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Assessing vegetation recovery in reclaimed opencast mines using Landsat time series and boosted regression trees

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ABSTRACT

Opencast mining is an activity that caters to many economic sectors; however, it has a large impact on society and the environment. After mining, the major concern is to restore the previous land cover, which was generally a natural vegetation cover. Establishing permanent vegetation cover can restore landscape connectivity and previous ecosystem functions, enhance aesthetic values and prevent off-site effects associated with post-mining landscapes. Opencast mining reclamation deals with these issues with several strategies that aim to develop a vegetation cover after mining activity has stopped. However, not all reclamation actions are effective, and assessing their efficiency by monitoring vegetation development at reclaimed sites is a time-consuming task because it usually involves extensive field work. In this study, we present a semi-automatic approach based on analysing satellite data (Landsat) time series and using a machine learning technique to identify suitable conditions for vegetation development at reclaimed opencast mines. We analysed the Teruel coalfield (Aragón, central-eastern Spain). This area is a representative Mediterranean-Continental region that is of particular interest due the diversity of reclamation actions that have been applied and the increase in drier conditions during the last decades. Conditions were described with topography derived variables, technical reclamation features and drought-occurrence variables as potential explanatory factors. The implemented approach allowed us to identify the main abiotic filters for vegetation of this geographic region: the water availability and soil retention (both controlled by the topographic slope), and the proximity to seed sources. The analysis evidenced the negative influence of drought occurrence on vegetation development, and different responses were found depending on the timescale at which drought is calculated. Our results indicate that the reclamation landform model is the main key factor

influencing vegetation development. A model such as the smooth berm-slope increases water availability and controls soil erosion, and hence, improves vegetation development. In addition, we found that further than 500-600m from the mine, the effect of seed source declines dramatically. Therefore, all these issues should be considered in future reclamation designs in a Mediterranean-Continental environment. Our methodology could be adapted to other geographic regions where spatial environmental data are available.

Keywords: mining reclamation, opencast mines, active reclamation, passive reclamation, Landsat, machine learning

1. Introduction

Mining is an economic activity which has intensified during the 20th and 21st centuries to satisfy the demands of industrial development. This activity has caused serious social, environmental and economic impacts, especially in resource rich regions. Therefore, it is necessary to develop tools and practices for managing the mining sector to obtain sustainable development (UNDP and UN Environment, 2018). Opencast mining is a surface technique for extracting minerals. It is considered to have more economic advantages than underground mining; however, it is a very polluting activity and has altered many terrestrial ecosystems. Post opencast mining landscapes lose their previous ecological, social and aesthetic values. One of the major concerns after mining stops is the negative impact on water quality due to the acid mine drainage and sediment overload that are exported to the river network (Akcil & Koldas 2006, Wei et al. 2011, Comin et al. 2009). This has off-site effects on river dynamics and habitats. In addition, reclaimed mining landscapes often become prone to erosion, increasing the water run-off and thus affecting the underground water storage (Nicolau 2002, Bastian et al. 2006, Comin et al. 2009). After mining,

soil conditions are nutrient poor, leading to slower vegetation development and landscape fragmentation, which also affects wildlife (Farina 2008; Šálek 2012) and water quality as watersheds dominated by forest tend to have better stream water quality (Xiao & Ji 2007). Cultural services such as landscape aesthetic values, recreation, cultural identity, scientific knowledge, etc. are also negatively affected by mining (Bastian et al. 2006; Santos-Martín et al. 2013), although there are some experiences that highlight the value of mining heritage to promote tourism opportunities (Conesa et al. 2008).

Several countries with abundant mineral resources have established national laws to regulate reclamation of mined lands. A good example is the Surface Mining Control and Reclamation Act (SMCRA) in the USA, approved in 1977, which establishes standards for reclaiming opencast mines (understanding reclamation as establishing permanent vegetative cover). Under SMCRA, more than 2.4 million acres of land were mined for coal in Appalachia (Adams et al. 2017), the main region affected by this activity. Some time later, many of the reclaimed areas show slow vegetation recovery rates and changes in ecosystem functions (nutrient cycle, hydrology, etc.) (Simmons et al. 2008). This led to a guide being developed for the successful reforestation of mining lands, published by the Forest Service of the U.S. Department of Agriculture (Adams et al. 2017). Legislation in Spain and the Aragón region (RD 975/2009 and D 98/1994 respectively) establishes that reclamation of opencast mines is mandatory to prevent environmental and social impacts; however, it only includes reclamation standards, and no specific guidelines or recommendations are provided for the reestablishment of a healthy and stable vegetation cover. Research has been carried out on the reclamation of opencast mines in the Spanish territory (Martinez-Ruiz 2005, 2007; Moreno-de las Heras et al. 2008; Alday et al. 2010) that could be used to develop a reference framework for reclamation projects. Alday et al. (2010) characterized the short-term plant community development of restored coal mines in a sub-humid region in relation

to topography and climate data. Moreno-de las Heras et al. (2008) analysed the trajectories of ecological succession in reclaimed artificial slopes in a Mediterranean-Continental environment recording variables related to topography, restoration techniques, vegetation, local disturbances and soil erosion. Nevertheless, more research is necessary because the results of most opencast mine reclamations have not yet been assessed. Due to this and, moreover, due to the diversity of applied reclamation models and the spatial environmental variability in Spain, future assessment approaches should be applied in a systematic way.

Analysing vegetation development in reclaimed sites can provide significant insights for improving future reclamation actions. Aerial photographs can be used to obtain detailed information about vegetation changes and their spatial pattern (Allen et al. 1998; Sluiter & de Jong 2007). However, human-aided mapping is a time consuming task when large areas are under study. Using remote-sensing techniques is considered the most appropriate approach for identifying robust spatial and temporal trends in vegetation dynamics (Wulder et al. 2008; Hermosilla et al. 2016; McDowell et al. 2015). Satellite imagery offers higher spectral and temporal resolution than aerial imagery, allowing better differentiation of vegetation types and phenological patterns. The NASA-USGS Global Land Survey dataset (Gutman et al. 2013), primarily comprised of Landsat images (30 m resolution) and openly available to the science community and general public since 2008, is a very important resource for detailed mapping from 1972 to the present. The use of Landsat imagery has been demonstrated to be effective in the detection and delineation of opencast mining (Prakash & Gupta 1998, Erenner 2011). Although there are other open-access sensors and missions useful for land-cover monitoring, such as MODIS and NOAA AVHRR, their spatial resolution (from 250 m up to and over 1 km) may be too coarse for monitoring vegetation and ecological processes

in reclaimed mining land, particularly where the resulting landscape units after mine reclamation (slopes, platforms, basins, etc.) have a size within the decametre/hectometre range.

Two main approaches can be applied for detecting vegetation changes using satellite images: techniques that identify changes between two dates, and techniques that define temporal trajectories using time series. The post-classification approach, resulting from overlapping two land cover maps, is widely used to detect vegetation changes between two different dates (Latifovic et al. 2005; Vidal-Macua 2016, 2017). Image classification procedures provide relatively detailed legends that include several vegetation types. On the other hand, spectral indices are more suitable for monitoring a gradual disturbance or recovery within the same vegetation cover. Techniques based on temporal trajectories normally use spectral indices to monitor change as a continual process, operating at both fast and slow rates (Kennedy et al. 2010). The Normalized Difference Vegetation Index (NDVI) is widely used in ecosystem monitoring and has been proven to be effective for identifying vegetation disturbances and patterns (McDowell et al. 2015; Vicente-Serrano et al. 2017). Changes in the NDVI reflect changes in the photosynthetic activity and associated greenness, which is linked, for example, to the amount of biomass or the leaf area (Chasmer et al. 2018). This index has been used to identify mining disturbances and vegetation recovery after mining activity has stopped. Townsend et al. (2009) used a classification approach and NDVI metrics derived from Landsat imagery to identify active and reclaimed mines in land-cover transitions in the Appalachian Mountain region. Sen et al. (2012) and Li et al. (2015) used Landsat imagery to analyse NDVI temporal trajectories in this geographic region and identified mining disturbances over time and space. Yang et al. (2018) classified disturbance-recovery patterns in the same region, characterizing the recovery of vegetation cover and its progression over time. Nevertheless, complementary methods are required to determine the factors driving

the different trajectories of vegetation dynamics, and thus identify the conditions for a successful reclamation project. For example, in Liu et al. (2016), the influence of factors on vegetation development in opencast mines was determined using a correlation analysis between the vegetation-cover trend (in terms of NDVI) and variables obtained from meteorological data and a digital elevation model.

Here, we analyse the influence of a series of physical, environmental and technical factors on the mining reclamation efficiency in the Teruel coalfield (central-eastern Spain) from 1985 to 2016. Opencast mining in Teruel started in 1976, and a first generation of mine reclamations was not carried out until 1982 when the first law about mining reclamation came into force. The first efforts to reclaim mines were focused on geotechnical stability to avoid landslides and rockfalls, but not on ecological stability (Nicolau 2003a). The period covering the mid-90s to the present corresponds to a technologically improved second stage, in which mines are reclaimed using techniques to control soil erosion and applying new revegetation treatments. Therefore, it is of great interest to gain an overall view of the reclamation techniques adopted so far to identify which techniques are successful and prevent unnecessary economic investments (Prach & Hobbs 2008). This is especially relevant when a broad geographic area is analysed, such as the Teruel coalfield, which is representative of the Mediterranean-Continental region regarding both temperature and precipitation regimes, and vegetation composition. Key environmental features of this region that influence vegetation dynamics can be identified. It should be noted that in recent decades the Mediterranean region has been particularly influenced by climate change dynamics (Vicente-Serrano 2014). Therefore, variables that spatially quantify drought occurrence for the 1985-2016 period have been included in this study.

We processed Landsat satellite imagery and obtained a NDVI time-series data set for analysing the vegetation development in reclaimed opencast mines. NDVI recovery trajectories and absolute NDVI change values were used as response variables in multivariable models to assess reclamation success. We did not define reclamation success as a vegetated state with a structure and functionality which approximates that of the surrounding reference systems (Palmer et al. 2016), but rather we determined suitable conditions for vegetation establishment and development. Reclaimed sites are characterized by a broad ecological gradient in terms of the spatial variability of topography effects and technical features within them. We used, then, a pixel-based approach to discriminate vegetation patterns within the same mine site. Features of the reclamation model, topography derived variables, distance to seed sources and variables quantifying drought occurrence were used as potentially explanatory factors (independent variables) of vegetation development at reclaimed sites. The importance of explanatory factors and how they influence vegetation development was analysed using boosted regression trees (BRT), a machine-learning technique that has been demonstrated to have a high prediction and inference performance (Elith et al. 2008, 2009; Vidal-Macua et al. 2017). This is a non-parametric method for determining dominant patterns by combining many classification trees through the boosting algorithm (Hastie & Tibshirani 2009). BRT models have fewer requirements on the data structure, and are able to handle large and heterogeneous datasets. They are much less influenced by correlated information or irrelevant variables than other statistical approaches (Crane et al. 2012, Dormann et al. 2013). These features make BRT well-suited to dealing with multi-causal scenarios, such as those of ecosystems, which are characterized by complex and often non-linear interactions between drivers and responses.

Therefore, our general aim was to better understand the proximate causes of reclamation efficiency or failure using a semi-automatic approach based on remote sensing, geographic

information systems (GIS) and a machine-learning technique. Our intention was to provide insights into the conditions that lead to vegetation development and establishment at reclaimed sites, focusing on topographic variables, seed sources, technical factors and the climatic water balance. Thus, the main objectives of this study were to determine: (1) key determinant factors of restoration success and their role in vegetation development at reclaimed sites; and (2) whether a more technical reclamation is able to control limiting factors for vegetation development in this geographic region.

2. Material and methods

2.1. Study Area

This study was carried out in the Teruel coalfield (Figure 1a), which is located in the Iberian chain (central-eastern Spain). The climate is Mediterranean-Continental. Mean annual temperature is 11-14 °C. The frost period runs for October to April. Mean annual precipitation (MAP) is 420-480 mm and potential evapotranspiration (PET) is 730-770 mm. The regional moisture regime, classified as dry Mediterranean according to Papadakis (1966), is characterized by the concentration of rainy episodes in spring and autumn, as well as a period of summer drought (300-400 mm of water deficit running from July to September). The long frost period and intense summer drought that characterize the climate of the region impose important constraints for the success of re-vegetation operations and vegetation production (Moreno-de las Heras et al., 2008; 2011a). The natural vegetation is composed of a mosaic of forest patches (mainly dominated by *Pinus* sp. and *Quercus* sp.) and abandoned agricultural terraces vegetated by sparse shrubs, alternating with agricultural patches of cereal crops and olive and almond trees (Montserrat, 1990).

Coal surface mining started in 1976. Over 40 years a total of 24 exploitations were opened, affecting around 3,500 hectares of land (Nicolau et al. 2010). During these four decades, reclamation practices evolved as a consequence of major legal requirements. The restoration law was first enacted in 1982, and therefore previous exploitations were not reclaimed or were reclaimed in a precarious way. In a second period, “first generation” reclamations were carried out (Nicolau 2003a). The topography was based on the berm-slope model (i.e., sequence of berms or terraces connected by steep, rectilinear slopes; Figure 1b), which frequently develops rill and gully erosive forms. Revegetation included an initial sowing of herbaceous species (grasses and leguminous) to control soil erosion and then tree and shrub plantations (Nicolau 2003b). “Second generation” restorations were set up from the mid 1990's. Topsoil was applied in a generalised way, but two variants have been identified: the basin (i.e, endorheic catchment design of reclaimed landforms limiting water and sediment outflow) and the smooth berm-slope (i.e., a modified berm-slope model with milder slopes) models. Basin restorations (Figure 1c) were designed to minimize the hydrological impacts of mining on external, downward natural watercourses. Runoff generated after precipitations was collected in a final pool. Revegetation was based on herbaceous sowing and no trees or shrubs were introduced. When these types of restorations were given back to the former owners, they were grazed by sheep herds. The smooth berm-slope model (Figure 1d) kept the conventional topography, but lowered the slope angle of the constructed slopes. Wide platforms are devoted mainly to agriculture (Figure 1e). Slope revegetation also conserved the herbaceous and shrub-tree phases, but drip irrigation and fertilisation were also included in many smooth berm-slope model restorations.

Figure 1. Geographic distribution of the opencast coal mining in the Teruel coalfield. The images at the bottom are representative examples of the different reclamation models applied in the study area.

2.2. Landsat image dataset

A dataset of 13 multispectral Landsat level-1 images (30-m resolution) covering the period 1985 – 2016 was created (Table 1) for remote sensing analysis. All images were downloaded from the ESA database (<https://esar-ds.eo.esa.int/oads/access/>). Only cloud-free products or those with less than 10% cloud coverage were selected. All the analysed images represent late spring scenes captured in June, when reclaimed vegetation typically reaches the annual peak of vegetation production in the study area (Espigares et al., 2011; Moreno-de las Heras et al., 2011a; Merino-Martín et al., 2015). Although vegetation activity and greenness might vary depending on

particular climatic anomalies during a year, or even on the type of vegetation cover (Vicente-Serrano, 2007), images from June are more likely to capture the moment when vegetation activity in this area is maximum.

Although the ESA database has images for all years between 1985 and 2016, only 13 were suitable for this study because the others had high cloud cover in the study area. We chose the Landsat program for two reasons. First, it is long enough in time to assess all the reclamation processes in the study area, since the Landsat program started in 1972 and mining reclamation in Teruel started in 1982. Second, the spatial resolution of these Landsat products (30 m) provides an excellent framework for monitoring vegetation development in the explored areas, where most reclaimed landforms and structures (i.e., mining berms, terraces and slopes) have a minimum size (length) of 40-70 m, and revegetated patches are even smaller. It must be noted that previous Landsat MSS sensor delivered images with a pixel size of 60 x 60 m, although it could be enough for monitoring some of the restored landscapes, this spatial resolution would be too large for a considerable number of slopes and platforms in these reclaimed mines, so we discarded the use of MSS products.

Year	Platform / sensor	Ac. Date
1985	LT5 TM	20/06/1985
1986	LT5 TM	07/06/1986
1994	LT5 TM	13/06/1994
1997	LT5 TM	21/06/1997
2000	LT5 TM	13/06/2000
2001	LT5 TM	16/06/2001
2002	LT5 TM	19/06/2002
2004	LT5 TM	08/06/2004
2008	LT5 TM	19/06/2008
2009	LT5 TM	22/06/2009
2014	LT8 OLI	20/06/2014
2015	LT8 OLI	07/06/2015
2016	LT8 OLI	25/06/2016

Table 1. List of the images, sensors, and acquisition dates selected for this study. No products from LT7 ETM+ were used as there were no cloud-free images and they had a stripping effect.

2.3. Image preprocessing and correction

In studies dealing with multitemporal remote sensing images it is necessary to make geometrical and radiometric corrections to make the data comparable.

The ESA dataset is already geometrically corrected, so only radiometric correction was necessary. This process was carried out following the steps described in Vicente Serrano et al. (2008). First, remaining clouds were removed using a mask. Then, a cross-calibration was performed to make the image's digital levels from different sensors comparable. This was done according to the regression coefficients between bands observed by Vogelmann et al. (2001) and Roy et al. (2016). Atmospheric correction was applied using the ATCOR-3 haze removal and atmospheric correction algorithms. Then, the resulting images were topographically corrected using the c-correction method (Teillet et al. 1982), assuming a non-lambertian surface, in order to avoid possible reflectance effects due to different illumination conditions.

Finally, all the images were relatively normalized to reduce possible noise and enhance homogeneity within the dataset (Yuan & Elvidge, 1996). For this, pseudo-invariant features between images were identified from high density zones in frequency scatterplots (Chen et al. 2005). Reflectance for these features is assumed to be relatively constant along the time series, so variations can be attributed to noise. Therefore, a reference image was selected, in this case the most recent, and linear regressions for each band were performed between the reference pixel values and the ones from the remaining images. The regression coefficients obtained for each band were then used to normalize the rest of the dataset.

2.4. Monitoring vegetation development

The Normalized Difference Vegetation Index (NDVI) was calculated for all dates using the red and near-infrared bands of the pre-processed Landsat images. In this work, the NDVI was used for assessing vegetation development after the reclamation intervention with two approaches based on pixels (Figure 2). In one approach, the temporal trajectory was analysed according to the slope of the linear regression for the NDVI time series from each reclamation date to the year 2016. The slope of the NDVI temporal trajectory of a pixel represents the trend of vegetation dynamics, i.e. it shows whether recovery (greenness increases to a vegetated state) or decline (greenness decreases) of vegetation follows a graduated trend or a fast, sharp trend. In the other approach, the NDVI change (difference of NDVI value between the reclamation date and the year 2016) was calculated in order to evaluate absolute gain or loss of vegetation greenness in terms of NDVI values. These two outputs were used as response variables for data analysis. We expected the results to be consistent when the two approaches were compared. To improve the interpretation of the results and graphical outputs, values of the NDVI slope were multiplied by 100, and NDVI change values were scaled between 0 and 100.

Figure 2. Example of the NDVI trajectory in a reclaimed mine. Two NDVI based parameters are used as response variables: the NDVI slope and the NDVI difference.

2.5. Potential explanatory variables

We monitored the vegetation dynamics at reclaimed mines in Teruel by implementing a multivariable model in which, together with the two response variables (i.e., NDVI slope and NDVI difference), a set of variables was included as potential explanatory factors (Table 2). The aim was to identify relevant variables that can be considered key factors in ecologically and technically consistent trajectories of vegetation change. For this purpose, various data from different sources were collected and processed to develop a multivariate data frame to be linked to every pixel of the study ambit, i.e. a multivariable data point at every 30 m according to Landsat resolution. Below we describe the explanatory variables according to their source and type of data.

Variable code	Description	Units
<i>Rec_Mod</i>	Reclamation model: basin, platform, berm slope or smooth berm slope	Categorical
<i>Years</i>	Years elapsed since reclamation to year 2016	Years
<i>Irrigation</i>	Indicates if the reclaimed site has been irrigated	Categorical
<i>Sowing</i>	Indicates if sowing has been applied	Categorical
<i>Plantation</i>	Indicates if plantation of shrubs and/or tree species has been applied	Categorical
<i>Substratum</i>	Overburden materials or topsoil	Categorical
<i>Livestock</i>	Indicates if cattle pass through or feed on the reclaimed site	Categorical
<i>TSlope</i>	Topographic Slope	Degrees
<i>TWI</i>	Topographic Wetness Index	Dimensionless
<i>Win_SRad</i>	Winter solar radiation	$10 \text{ kJ} \cdot \text{m}^{-2} \cdot \text{day}^{-1}$
<i>Sum_SRad</i>	Summer solar radiation	$10 \text{ kJ} \cdot \text{m}^{-2} \cdot \text{day}^{-1}$
<i>Dist_For</i>	Distance to seed sources	Meters
<i>SPEI6_4m</i> (example)	Every drought variable is coded as follows: "SPEI6" - Indicate the SPEI time-scale (6, 12 or 24 months) "4m" - Indicates drought episode duration	Number of drought episodes

Table 2. Potentially explanatory variables

Mine data sheet

Technical data were collected from a set of data sheets of the explored reclaimed mines (Mellado-García, 2006). These technical data sheets, periodically updated since 1985 until 2012-13 (when the latest mine closures and reclamations of the sites explored in this study took place), were generated by applying inspection of the reclamation project descriptions and data registers of the mining companies, interviews with the operators of the reclamation projects and the post-reclamation managers of the affected areas, and field visits of the reclaimed mines. Since different reclamation actions may be carried out at the same mine site, we spatially zoned these data (by photointerpretation at a 1:5000 scale).

- Reclamation model (*Rec_Mod*). This information refers to the landform design applied to the topography after cessation of mining activity. *Rec_Mod* is a categorical variable containing the following classes: Basin (B), when the landform has a catchment shape that does not allow water drainage outflow; Platform (P), the topographic shape is designed as a flat area; Berm-slope (BS), a terraced slope following a stepwise design, where berms (terraces) are arranged at different levels; Smooth berm-slope (SBS), has the same design as the berm-slope but with softer and shorter slopes between berms.
- Years since reclamation date (*Years*). Years elapsed since reclamation to year 2016.
- Categorical variables indicating whether the following revegetation treatments have been applied: *Irrigation* (i.e., drip irrigation during the plant establishment phase), *Sowing* (herbaceous plants) and *Plantation* of shrub and/or tree species
- Type of Substratum (*Substratum*). This variable has two categories: overburden materials and topsoil.

- *Livestock*. Categorical variable indicating if cattle pass through or feed on the reclaimed site.

Digital Elevation Model (DEM)

A 5-m DEM was created from 1:5000 map sheets of the National Aerial Orthophotography and LIDAR Plan 2015 (PNOA-LIDAR) and the following variables were derived from it:

- Topographic slope in degrees (*TSlope*). This variable can be used as a soil erosion risk indicator, and as a proxy of the availability of moisture and nutrients for plants.
- Topographic Wetness Index (*TWI*), which is a dimensionless DEM-based soil moisture index. Its calculation is based on the catchment area and the slope angle (Beven and Kirkby, 1979; Kopecký and Čížková, 2010). This index generally ranges from 3 to 30, where higher values indicate higher moisture availability.
- Winter and summer solar radiation (units in $10 \text{ kJ m}^{-2} \text{ day}^{-1}$) (*Win_SRad* and *Sum_SRad*), which is related to terrain aspect and the total amount of incident solar radiation for each pixel at the winter and summer solstice dates, following the methodology of Pons and Ninyerola (2008). Solar radiation modelling can be used to identify thresholds in the vegetation dynamics since this variable can be related to factors such as the water evaporation or the shade tolerance of plants.

These variables are related to physical and environmental factors that could influence vegetation dynamics. The intention was to determine how vegetation adapts to the environmental variability and the different topo-climatic contexts of the reclaimed mines.

Land cover database

In order to determine whether the distance from natural seed sources influences vegetation recovery, a variable (*Dist_For*) was obtained by calculating the Euclidean distance to forest and shrub patches (at a 30-m resolution). Vegetation patches were extracted from the SIOSE 2014 (Land Occupation Information System of Spain), a spatial database developed at a 1:25.000 scale (<http://www.siose.es/>).

The MiraMon 8.2, ArcGis 10.5 and SAGA 2.1.2 software were used to calculate this variable and those derived from the DEM.

Climate data

Since climatic water balance is determinant in vegetation dynamics and distribution, we elaborated a set of variables that indicate recurrent drought episodes for the 1985-2016 period. Data were obtained from the updated Climatic Atlas of the Iberian Peninsula, following the methodology of Ninyerola et al. 2005. The database includes temperature and precipitation maps at 100 m spatial resolution for the entire Iberian Peninsula from 1950 to 2016. To spatially quantify the occurrence of droughts we used the Standardized Precipitation Evapotranspiration Index (SPEI) (Vicente-Serrano et al. 2010), which is based on precipitation and mean temperature (to estimate potential evapotranspiration). This index is calculated in relation to a time scale that indicates the number of consecutive weeks or months for which the water deficit is calculated. We computed the SPEI at time scales 6, 12 and 24 months, since these represent typical time scales for water deficit that affect the water streamflow, ground water level and reservoir storage level, respectively (McKee et al. 1993). For each time scale, the number of drought episodes (negative SPEI values that indicate less than average water balance) with durations of a minimum of 4, 5, 7

or 8 consecutive months, as representative lengths that may cause harmful effects (Vidal-Macua et al. 2017), were counted for the period 1985-2016. The MiraMon 8.2 software was used to calculate the SPEIs and spatially quantify the recurrence of droughts.

Although, compared to other modelling methods, BRT deals quite well with collinear data (Crase et al. 2012, Dormann et al. 2013), a collinearity analysis was carried out before the models were run to avoid the presence of correlated drought variables and reduce processing times. The initial set of 12 drought variables was resized using Variance Inflation Factors (VIF) and applying a VIF threshold of 5 (Zuur et al. 2009; O'brien 2007).

2.6. Data analysis

Boosted Regression Trees (BRT) was the machine-learning technique used to identify the most important variables and to describe the relationships between vegetation development and explanatory variables. BRT is a tree-based method combined with a boosting algorithm (Hastie & Tibshirani 2009). By boosting, hundreds or thousands of trees are built using a random fraction of the observations in each new tree, using a different random subset of variables in each of them. Trees are not fitted individually but additively because each new tree is fitted to the residuals of the previous tree (Friedman 2002; Hastie & Tibshirani 2009).

The bag fraction is the BRT parameter that controls the randomly selected observations for each new tree. We used a bag fraction of 0.5 (50% of the observations) as suggested in other works (Friedman 2002; Elith et al. 2008). The other main parameters of the BRT models are: tree complexity, learning rate and number of trees. Tree complexity is the number of splits allowed for fitting at each iteration (tree) and is related to the interaction level between variables. A tree complexity of 1 means that all trees are composed of a single candidate variable (which might

differ from one tree to another) and no interaction with other variables is allowed. Instead, an overly complex tree (involving many variables) could overfit the training data and devalue predictions in a test dataset. The learning rate parameter works like the shrinkage techniques in other linear models (Hastie & Tibshirani 2009), scaling the contribution of each new term (i.e. the constituent trees) in the additive model by a factor between 0 and 1. A low learning rate allows more complex trees to be added gradually without overfitting the model, thus diverse interaction structures are taken into account in the additive model. Finally, the optimal number of trees depends on the choice of the two previous parameters. Normally, low learning rates, in a range of 0.001-0.01, imply that the number of trees needs to be increased to achieve a good performance (Elith et al. 2008; Hastie & Tibshirani 2009).

BRTs were applied in the R software using the *dismo* package (Elith et al. 2008). In order to determine the best parameterization, we ran a model for all possible combinations of learning rates 0.001, 0.0025, 0.005 and 0.01 and tree complexities from 1 to 5. For each of these models the optimal number of trees was identified by a 10-fold cross-validation (Elith et al. 2008, Vidal-Macua et al. 2017), setting the maximum to a 20000-tree model. As trees were added to the additive model (by groups of 50 trees) the predictive performance was determined by calculating the Mean Square Error (MSE) by the 10-fold cross-validation. The model with the lowest MSE value (Tables A.1 to A.6 of the Appendix) was selected to obtain and interpret the results.

Initially, three models were developed:

1. A full-model including all potential explanatory variables and all reclaimed sites.
2. A model that represents active reclamation, including only sites where one or more of the revegetation treatments have been applied (Irrigation, Sowing, Plantation of shrubs and/or tree species and topsoil Substratum).

3. A passive reclamation model, with those reclaimed sites where no revegetation treatment was applied (9.2 % of the observations). The variable *Years* was also removed because all these sites were reclaimed in 1985.

After this stage, dominant input variables were experimentally left out. The purpose was to capture the variance explained by those dominant variables by other variables that could provide informative insights. The initial results showed that the reclamation model (*Rec_Mod*) was the variable that contributed most notably in the full-model and the active-reclamation model; therefore, in both cases, we decided to run an additional model that did not include this variable. In the passive reclamation model, the *Rec_Mod* variable, which only included “platform” and “berm-slope” designs, made a much smaller contribution. Even so, we decided to run a model without including this variable since, as a model that is representative of passive regeneration, we focused on isolating, as much as possible, the influence of physical and environmental factors.

2.7. Model inference

The importance of the potentially explanatory variables in the BRT models is determined by considering their contributions in the additive model. The relative importance is measured based on the number of times a variable is selected for splitting, weighted by the squared improvement to the model as a result of each split, and averaged by the number of trees (Hastie & Tibshirani 2009). Then, results are scaled between 1 and 100.

The relationship between vegetation dynamics and an explanatory variable was interpreted using dependence plots, which is a visualization of the fitted functions in a BRT model. This graphical output shows the effect of an explanatory variable after the average effects of all other variables are accounted for, using the weighted tree traversal method described in Friedman 2002. Thus,

these plots depict where the suitable conditions are for vegetation greenness to increase. For improved interpretation, dependence plots were smoothed using a smoothing spline.

The BRT models were fitted using 50 bootstrap samples (Hastie & Tibshirani 2009) to average the importance of each variable. Fitted functions of the bootstrap samples were also visualized with the dependence plots to show dominant patterns together with the fitted curve that includes the complete dataset.

3. Results

In order to synthesize the results, our analyses mainly focus on the active-reclamation and the passive-reclamation models when the *Rec_Mod* variable is not included. Variable contribution when *Rec_Mod* is included is showed in Figure 4. Figure A.1 of the Appendix show dependence plots for the full-model. In addition, explanations are based on the variables with higher importance than expected to chance (the ratio obtained by dividing 100 by the number of variables) in each of these two models: first eight variables of the active-reclamation model (threshold 4.54 %) and first six variables of the passive-reclamation model (threshold 5.88 %). We only consider the fitted function that lies between the percentiles 0.5 and 0.95 of variable values as relevant for interpretation.

Some examples of reclaimed mines are shown in Figure 3.

Figure 3. Some examples of reclaimed mines. The applied reclamation model and the NDVI metrics spatial distribution within the mine are indicated. SBS: smooth berm-slope; BS: berm-slope; B: basin; P: platform; IR: irrigated; NIR: non-irrigated.

3.1. Model comparison based on the response variable

Two approaches were applied for monitoring vegetation development after reclamation, based on the response variable in the BRT models: the NDVI recovery slope and the NDVI difference, both measured for the period elapsed between the year of reclamation and year 2016. The results are quite consistent when outputs of these two pixel based approaches are compared. Although the average contribution of some explanatory variables differs between 5 and 10 % (as for example, the *Rec_Mod* variable, Figure 4A and 4B), most of the variables with higher importance show

differences below 3 %. The dependence plots (Figures 6 and 7) show that, except for subtle differences, patterns in response to explanatory variables follow similar trends.

Figure 4. Variable contribution (first twelve variables). A) full-model including the *Rec_Mod* variable; B) active reclamation model including the *Rec_Mod* variable; and C) passive reclamation model including the *Rec_Mod* variable.

Figure 5. Variable contribution (first twelve variables). A) active reclamation model not including the *Rec_Mod* variable; and B) passive reclamation model not including the *Rec_Mod* variable.

3.2. Response to explanatory variables in the active-reclamation model

The reclamation model (*Rec_Mod*) is the factor that contributes most when active reclamation has been applied (Figure 4B), which is also reflected in the full-model (Figure 4A). The smooth berm-slope (SBS) is the most suitable landform design for vegetation development, followed by the platform and berm-slope designs (Figure 8A and Figure 8B).

When the *Rec_Mod* variable is not included, distance from natural seed sources (*Dist_for*) is the most important variable (Figure 5A). The overall pattern is as follows (Figure 6): vegetation development decreases as distance from seed sources increases. The trend shifts around 1000 – 1200 m, where suitability for vegetation development increases until around 1700 m. We identified that more than half of the SBS pixels are located between 1200 and 1700 m (Fig. 8 C), and the Irrigation variable (with irrigated sites as the most suitable for vegetation dynamics (Figure 6)) has a distribution (Figure 8D) that fits quite well with the response to the *Dist_For* variable.

The second most important variable is winter solar radiation (*Win_SRad*), whose dependence plot clearly indicates that locations with lower solar radiation are more suitable. Years elapsed since reclamation to year 2016 (*Years*) is the third factor that contributes most. Pattern in response to *Years* shows that recently reclaimed sites (in the last five years) are highly suitable, followed by an inflection point from which suitability decreases sharply and then gradually increases over time.

The variables *SPEI6_4m*, *TWI*, *Sum_SRad*, *Irrigation* and *TSlope* have a similar relative importance, but in a different order depending on the NDVI response variable. The response to *SPEI6_4m*, *TWI* and *Irrigation* have well-defined patterns, indicating that suitability increases as water availability increases (the *SPEI6_4m* dependence plot shows that as repetition of drought events increases, vegetation development decreases). Topographic slope (*TSlope*) and summer solar radiation (*Sum_SRad*) have less defined patterns, although an overall trend indicating less suitability as the value of these variables increases is found when the NDVI slope is used as the response variable.

The distribution of irrigated and non-irrigated sites along the slope gradient suggests that irrigated sites could increase suitability on slopes between 15 and 22 degrees (Figure 8E).

Figure 6. Response of vegetation development to the most important variables in the active reclamation model not including *Rec_Mod*. The density of observations is represented by vertical lines above the x-axes, and overlaid solid black ticks depict the 0.05, 0.5 and 0.95 percentiles. The thick blue line and thick red line depict the fitted curves for the NDVI slope and the NDVI difference respectively. The thin blue and thin red lines depict the fitted curves for the bootstrap samples (using a 50 % random sample of the observations each time).

Figure 7. Response of vegetation development to the most important variables in the passive reclamation model not including *Rec_Mod*. The density of observations is represented by vertical lines above the x-axes, and overlaid solid black ticks depict the 0.05, 0.5 and 0.95 percentiles. The thick blue line and thick red line depict the fitted curves for the NDVI slope and the NDVI difference respectively. The thin blue and thin red lines depict the fitted curves for the bootstrap samples (each fitted curve uses a random sample of 50 % of observations).

Figure 8. Full-model*: A) Distribution of NDVI slope values by reclamation model; B) Distribution of NDVI difference values by reclamation model. Active-reclamation model: C) Distribution of reclamation models according to the distance to seed sources; D) Distribution of irrigated and non-irrigated sites according to the distance to seed sources; E) Distribution of irrigated and non-irrigated sites according to the topographic slope; F) Distribution of irrigated and non-irrigated sites according to reclamation age. * The platform design can only be seen at sites where passive reclamation has been applied.

3.3. Response to explanatory variables in the passive reclamation model

The topographic slope (*TSlope*) is clearly the most important variable in explaining vegetation development when a passive reclamation is applied (Figure 4C and Figure 5B). Response to this variable (Figure 7) shows that steeper slopes are less suitable for vegetation dynamics. Distance from natural seed sources (*Dist_for*) is the second variable that contributes most in this model. Compared to the previous model, response to this variable has a more stable trend (especially when the NDVI difference is used as the response variable): suitability decreases as distance from shrubs or forests increases.

As in the previous models, dependence on water availability is reflected in the response to the next most important variables: suitable conditions are located at sites with higher *TWI* values, lower *Win_SRad* values and less repetitions of a long-term drought of 7-month duration (*SPEI24_7m*). The pattern for the summer solar radiation (*Sum_SRad*) is less clear than the *Win_SRad* pattern. This could be because the summer shadows are shorter, resulting in a more homogeneous spatial distribution of the incident solar radiation.

4. Discussion

In this study, we use Landsat time series of remotely sensed vegetation greenness (NDVI) over the Teruel coalfield, central-eastern Spain, (1) to identify the main determinant factors that rule mining restoration success and explore their influences in the long-term vegetation development of these reclaimed areas, and (2) to assess whether a more technical reclamation provides a better strategy to control the main abiotic and biotic filters that limit the development of reclaimed vegetation in this broad geographical region. According to the ecological theory, there are three processes explaining vegetation establishment and early ecosystem development (Kraft & Ackerly, 2014): a) dispersal from the species pool; b) abiotic tolerance of colonists; and c) biotic interactions. Using two NDVI based response variables in the BRT models allowed us to identify those factors conditioning vegetation development related to dispersal and abiotic filters in reclaimed mines of Teruel, also identifying the best technological land reclamation alternatives for securing the success of mine restoration operations in this Mediterranean-Continental regional context.

In previous research (based on plants, soils and rill/sheet erosion field data), Moreno-de las Heras et al. (2008) identified several relevant physical, climate and biological factors determining ecosystem development in 87 constructed slopes from a sample of the 24 surface mines of the Teruel coalfield. Soil quality and soil erosion, climate conditions, re-vegetation treatments and the influence of well-preserved propagule sources in the vicinity of reclaimed areas were found to be the main driving forces behind the development of vegetation and plant succession. Accordingly, our boosted regression tree model results reveal the key importance of physical (*TSlope*, *TWI*, *Rec_Mod*), biological (*Dist_for*) and climate factors (*Wind_SRad*, *SPEI*) for the development of vegetation and long-term restoration success in the Teruel coalfield.

In the passive-regeneration model, the topographic slope is the main limiting factor for vegetation development in the explored reclaimed landscapes. This variable is associated with soil erosion risk. Bradshaw (1988) stated that soil recovery should be the base of mining reclamation actions. Later, Whisenant (1995) specified that the priority in climates with energetic rainfalls is to ensure the stability of edaphic resources, which are menaced by soil erosion. This is especially relevant in the Mediterranean region, where heavy rainfall events are common, and soil is lost at high rates due to erosion in reclaimed mining areas with rough terrain (Comín et al. 2009, Trabucchi et al. 2012). Soil erosion (namely rill erosion) was also identified by Moreno-de las Heras et al. (2011a) as one of the main restrictions for the development and production of vegetation in constructed mining slopes of the Teruel region. The main ecological effects of rill erosion in the area are mainly caused by the intensification of the hydrological deficit of the soils, rather than the loss of seeds or soil fertility. Rill systems are very efficient at evacuating rainfall/runoff from the reclaimed systems, which reduces on-site soil moisture content. As soil water availability for plants decreases with the development of the rill networks, both plant cover and diversity as well as seed bank richness and seed germination are also reduced in the reclaimed slope systems (Espigares et al. 2011). In addition, the high physical instability of the rill beds (caused by the mechanical effects of concentrated runoff flow) prevents the establishment of vegetation and further stabilization of the rill networks (Moreno-de las Heras et al. 2011b). These topographic effects on water runoff and water availability for plant growth are also represented by the TWI variable, which indicates that softer slopes allow higher soil moisture retention. These results are in line with similar studies carried out in semi-arid continental regions (Liu et al. 2016). Steeper slopes can lead, then, to a combination of abiotic stress effects, reducing the colonization ability of plants and vegetation growth in both plantations and sowings. Indeed, one of the features of the smooth berm-slope (SBS) reclamation model, identified by our full and active restoration boosted regression tree

models as the best alternative geomorphological design for the long term development of reclaimed vegetation (Figures 8A and 8B), is the more even topography (composed by large flat platforms and soft slopes), which reduces local erosion risk and favours both soil stability and on-site water supply to plants.

Distance from natural seed sources (*Dist_for*) (as an indicator of the dispersal process) is a key factor determining vegetation development in both active and passive reclamations (Holl 2002, Moreno-de las Heras et al. 2008, Alday et al. 2010, Liu et al. 2016, Adams et al. 2017). Models show a decrease in NDVI values as distance increases from 0 to 1000 m. Then, NDVI increases at longer distances in active reclamations (Figure 6). These later sites are represented by mines that were reclaimed using irrigation and the smooth berm-slope model (Figure 8C and 8D). Hence, we consider that reclamation practices in these sites have been successful, compensating remoteness from naturally vegetated areas. On the other hand, our models show a dramatic NDVI decrease from a distance of 600 m, which poses the question: Is this distance a threshold in dispersal capacity of most of the flora species of the remnant vegetation patches in the Teruel region? We cannot explore this question in this study, because there is very little information about dispersal mechanisms of the dominant plant species of the region. However, from a practical point of view, it should be kept in mind in order to assess the plant recovery potential in reclamation projects. The combination of lack of seed sources and abiotic constraints leads to an absence of forest species (Holl 2002), and thus, to landscape fragmentation. Hence, it is important to retain remnant patches of woody vegetation whenever possible while mining is active.

Solar radiation is an important abiotic factor that, together with the slope, controls water availability. Lower water evaporation rates are more suitable for early stages of vegetation dynamics (Benayas 1998, Castro et al. 2004, Vidal-Macua et al. 2017), accelerating plant growth and increasing vegetation cover at irrigated sites (Alday et al. 2010). Although with less relative

importance, the climatic water balance has also a relevant influence on vegetation dynamics (Moreno-de las Heras 2008, Vidal-Macua et al. 2017), and our results evidence the decrease in reclamation efficiency at sites that are more affected by drought events, which is in line with findings reported for other regions with water-limited ecosystems (Liu et al. 2016). Furthermore, it is worth looking at the drought time-scales that appear within the most important variables (Figures 6 and 7). Vegetation development in active reclamations is more vulnerable to a medium-term drought ($SPEI6$), which is a logical result since introduced herbaceous plants are more dependent on moisture conditions recorded during shorter periods, as their root system is not able to penetrate into the deeper soil levels. On the other hand, a long-term drought ($SPEI24$) has a larger negative contribution when passive reclamation (natural succession) is analysed. This is also consistent with the fact that native species have a more developed root system that can reach deeper levels. They are therefore able to cope with the effect of short and medium-term droughts, but are more vulnerable to long-term droughts that would affect deep soil moisture levels. These results are in line with recent research on the impacts of drought on vegetation activity in Spain (Vicente-Serrano et al. 2019).

Figure 9. Example of a NDVI trajectory showing that the effects of irrigation on sowing/plantations could have a temporal character.

Regarding the temporal evolution of vegetation, certain recovery trajectories could have been overestimated in the present research, as can be seen in response to the reclamation age (*Years* in Figure 6). Linear regression of a short time series could overstate reclamation success in some cases (Figure 9). The effects of irrigation could have a temporal character (Martinez-Ruiz et al. 2005, 2007), accelerating vegetation development mainly in the early stages, compared to spontaneous succession, which proceeds further along the successional gradient over time (Hadacová & Prach 2003). Another explanation could be that some of the introduced, fast-growing herbaceous species germinate easily after sowing, but their self-regeneration ability (seed production) decreases over time, such as the legumes *Melilotus officinalis* and *Onobrychis sativa* or the grasses *Lolium perenne*, *Festuca arundinacea* or *Agropyron cristatum*. It is well-known that initial sowing and planting in mining revegetation aim to control soil erosion and contribute to the development of the soil organic matter pools in the first stages of ecosystem evolution, then facilitating the spontaneous colonization of the surrounding species. In fact, the *Years* dependence plot (Figure 6) shows that, after 6-8 years of reclamation, suitability increases progressively towards more vegetation, which is consistent with the idea that the probability that propagules of a species reach a newly generated, reclaimed site increases with time (Prach et al. 2013). This pattern can also be seen when the NDVI difference is used, although with a less pronounced peak at younger sites. Then, recently restored sites with high slope values should be monitored after this study in order to assess the effects of revegetation treatments over time. The use of the NDVI has other limitations, as this index saturates when a certain cumulative vegetation cover has been reached (Chasmer et al. 2018). We did not observe NDVI saturation effects in the explored reclaimed mines of the Teruel coalfield with the present levels of vegetation development for the

1985-2016 period. However, these effects should be taken into account for future research, in order to monitor longer term vegetation dynamics in the reclaimed sites of this geographic region. In the case of tree plantations, this limitation could mask shrub understory development under dense tree canopy. This makes it difficult to monitor mature tree plantations unless other remote sensing data, such as LIDAR, are combined with the satellite data (Montealegre et al. 2016, Domingo et al. 2018).

In summary, our results confirm the key role played by reclamation practices on vegetation development and restoration success for the studied Mediterranean-Continental region, since the reclamation model (*Rec_Mod*) is the most important explanatory variable for the analysed vegetation dynamics in our full and active-reclamation models (Figures 4 and 5). This suggests that the reclamation strategy applied in the Teruel coalfield has been useful for overcoming the abiotic, major physical filters that limit plant development in the region. In particular, the smooth berm-slope (SBS) is the most effective reclamation model for guaranteeing the system stability against erosion, as well as for securing water availability for vegetation, which constitute the main abiotic filters for the establishment and development of reclaimed vegetation in the region (Moreno-de las Heras et al., 2011a; Espigares et al., 2011; Merino-Martín et al., 2015). In addition, maintaining natural vegetation patches within a radius of 600 m could be essential for both passive and active restoration strategies. In fact, these patches of natural vegetation constitute the only source of propagules for the passive restoration strategies, while they also provide an essential source of seeds for the long-term dynamics of vegetation under the analysed active restoration scenarios, where the regenerative capacity of the introduced plant species commonly decreases after the initial revegetation stage.

Some trade-off mechanisms should be considered in opencast mining restoration in Mediterranean-Continental environments, not only to provide suitable conditions for spontaneous

succession at the mine scale but also to avoid off-site effects at the basin scale, as for example, sediments impacting downward river waters and ecosystems. We believe that future reclamation models in regions with an energetic rainfall regime could be improved by integrating a geomorphological component, i.e. considering a physical design resembling natural terrain surfaces (Evans 2000, Nicolau 2003b, Martín-Duque 2010), with the aim of stabilizing drainage and water availability as well as improving soil formation. Reclamation strategies based on this model may be slower than active sowing or planting in reaching a target vegetation stage, but they are able to maintain themselves in the long-term and become integrated with the surrounding environment, reducing off-site effects (Nicolau 2003b).

Analysing the effect of the data spatial-resolution on results is outside the scope of this work, however, some aspects can be considered. Variables at finer spatial resolution, such as those derived from the 5-m resolution DEM, can more effectively define the relationship between the environmental variability and the spatial and temporal patterns of vegetation. This may result in more reliable response patterns and a higher relative importance, which in BRT is calculated regarding the number of times the variable is selected to construct a tree in the additive model, and the improvement in terms of prediction that the variable provides. On the other hand, the sampling procedure and the response variable are based on the 30-m Landsat resolution. Therefore, using a different data structure in the explanatory and the response variables may influence the results, especially in terms of relative importance. Nevertheless, the stochasticity and the additive modelling procedure that BRT models are based on (Friedman 2002, Elith et al. 2008), have allowed us to deal with the heterogeneity of our data structure and, finally, to obtain ecologically and technically consistent trajectories of vegetation change in relation to key factors.

Our study approach, based on the analysis of temporal NDVI trends, provides information on the dynamics of vegetation coverage and biomass in the explored reclaimed areas, but not on their

diversity and species composition, which may constitute other important sources of information for the evaluation of restoration success. In addition, we have not introduced the edaphic factor directly, which is key in mining reclamation, although it is indirectly related to reclamation model in our analysis. We are aware that field work and other novel remote sensing techniques, such as the use of Unmanned Aerial Systems (UAS), can increase site-specific thematic and spatial resolution. Indeed, it has already been shown that the use of imagery obtained by multispectral sensors on-board UAS is a potential tool for monitoring opencast mining reclamation, as it makes it possible to obtain rigorous vegetation cartography at different restoration stages (Padró et al. 2019). This makes comparisons with the surrounding reference landscapes easier. Nevertheless, we believe that the consistency that our spatially extensive and semi-automatic approach provides, gained by the broad region and period explored and the robustness of the applied BRT models, allows us to make some important generalisations for assessing the success of the adopted surface mine reclamation actions in Mediterranean environments.

5. Conclusions

Vegetation evolution in both active and passive reclamations of surface mines in the Teruel coalfield has been analysed considering the role of variables related to dispersal processes, abiotic factor filters and reclamation practices. Topographic slope has the highest relative importance as a factor explaining vegetation development in passive regeneration. It is known that slope gradient strongly conditions water availability, erosion risk and soil stability. On the other hand, reclamation model is the most influential factor in active reclamations, where the smooth berm-slope model (organized in wide platforms and smooth terraces connected by low-gradient slopes) is the most suitable geomorphological design for vegetation development. This is an effective

reclamation approach that guarantees the system's stability by reducing soil erosion and increasing soil moisture availability, the two main abiotic filters that regulate vegetation establishment and further development in this Mediterranean-Continental region. Therefore, reclamations based on this model make it possible to control the determining role of the topographic slope. Water availability is also determined by the solar radiation, as reclaimed sites with lower water evaporation are more suitable for vegetation development in both passive and active reclamations. Moreover, drought occurrence has a negative influence in these two reclamation strategies, and this study reinforces the importance of the drought time-scale effect on both active and passive reclamations. Introduced species at reclaimed sites are more vulnerable to medium-term droughts, whereas native species, with a more developed root system, are more vulnerable to long-term droughts. Distance from seed sources is the second most influential factor for plant development in both passive and active reclamations. Further than 500-600m from the mine, the effect of seed source declines dramatically, which should be considered in reclamation designs.

The evolution of plant development over time in actively reclaimed mines shows a biomass peak (NDVI) in the first 5 years, probably reflecting the positive effects of revegetation practices. Then biomass declines, progressively going up again from the eighth-ninth year, possibly because of the input of spontaneous colonization from surrounding natural areas in later stages.

From the practical point of view, in Mediterranean-Continental environments we recommend constructing soft topographies, which may also include sowing, planting and irrigation since future climate trends are expected to be characterized by increased drought severity and recurrence. The use of soft topographies with planting and irrigation during the plant establishment phase is particularly advisable when natural seed sources are located further than 500-600 m from the

mine. Active revegetation should consider including plant species with deep root systems that are able to withstand longer droughts.

The methodology described in this work has the advantage of being a semi-automatic approach that can be systematically applied, so it is reproducible in other areas of the world where up-to-date databases of environmental data are available from national or international institutions.

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CONFLICT OF INTEREST STATEMENT

No potential conflict of interest is reported by the authors.

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Graphical abstract

HIGHLIGHTS

Analysis of active and passive reclamation models

Topography as a key factor determining water availability for vegetation development

A proper reclamation model is able to manage the determining role of topography effects

Further than 500-600 m from the mine the effect of seed sources declines dramatically

Vegetation has different responses to the drought timescale