

# Satellite-taken soil moisture, as a reliable radial increment driver in lowland *Quercus robur* L. forest across SE Europe

Saša Kostić<sup>1\*</sup>, Wolfgang Wagner<sup>2</sup>, Tom Levanič<sup>3</sup>, Dejan B. Stojanović<sup>1</sup>, Tzvetan Zlatanov<sup>4</sup>, Ernest Goršič<sup>5</sup>, Saša Orlović<sup>1</sup>

<sup>1</sup> Institute of Lowland Forestry and Environment University of Novi Sad Antona Čehova 13d Serbia;  
<sup>2</sup> Department of Geodesy and Geoinformation TU Wien Austria;  
<sup>3</sup> Slovenian Forestry Institute Večna pot 2 Slovenia;  
<sup>4</sup> Institute of Biodiversity and Ecosystem Research Bulgarian Academy of Sciences Bulgaria;  
<sup>5</sup> Department of Forest Management Planning and Inventory Faculty of Forestry University of Zagreb.

## ABSTRACT

Drought and wetness conditions are typically regarded as among the primary environmental drivers in pedunculate oak (*Quercus robur* L.) forests throughout SE Europe. Across SE Europe, 22 stands were collected. The stands were divided into three wetness groups (WGs): dry (650), moderate (650–750), and wet (750 mm m<sup>-2</sup>). A 38 environmental and climate parameters (temperature, precipitation, soil moisture, river water level, and drought indices) were included in the Generalized Additive Mixed Model (GAMM). Due to the changes in stand-wetness conditions, GAMM outputs revealed diverse responses to the majority of factors. Furthermore, more than half of these variables displayed nonlinear patterns, which are more appropriate for nonlinear modeling (such as GAMM) in tree-ring studies. Our results also show that all pedunculate oak stands under study are extremely susceptible to environmental influences and can be employed in environmental modeling and reconstruction based on tree ring data.

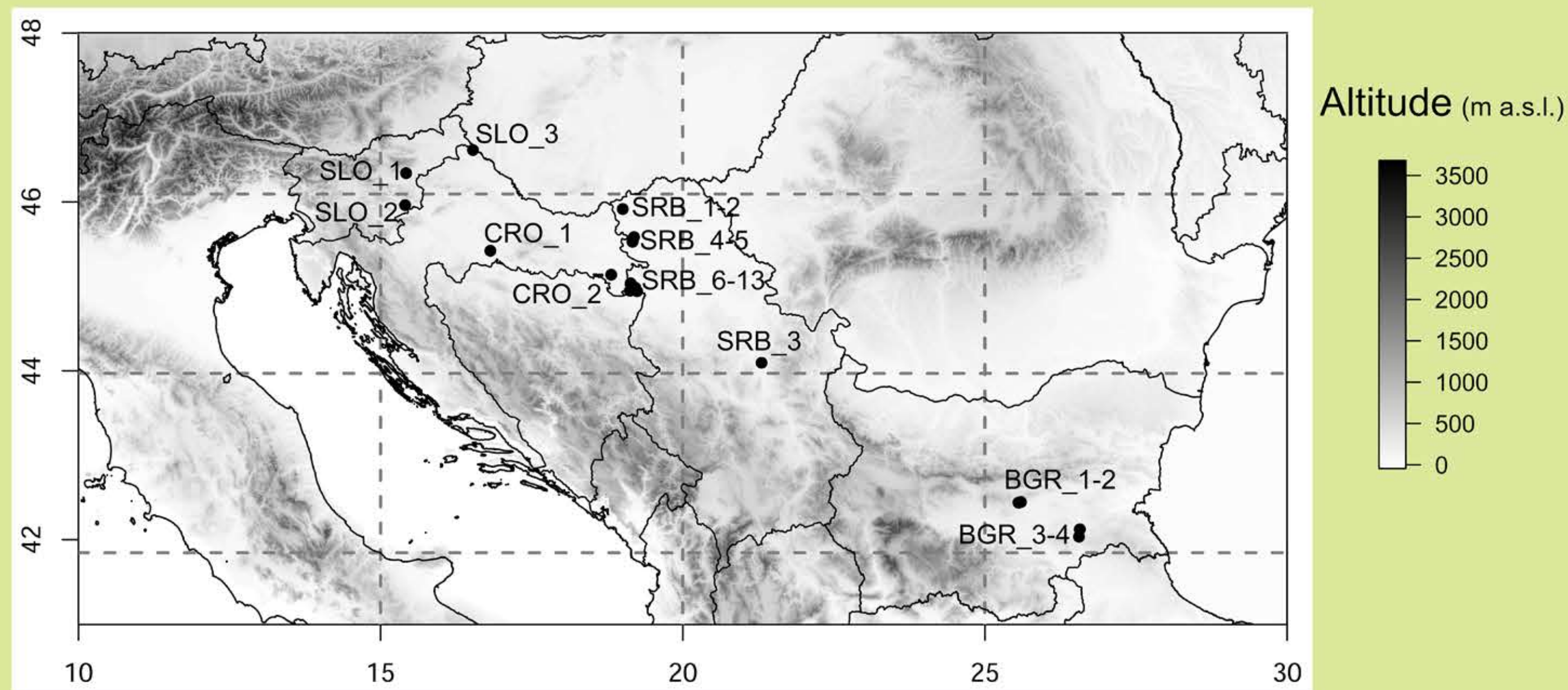


Fig. 1. Study area

## INTRODUCTION

Forest ecosystems in southeastern (SE) Europe will be exposed to a warmer and likely drier climate in the near future, following the 4.5 and more severe representative concentration pathway (RCP) scenarios (IPCC, 2019). These new stand conditions will adversely affect forests, compromising both wood quality and radial growth (Boisvenue and Running, 2006; Paquette et al., 2018). According to the RCP scenarios, the most severe impacts are expected on climate-sensitive species such as pedunculate oak (*Quercus robur* L.), resulting in significantly reduced radial growth until 2100 (Bauwe et al., 2018). This prediction is of great importance because pedunculate oak is the most important economic species in lowland forests in SE Europe; furthermore, it is one of the most endangered tree species in temperate forest ecosystems (EUFORGEN, 2009; Hanewinkel et al., 2012).

Remote sensing satellites have provided a growing number of new data sets describing vegetation cover and other Earth surface features (Wang et al., 2004). This has resulted in an increased use of remotely sensed data in dendrochronology (Reiche et al., 2016; White et al., 2016). In particular, normalized difference vegetation index (NDVI) datasets are widely used, as the NDVI allows the estimation of forest cover degradation based on canopy color changes (Carlson and Ripley, 1997). Recent studies indicate that the NDVI is highly correlated with radial increments in different environments (Srur et al., 2011; Brehaut and Danby, 2018; Correa-Díaz et al., 2019; Muñoz et al., 2014; Martínez-Fernández et al., 2019). The remotely sensed index used in this study is soil moisture (SM), which was derived from microwave remote sensing measurements (see Wagner et al. 2007 for more information). Serving as a potential proxy for water availability in forest ecosystems (Kim et al., 2020), microwave-based SM data significantly differ from NDVI data in terms of their prognostic value; such data depict changes in trees via tree crown reflectance. Hence, SM should be a valuable and uniform water proxy for the whole Earth system from 1978 to date, with wide implications in water-plant related studies.

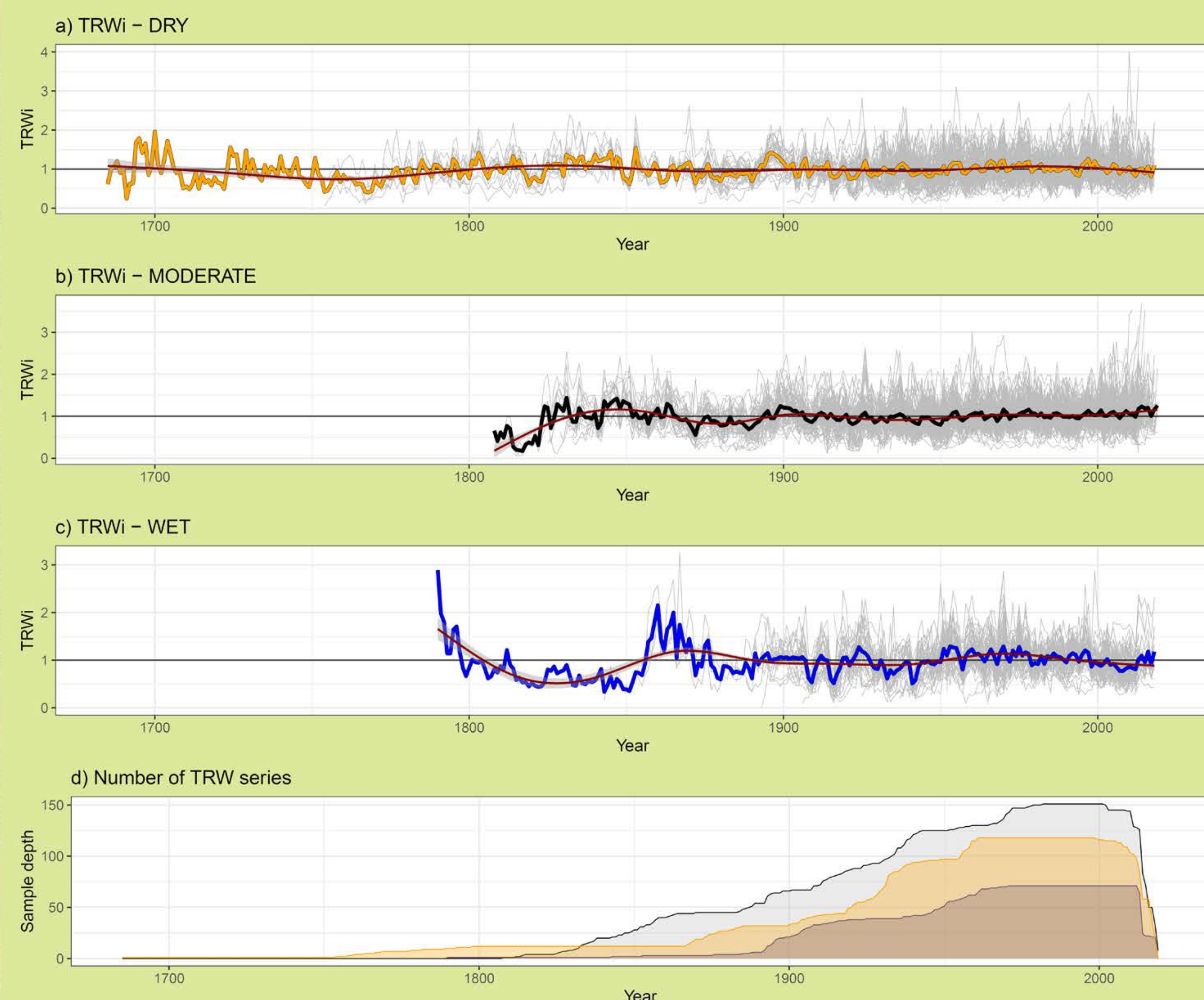
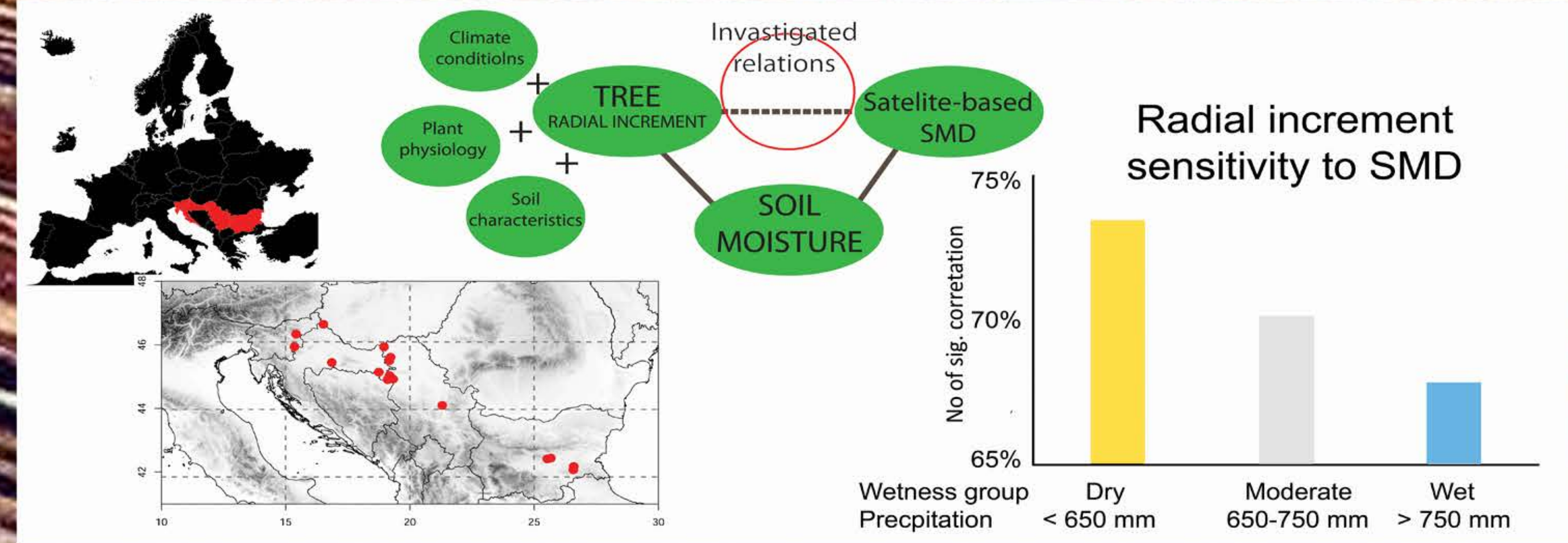


Figure 2. TRW chronologies of oaks that growth on (a) dry, (b) moderate, (c) wet stands, and (d) sample depth.

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**Note:** This contribution is a summary of a study by Kostić, S., Wagner, W., Orlović, S., Levanič, T., Zlatanov, T., Goršič, E., ... & Stojanović, D. B. (2021). Different tree-ring width sensitivities to satellite-based soil moisture from dry, moderate and wet pedunculate oak (*Quercus robur* L.) stands across a southeastern distribution margin. *Science of The Total Environment*, 800, 149536. <https://doi.org/10.1016/j.scitotenv.2021.149536>



## MATERIAL AND METHODS

### Data and stand descriptions

The present study was conducted on 22 stands across four SE European countries. The sample consisted of 341 individual TRW series. Specifically, we had three locations in Slovenia, two in Croatia, 14 in Serbia, and four in Bulgaria. For this study, we collected published and unpublished TRW chronologies from SE Europe. The sample included only visually healthy, mature, dominant trees from natural stands. Each individual TRW series was calculated as an average from two core samples and was interpreted as the whole annual radial increment (early and late wood together).

### Statistical data processing

All statistical data processing was carried out using R (R Core Team, 2013). Following the increasing application of nonlinear models in radial growth modeling (Marchand et al., 2020; Kostić et al., 2021; Wernicke et al., 2021) and after testing both linear and nonlinear model approaches, we selected a nonlinear model for this study. Using a generalized additive mixed model (GAMM), we describe the relationships among the radial growth chronologies and surrounding factors from different WGs. In detail, 38 variables were used for GAMM construction, with equal effects on the model. The GAMM outputs were used to describe the implications and reliability of the interactions of the remotely sensed SM of the radial growth-surrounded environment and compare the remotely sensed data with traditionally measured parameters such as temperature, precipitation, river water level, etc.

A GAMMs were provided by EQ. 2, and a GAMMs were then constructed for each WG (dry, moderate, and wet), each for a 30-year timespan (1980–2010). In all three cases, the same 38 variables were used as the inputs to the second model. Only TRW chronologies that covered the mentioned 30-year period were included in the model. In total, 118, 152, and 71 tree chronologies from dry, moderate, and wet stands were included in the second model. The GAMMs were developed using the “mgcv” R package (Wood, 2015) via Equation 2:

$$\begin{aligned} \text{TRW}_i = & 1 + s(\text{PRCP}) + s(\text{PRCP\_MAM}) + s(\text{PRCP\_JJA}) + s(\text{PRCP\_Y2}) + s(\text{TEMP}) + s(\text{TEMP\_MAM}) + s(\text{TEMP\_JJA}) \\ & + s(\text{TEMP\_Y2}) + s(\text{SM}) + s(\text{SM\_MAM}) + s(\text{SM\_JJA}) + s(\text{SM\_Y2}) + s(\text{RWL}) + s(\text{RWL\_MAM}) + s(\text{RWL\_JJA}) \\ & + s(\text{RWL\_Y2}) + s(\text{SPI\_3\_JUN}) + s(\text{SPI\_3\_JUL}) + s(\text{SPI\_3\_AUG}) + s(\text{SPI\_6\_MAR}) + s(\text{SPI\_6\_JUN}) + s(\text{SPI\_6\_AUG}) \\ & + s(\text{SPI\_12\_MAR}) + s(\text{SPI\_12\_JUN}) + s(\text{SPI\_12\_AUG}) + s(\text{SPI\_24\_MAR}) + s(\text{SPI\_24\_JUN}) + s(\text{SPI\_24\_AUG}) \\ & + s(\text{SPI\_36\_MAR}) + s(\text{SPI\_36\_JUN}) + s(\text{SPI\_36\_AUG}) + s(\text{SPI\_48\_MAR}) + s(\text{SPI\_48\_JUN}) \\ & + s(\text{SPI\_48\_AUG}) + s(\text{SPI\_60\_MAR}) + s(\text{SPI\_60\_JUN}) + s(\text{SPI\_60\_AUG}) + (\text{Site/Tree}) + \text{CorCAR1}(\text{Year} \mid (\text{Site/Tree})) \end{aligned}$$

Table 2

Generalized additive mixed model (GAMM) outputs to oaks that growing on drier, moderate, and wetter stands.

| Variable                    | Dry   |                     |             | Moderate                    |                     |         | Wet                         |                     |         |
|-----------------------------|-------|---------------------|-------------|-----------------------------|---------------------|---------|-----------------------------|---------------------|---------|
|                             | EDF   | F (p)               | k-Index (p) | EDF                         | F (p)               | k-Index | EDF                         | F (p)               | k-Index |
| PRCP                        | 1     | 5.053***            | 0.93***     | 1                           | 78.097***           | 0.93*** | 0.999                       | 12.653***           | 0.95*   |
| PRCP_MAM                    | 4.511 | 5.780***            | 0.89***     | 4.536                       | 8.557***            | 0.89*** | 1                           | 7.908**             | 0.92*** |
| PRCP_JJA                    | 5.399 | 0.206 <sup>NS</sup> | 0.91***     | 6.083                       | 5.189***            | 0.90*** | 1                           | 1.452 <sup>NS</sup> | 0.95**  |
| PRCP_Y2                     | 2.656 | 8.881***            | 0.89***     | 1                           | 0.264 <sup>NS</sup> | 0.91*** | 1                           | 18.787***           | 0.97*   |
| TEMP                        | 3.006 | 1.875 <sup>NS</sup> | 0.90***     | 5.073                       | 6.400***            | 0.91*** | 0.999                       | 4.928*              | 0.92*** |
| TEMP_MAM                    | 4.704 | 3.365**             | 0.89***     | 6.762                       | 5.933***            | 0.91*** | 1                           | 11.75***            | 0.93*** |
| TEMP_JJA                    | 7.184 | 3.134**             | 0.89***     | 1                           | 3.850*              | 0.89*** | 1                           | 0.397 <sup>NS</sup> | 0.93*** |
| TEMP_Y2                     | 7.336 | 6.591***            | 0.89***     | 1                           | 13.410***           | 0.90*** | 1                           | 0.501 <sup>NS</sup> | 0.92*** |
| SM                          | 1     | 8.565**             | 0.88***     | 7.875                       | 4.625***            | 0.90*** | 1                           | 8.049**             | 0.93*** |
| SM_Y2                       | 3.939 | 2.161 <sup>NS</sup> | 0.87***     | 8.164                       | 7.795***            | 0.90*** | 0.999                       | 17.97***            | 0.94**  |
| SM_MAM                      | 5.782 | 6.762***            | 0.90***     | 8.521                       | 7.600***            | 0.91*** | 4.834                       | 3.850**             | 0.89*** |
| SM_JJA                      | 4.989 | 5.490***            | 0.89***     | 7.04                        | 8.244***            | 0.90*** | 1                           | 0.419 <sup>NS</sup> | 0.90*** |
| SM_Y2                       | 8.176 | 8.367***            | 0.88***     | 5.696                       | 7.409***            | 0.88*** | 1.001                       | 11.315***           | 0.93*** |
| RWL_MAM                     | 6.837 | 7.924***            | 0.89***     | 8.316                       | 14.464***           | 0.89*** | 1                           | 27.029***           | 0.93*** |
| RWL_JJA                     | 8.648 | 17.069***           | 0.89***     | 7.529                       | 6.463***            | 0.89*** | 1                           | 10.646**            | 0.92*** |
| SPI_3_MAR                   | 4.983 | 4.380**             | 0.88***     | 1                           | 0.459 <sup>NS</sup> | 0.90*** | 0.999                       | 34.684***           | 0.91*** |
| SPI_3_JUN                   | 7.623 | 4.716**             | 0.88***     | 7.541                       | 11.657***           | 0.89*** | 1.001                       | 28.003***           | 0.92*** |
| SPI_3_AUG                   | 6.228 | 8.016**             | 0.89***     | 3.403                       | 4.557*              | 0.90*** | 1.001                       | 2.726 <sup>NS</sup> | 0.94*   |
| SPI_6_MAR                   | 1     | 6.082*              | 0.89***     | 1                           | 0.480 <sup>NS</sup> | 0.90*** | 1                           | 17.028***           | 0.92*** |
| SPI_6_JUN                   | 0.999 | 0.893 <sup>NS</sup> | 0.89***     | 4.286                       | 6.305***            | 0.90*** | 0.999                       | 36.312***           | 0.94**  |
| SPI_6_AUG                   | 0.999 | 2.965 <sup>NS</sup> | 0.91***     | 5.495                       | 5.779***            | 0.89*** | 2.178                       | 2.790 <sup>NS</sup> | 0.94*** |
| SPI_12_MAR                  | 2.600 | 15.024***           | 0.90***     | 1                           | 21.757***           | 0.91*** | 1                           | 0.011 <sup>NS</sup> | 0.95*   |
| SPI_12_JUN                  | 1     | 2.186 <sup>NS</sup> | 0.88***     | 1                           | 48.141***           | 0.89*** | 1                           | 0.827 <sup>NS</sup> | 0.93*** |
| SPI_12_AUG                  | 1     | 0.469 <sup>NS</sup> | 0.88***     | 1                           | 1.905 <sup>NS</sup> | 0.92*** | 0.999                       | 18.575***           | 0.94**  |
| SPI_24_MAR                  | 5.198 | 3.974**             | 0.89***     | 1                           | 0.253 <sup>NS</sup> | 0.91*** | 1                           | 29.598***           | 0.92*** |
| SPI_24_JUN                  | 7.154 | 10.926***           | 0.88***     | 1.050                       | 0.266 <sup>NS</sup> | 0.90*** | 1                           | 8.244**             | 0.93*** |
| SPI_24_AUG                  | 5.562 | 11.340***           | 0.89***     | 6.507                       | 8.732***            | 0.91*** | 6.073                       | 6.226**             | 0.94*** |
| SPI_36_MAR                  | 1     | 23.579***           | 0.87***     | 4.681                       | 8.743***            | 0.90*** | 3.902                       | 5.697***            | 0.92*** |
| SPI_36_JUN                  | 5.225 | 8.050***            | 0.88***     | 1                           | 4.433*              | 0.88*** | 1                           | 8.194**             | 0.94**  |
| SPI_36_AUG                  | 1     | 1.113 <sup>NS</sup> | 0.90***     | 1.002                       | 3.069 <sup>NS</sup> | 0.90*** | 1                           | 0.186 <sup>NS</sup> | 0.91*** |
| SPI_48_MAR                  | 1     | 0.023 <sup>NS</sup> | 0.88***     | 1                           | 0.437 <sup>NS</sup> | 0.89*** | 1                           | 0.360 <sup>NS</sup> | 0.93*** |
| SPI_48_JUN                  | 5.133 | 12.753***           | 0.87***     | 7.020                       | 21.690***           | 0.89*** | 0.999                       | 0.047 <sup>NS</sup> | 0.92*** |
| SPI_48_AUG                  | 1     | 33.681***           | 0.89***     | 1                           | 11.882**            | 0.92*** | 1                           | 0.014 <sup>NS</sup> | 0.92*** |
| SPI_60_MAR                  | 6.808 | 5.915***            | 0.88***     | 4.219                       | 9.040***            | 0.89*** | 1                           | 3.042 <sup>NS</sup> | 0.93*** |
| SPI_60_JUN                  | 1     | 0.648 <sup>NS</sup> | 0.88***     | 1                           | 5.292*              | 0.90*** | 1.003                       | 1.295 <sup>NS</sup> | 0.92*** |
| SPI_60_AUG                  | 1     | 0.054 <sup>NS</sup> | 0.90***     | 1                           | 9.336**             | 0.90*** | 3.672                       | 12.421***           | 0.94*** |
| EQ                          | 5.886 | 9.366***            | 0.88***     | 7.725                       | 21.478***           | 0.89*** | 2.849                       | 8.072***            | 0.92*** |
| Adj. R <sup>2</sup> = 0.570 |       |                     |             | Adj. R <sup>2</sup> = 0.459 |                     |         | Adj. R <sup>2</sup> = 0.436 |                     |         |
| n = 3397                    |       |                     | K = 9       | n = 4433                    |                     | K = 9   | n = 2201                    |                     | K = 9   |

Note: GAMM - Generalized additive mixed model; EDF - Estimated degree of freedom (GAMM); F - Fisher test (GAMM); p - statistically significance. Signif. code: (<sup>NS</sup>) - non-significant; (\*) <0.1, (\*\*) <0.01; (\*\*\*) <0.001. Timespan = 1980–2010.

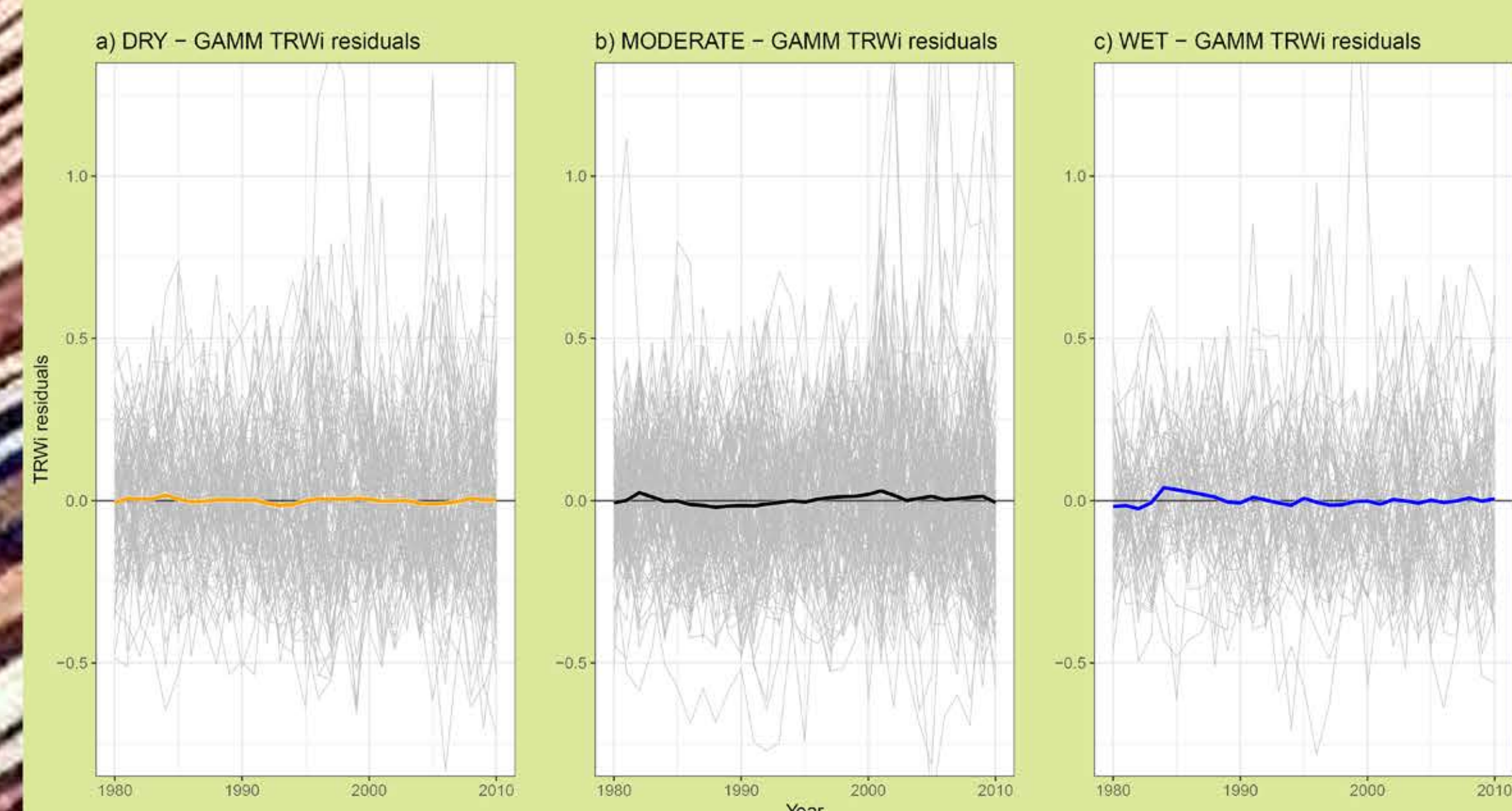


Fig. 6. GAMM residuals for oak that growing in dry (a), moderate (b), and wet (c) wetness group. In timespan from 1980 to 2010.