{-1}\) and 5.9%·decade\(^{-1}\) depending on the total afforested area. These trends were linked with the growth of vegetation over time, leading to increases in TRANS losses, particularly during the wet season. These changes ultimately stabilize as vegetation reaches maturity. Changes in TRANS and STR with a warming climate on the other hand were smaller.

The multi-decadal scale of this study has permitted to underline important findings on the effects of management plans and climate on water regimes in Mediterranean mountains. Our study demonstrated that the adopted management plan, the spatial scale of management and the age of management as well as climate could condition the hydrological response in Mediterranean mountain areas. These results could be of high interest to help quantifying the potential changes to hydrological processes following management of abandoned cropland areas. Such quantification is of crucial importance when elaborating land management plans particularly in water limited environments as it is the Mediterranean region. Nevertheless, studies at medium to large spatial scales are of big interest to validated the obtained results and ensure the efficiency of future land management plans.

ACKNOWLEDGEMENTS

This research was supported by the ESPAS and MANMOUNT projects (CGL2015-65569-R and PID2019-105983RB-100/AEI/10.13039/501100011033), funded by the MINECO-FEDER and MICINN-FEDER). The ‘Geoenvironmental Processes and Global Change’ (EO2_17E) research group were financed by the Aragón Government and the European Social Fund (ESF-FSE). Makki Khorchani is working with an FPI contract (BES-2016-077992) from the Spanish Ministry of Economy and Competitiveness associated to the ESPAS project. The data from Arnás catchment have been collected since 1996 at IPE-CSIC thanks to regional, national and European funding and thanks to all the people who carried out this work.

DATA AVAILABILITY STATEMENT

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

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**How to cite this article:** Khorchani, M., Nadal-Romero, E., Lasanta, T., & Tague, C. (2021). Natural revegetation and afforestation in abandoned cropland areas: Hydrological trends and changes in Mediterranean mountains. *Hydrological Processes*, 35: e14191. https://doi.org/10.1002/hyp.14191