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Rehabilitation planning in an oilfield in the Monte Austral: mapping sand-sized sediment availability and assessing its effect on microtopography rehabilitation

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Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Ethical statement

The authors declare that all ethical practices have been followed in relation to the development, writing, and publication of the article.

Abstract

In drylands, the microtopography is formed by mound-shaped dunes of eolian deposition that occurs around shrubs or other vegetation in clumps. These mounds are characteristic of the Monte Austral, which covers 20% of Argentina (approximately 50 million ha), has a strong water deficit and is subjected to land degradation by the oil industry. Considering the biogeomorphological approach, oilfield rehabilitation should begin with regeneration of the mounds as they provide safe sites for vegetation. Since rehabilitation success may be influenced by sand-sized sediment availability, we addressed two objectives: mapping the sediment availability in an oilfield and evaluating its effect on microtopography rehabilitation. We used a Sentinel-2 MSI scene and assessed three approaches to map the sediments: two expressions of the Normalized

Difference Sand Index (NDSI) and the Brightness of the Tasseled Cap Transformation (TCB) feature. We validated the three maps using a geomorphological map. Two maps showed the highest agreement with the geomorphological map and errors were associated with the detection of bright lithified or cohesive material not available for sediment transportation. Then, we evaluated the effect of sediments on microtopography rehabilitation. We compared the morphometric traits of mounds (height, maximum and minimum length) located in areas of low and high sediment availability, in both natural and scarified areas. We considered the time since scarification was applied (8-13, 4-8, or less than 4 years ago). The mounds in the natural areas were larger than the mounds in the scarified areas, so complete microtopography rehabilitation is not achieved 13 years after scarification. The mounds in high sediment availability areas were different from the initial condition 4 years after scarification, whereas differences took 8 years to become evident with low sediment availability. Sediment availability must be considered when designing rehabilitation techniques to ensure the success and sustainability of the project. Our results have implications for the development of a biogeomorphological model to guide rehabilitation planning.

Keywords: drylands, mounds, oil industry, restoration planning, satellite images, scarification

Introduction

Drylands occupy approximately 47% of the terrestrial land surface (Koutroulis, 2019). Among their distinctive traits, vegetation and environmental conditions present great spatial heterogeneity (Breshears et al., 1998; Schlesinger and Pilmanis, 1998), mainly caused by eolian and fluvial geomorphological processes that continuously modify the topography at multiple scales (Aguiar and Sala, 1999; Litchfield and Mabbutt, 1962; Okin et al., 2001, 2006; Sanchez and Puigdefabregas, 1994; Tongway et al., 2004). In particular, eolian sediment transportation follows two mechanisms, saltation, and suspension, which result in different particle transport distances that have effects at different scales. While sediments transported by saltation have a local influence on vegetation and soils (Raupach et al., 2001), sediments transported in suspension may influence land over thousands of kilometers (Gillette, 1974; Okin et al., 2006). Thus, eolian geomorphological processes create zones with elevated concentrations of resources (such as water, sediments, nutrients, and organic matter), or propagules (seeds and spores). From a biogeomorphological point of view, these zones progressively form “fertility islands or patches” (Brown and Porembski, 1997; El-Bana et al., 2002; Zhang et al., 2011), also known as mounds (Aguiar and Sala, 1994, 1999; Mcauliffe et al., 2014; Seifert et al., 2009). Biogeomorphology studies the multiple interactions between ecological and geomorphological processes and contributes to understanding the responses of terrestrial systems to disturbances (Haussmann, 2011; Viles et al., 2008).

Mounds form a system of patches comprised of bushes (of one or more species) around which sediments accumulate (Aguiar and Sala, 1994, 1999). Their morphology is similar to other landforms that have been described as nebkhas (Gunatilaka and Mwango, 1987; Tengberg and Chen, 1998), coppice dunes (Gile, 1966; Thomas and Tsoar, 1990), or *heuweltjie* earth mounds (Mcauliffe et al., 2014). They act as fertility patches and are part of the energy and matter fluxes in arid and semi-arid ecosystems (Brown and Porembski, 1997; El-Bana et al., 2002), as they are rich in potassium, phosphate and nitrate, and they conserve organic matter and humidity under their foliage (El-Bana et al., 2002, 2003). Several studies have highlighted their role as basic structural and functional units of edaphic, ecological, and geomorphological processes in these ecosystems (Aguiar and Sala, 1999; Brown and Porembski, 1997; El-Bana et al., 2002). Different hypotheses explain the formation of the typical microtopography composed of mounds and inter-mound spaces. Whether they are formed by the accumulation of sediments under the vegetation canopy (Dougill and Thomas, 2002; Mcauliffe et al., 2014), or by the combination of raindrop erosion and superficial flows that locally redistribute sediments from the inter-mound zone (Parsons et al., 1992), or by deflation of unvegetated inter-mound areas and local redeposition behind shrub windbreaks (Rostagno and del Valle, 1988; Seifert et al., 2009), all these authors agreed that the development and evolution of mounds depend on time and geomorphological dynamics. Morphometric traits of mounds, such as area (El-Bana et al., 2003), height, or the relationship between length and width or height (Tengberg, 1994, 1995; Tengberg and Chen, 1998), have been used as indicators of soil and microtopography degradation and restoration.

The oil industry produces intense environmental impacts on the local scale. Exploration, production, and development require the construction and maintenance of infrastructure, e.g., seismic lines, roads, pipelines, and production boreholes (Woodward, 1996). These activities severely alter the vegetation, soil, and microtopography. In particular, the construction of drilling facilities affects an area of approximately 0.6-1 ha around the boreholes. In these areas, the vegetation is eliminated, and the upper soil layer is replaced by gravel and then compacted, consequently causing the modification of the microtopography. The landscape structure is also altered in the oilfield since the numerous and adjacent repetition of such intervention fragments the original matrix. Thus, vegetation and soil cover are lost, decreasing the probability of colonization by propagules due to soil compaction, which in turn reduces water infiltration into the soil profile (Castellano and Valone, 2007; Woodward, 1996). In Argentina, one of the most significant impacts occurring in the Monte Austral in Northern Patagonia is derived from the oil industry (Dalmasso, 2007; Fiori and Zalba, 2003; Pérez et al., 2011; Zuleta et al., 2011a). The Monte desert is one of the most arid territories in Argentina and extends over 50 million ha. Its southern part is a landscape of plains characterized by a mean temperature of 12–14 °C and annual precipitation of 200–300 mm (Busso and Fernández, 2017).

In oilfields, recovery objectives are imposed on the company and agreed with the authorities and the local community (Gratzfeld, 2003). They predominantly include removing or burying surface materials, recontouring subsoil to approximate original contours, distributing stored topsoil, and revegetating (Simmers and Galatowitsch, 2010). In the case of oil spills, there have been many experiences regarding remediation and passive restoration of the vegetation (Girsowicz et al., 2018; Ignat et al., 2021; Kalander et al., 2021; Panchenko et al., 2018). In the Monte Austral, a variety of techniques has been tested, which include de-compaction (Apcarian et al., 2002; Dalmasso, 2010), installation of plant branches (Zuleta et al., 2003), application of organic amendments (Li Puma et al., 2004), planting (Dalmasso, 2010; Pérez et al., 2011), and the use of insoluble gel-forming polymers or hydrogel (Pérez et al., 2010). Some of these experiences have proved that significant recovery of degraded sites in drylands is possible. However, the limited availability of critical resources in these environments, such as water or nutrients, conditions the processes involved in regeneration (Aguiar and Sala, 1999; Schlesinger et al., 1990). Therefore, eco-technology used to restore arid ecosystems is usually based on the manipulation of resource fluxes (Tongway et al., 2004). Although mounds have been studied extensively in arid and coastal areas (Ayyad and El-Ghareeb, 1982; El-Bana et al., 2003; Hesp and McLachlan, 2000; Khalaf, 1989; Langford, 2000;

Mcauliffe et al., 2014; Tengberg, 1994, 1995; Tengberg and Chen, 1998), knowledge of their structure and functioning has not been fully applied to restore degraded drylands. In this context, the biogeomorphology framework can provide models for predicting how systems can recover from disturbances (Reinhardt et al., 2010) and, if necessary, assist regeneration. Mounds can be considered “safe sites” for vegetation as they act as resource sinks (Bochet et al., 2000; El-Bana et al., 2003; Ludwig and Tongway, 1996; Shachak and Lovett, 1998; Tongway and Ludwig, 1996). Consequently, regeneration of the microtopography, formed by the mound and inter-mound system, should be the first step in any restoration project of severely degraded sites in drylands and the availability of sandy sediment may influence the success of rehabilitation techniques.

It has been widely accepted that rehabilitation planning at the landscape scale maximizes the probability of success of any project. However, there is a knowledge gap regarding the interaction of abiotic and biotic processes and their feedback on a large scale (Reinhardt et al., 2010). This study represents a first approach to the development of a biogeomorphological model to guide the rehabilitation of degraded drylands in the Monte Austral. At this early stage, we were interested in understanding the effect of sand availability on microtopography recovery because a tool that could remotely detect sediments would be useful for planning microtopography rehabilitation at the landscape scale. The use of variables and indices derived from satellite images enables the identification of suitable sites for rehabilitation (Guida-Johnson, 2021). Moreover, it allows the monitoring and evaluation of interventions (Meroni et al., 2017; del Río-Mena et al., 2020). Although there are not many examples reported in the literature, some variables derived from satellite images have been tested to identify soil texture (Danoedoro and Zukhrufiyati, 2015; Fadhil, 2013; Lamqadem et al., 2018; Pan et al., 2018). The objectives of this study were to map the availability of sand-sized sediments in an oilfield in the Monte Austral (Argentina) and evaluate their effect on microtopography rehabilitation.

Materials and methods

Study area

The Neuquén basin, located in northwestern Patagonia, is one of the most productive oil regions in Argentina. The study area is an oilfield in the north of Neuquén province (Figure 1) that comprises 21,900 ha and more than 1,100 oil wells. Since 1998 regeneration techniques have been applied to restore environmental conditions, complying with the requirements of the local authority and national recommendations (IAPG, 2009). The so-called scarification is the most frequently applied technique to rehabilitate drilling facilities and seismic lines. It consists of the mechanical decompaction of the upper soil layer, carried out by a scarifier or ripper on the rear of a bulldozer (Figure 2). The objective of the technique is to promote soil and vegetation regeneration by facilitating water infiltration and root system development (Bainbridge, 2007; Dalmasso and Martínez Carretero, 2021). In the study area, scarification is usually performed in a north-south direction, perpendicular to the regional slope and the predominant direction of the prevailing winds (west-east). Scarification is widely used in the Monte Austral and can improve soil structure and accelerate regeneration.

The climate is semi-arid, the mean annual temperature is 15°C, and the mean annual precipitation is 185,3 mm. The most intense and frequent rainfall occurs between September and April. Wind intensity is constant throughout the year, mean velocity is 7 km/h. However, the maximum velocity recorded reaches 106 km/h (Zuleta et al., 2011b).

The Neuquén basin is a Mesozoic sedimentary basin, located to the east and outside the Andean orogenic front, where the Neuquén Group (or "Strata with Dinosaurs") stands out. The geological history of the Quaternary in North Patagonia corresponds to a complex interrelation between the tectonism generated by the Andes and the predominant alluvial-fluvial sedimentary processes. On a regional scale, the study area is located in a geomorphological unit called "structural plains by razing" where the dominant vegetation corresponds to the Monte Austral (González Díaz and Ferrer, 1986). The relief is predominantly composed of flat-topped highlands, attributable to the influence of the geological structure of the strata, which are of continental origin and Mesozoic age. This sector is characterized by wide watersheds, shaped by diffuse and exceptionally concentrated runoffs, responsible for the isolated presence of severely dissected landscape segments called “badlands” (González Díaz and Ferrer, 1986). Other characteristic landforms are the old, dissected foothills, alluvial fans, and alluvial plains. The pediments, slopes and alluvial cones, low alluvial terraces, flood plains, and centripetal basins, complete the set of landforms of flat and stepped appearance (González Díaz and Ferrer, 1986).

Mapping sand-sized sediment availability using remote sensors

We mapped sandy sediment availability using a Sentinel-2 MSI (ESA) winter scene obtained on August 25th, 2015 because we expected annual vegetation to be minimal. We downloaded it from the U.S. Geological Survey Earth Resources Observation and Science (EROS) Center. Firstly, we discarded pixels covered with vegetation based on an NDVI > 0.25 (Bousbih et al., 2019). We used the remaining pixels to assess three approaches to estimate sand-sized sediment availability. We calculated two indices and a Tasseled Cap Transformation (Table 1) previously used to evaluate soil texture (Danoedoro and Zukhrufiyati, 2015; Fadhil, 2013; Lamqadem et al., 2018). In this case, we were interested in detecting zones with high availability of sand. The Normalized Difference Sand Index would highlight the occurrence of sand (Fadhil, 2013), another expression of the Normalized Difference Sand Index would detect higher content of sand distinguishing sand from soil (Pan et al., 2018), and the feature Brightness of the Tasseled Cap Transformation would reveal the bright soil with bare land and sand texture (Lamqadem et al., 2018). We derived a sandy sediment availability map from each index. Each map was composed of two categories: high and low sediment availability. The categories were divided according to Jenks natural breaks classification method, which is a data classification method that seeks to minimize the average deviation of each category with respect to the category mean and maximize the deviation of each category with respect to the means of the other groups (Chen et al., 2013). Finally, we applied a majority filter using a kernel of eight nearest neighbors.

We validated the three sandy sediment availability maps using a geomorphological map of the study area. The latter was elaborated by photointerpretation and manual digitalization at a scale of 1:10.000 using high-resolution satellite images: two Ikonos scenes obtained in 2007 and 2011 and a Quick Bird scene obtained in 2005. Geomorphological units were validated with 186 control points during a field survey carried out in 2011.

The validation of the three sandy sediment availability maps derived from Sentinel images consisted of a comparison between each one and a sediment availability map derived from the geomorphological map. To that end, the latter was re-categorized into high and low sand-sized sediment availability classes. Then, we produced 130 random points stratified by geomorphological units. We recorded the corresponding sediment availability class for each point and compared each pair of maps (derived from Sentinel vs. derived from the geomorphological map) producing an error matrix. We calculated a total accuracy value (interpreted as the proportion of points associated with the same level of sediment availability in both maps of each pair) and the Kappa coefficient. The Kappa analysis is a discrete multivariate technique used to statistically determine whether the agreement between two classifications is significantly greater than 0, i.e., better than a random agreement (Congalton and Green, 2009).

Field assessment of mounds morphometric traits

To corroborate the effect of sand-sized sediment availability on the rehabilitation of the microtopography, we evaluated the morphometric traits of the mounds, considering the level of sediment availability derived from the geomorphological map. We compared the mounds located in the study area under two different conditions: (1) mounds occurring in natural areas, which were defined as reference areas located 20 m west of each drilling facility, with no presence of disturbance indicators; and (2) mounds located in scarified areas, which were sectors of the drilling facility where this physical rehabilitation technique had been applied. We conducted a field survey in the study area between December 2010 and May 2011. At that time, data was available regarding the time elapsed since the application of the rehabilitation treatment: between 8-13 years from scarification, between 4-8 years from scarification, or less than 4 years from scarification. We measured the height, and the maximum and minimum length of the mounds that intersected 50 m long transects located in 74 natural areas and 92 scarified areas. Among the latter, 24 transects were located in scarified areas 8 to 13 years old, 28 transects in scarified areas 4 to 8 years old, and 40 transects in scarified areas less than 4 years old (Figure 3).

We compared the effects of sediment availability and time since the scarification treatment had been applied on the morphometric traits of mounds, using a Kruskal Wallis analysis as the data did not meet normality assumptions. Response variables were the height, maximum and minimum length of mounds, considering the mounds classified simultaneously by condition (natural, and 8-13 year old, 4-8 year old, or less than 4 years old scarified areas) and level of sand-sized sediment availability (high or low). We performed multiple comparisons to distinguish between both effects. All analyses were performed using Infostat (Di Rienzo et al., 2019).

Results

Sand-sized sediment availability map comparisons

We identified 13 geomorphological units by photointerpretation of high-resolution satellite images in the study area: (1) Holocene fans and alluvial terraces, (2) ancient Pleistocene piedmont, (3) *barreal* and dry playas, (4) dunes, (5) slopes, and badlands, (6) volcanic-structure forms, (7) sand mantle, (8) Holocene pediments, (9) Holocene pediments covered by eolian sands, (10) Pleistocene dissected pediments, (11) Punta Mahuida structural plain, (12) floodplains, and arroyos or washes and, (13) spill zones and alluvial sedimentation lobes. We transformed the geomorphological map to a sand-sized sediment availability map considering whether geomorphological units were associated with a high or low level of sediment cover (Figure 4), based on the field observations described in Table 2.

The Normalized Difference Sand Index 2 (NDSI2) produced the sand-sized sediment availability map with the highest level of coincidence with the sediment map derived from the geomorphological map (72% of total accuracy and a Kappa coefficient of 0.38), followed by the feature Brightness of the Tasseled Cap Transformation (TCB) (67% of total accuracy and a Kappa coefficient of 0.32) (Figure 5). When comparing landforms, the level of agreement between both maps of each pair varied greatly. The total accuracy ranged from 80 to 100% for NDSI2 and TCB for Holocene fans and alluvial terraces, dunes, volcanic-structure forms, sand mantle, Holocene pediments, Holocene pediments covered by eolian sands, Punta Mahuida structural plain, floodplains and arroyos or washes and, spill zones and alluvial sedimentation lobes. The total accuracy ranged from 20 to 60% for NDSI2, and from 30 to 70% for TCB, for ancient Pleistocene piedmont, *barreal* and dry playas, slopes and badlands, and Pleistocene dissected pediments. In the case of *barreal* and dry playas, slopes and badlands, and Pleistocene dissected pediments, variables derived from Sentinel images detected bright lithified or cohesive material not available for sediment transportation.

Effect of sandy sediment availability on microtopography rehabilitation

We detected significant effects of the sediment availability and time since application of the scarification treatment on the three morphometric traits of the mounds: height ($p<0.0001$; Table 3), maximum length ($p<0.0001$; Table 5), and minimum length ($p<0.0001$; Table 7). In general, the mounds in natural areas were significantly larger in size than the mounds occurring in scarified areas. This implies that even 13 years after scarification, microtopography rehabilitation was not complete. Multiple comparisons enabled a more detailed analysis.

In the case of height, the mounds located in natural areas and associated with higher availability of sand-sized sediments were significantly higher than the mounds from natural areas associated with low sediment availability (Table 4, Figure 6). With regards to the mounds located in scarified platforms, they tended to be higher with more time since the scarification had been applied. However, in areas of high availability of sandy sediments the mounds formed after scarification were significantly higher from the fourth year after the treatment was applied (4–8-year-old mounds: 0.10 ± 0.01 m; mounds less than 4 years old: 0.05 ± 0.0048 m). On the contrary, mounds located in low sediment availability areas took at least 8 years after scarification to be significantly higher (8–13-year-old mounds: 0.08 ± 0.01 m; mounds less than 4 years old: 0.04 ± 0.01 m).

Although there was no effect of sandy sediment availability considering the mounds located in natural areas with regards to maximum length, we detected the same pattern regarding microtopography rehabilitation (Table 6, Figure 7). The mounds tended to become longer with the passage of time since the scarification treatment had been applied. However, when the mounds were in areas of high sediment availability, they were significantly longer from the fourth year after scarification had been applied (4–8-year-old mounds: 1.09 ± 0.07 m; mounds less than 4 years old: 0.64 ± 0.07 m). But when the mounds were associated with low levels of sediment availability, significant differences were only detected from the eighth year (8–13-year-old mounds: 1.34 ± 0.14 m; mounds less than 4 years old: 0.71 ± 0.06 m).

In the case of minimum length, the mounds located in natural areas and associated with higher availability of sand-sized sediments were significantly longer than the mounds associated with low sediment availability (Table 8, Figure 8). Regarding this morphometric trait, the mounds also showed a tendency to become longer with the passage of time since the scarification technique had been applied. We also found that the high availability of sandy sediments determined that the mounds forming after scarification were significantly longer after the fourth year since the treatment had been applied (4–8-year-old mounds: 0.74 ± 0.06 m; mounds less than 4 years old: 0.38 ± 0.05 m). However, when sediment availability was low, the mounds took at least 8 years after scarification to become longer (8–13-year-old mounds: 0.92 ± 0.08 m; mounds less than 4 years old: 0.52 ± 0.05 m). In this case, 8-year-old mounds were no different from the mounds occurring in natural areas.

Discussion

In drylands, sand-sized sediments are transported and have a local influence on vegetation and soils since they contribute to forming fertility islands (Aguiar and Sala, 1994, 1999; El-Bana et al., 2002) or mounds (Mcauliffe et al., 2014). The mounds are rich in nutrients, organic matter, and humidity (El-Bana et al., 2002, 2003; Li Puma et al., 2004), so they act as resource sinks and provide safe sites for vegetation (El-Bana et al., 2003; Ludwig and Tongway, 1996). They also provide a site where feedback between ecological and geomorphological processes is promoted, aiding stabilization and vegetation survival, as well as soil profile development. Therefore, their regeneration should be the first target for rehabilitating oilfields in arid and semi-arid environments. Considering that sand-sized sediment availability may influence the success of mound rehabilitation, as the sediments would act as parental material for the development of incipient soils, we addressed two objectives: the development of a tool to map sediment availability in an oilfield in the Monte Austral and the evaluation of its effect on microtopography rehabilitation. Results derived from this study have implications for the development of a biogeomorphological model to guide rehabilitation planning post-exploitation.

A biogeomorphological model could provide a framework to evaluate the life cycle of mounds in the study area, as other authors have developed in diverse geographical areas (Hugenholtz and Wolfe, 2005; Lancaster, 1997; Tsoar, 2005; Viles et al., 2008). A full understanding of the functioning of the stabilizing and destabilizing effects of biotic influences on abiotic processes, as well as their interactions, is vital to understanding the responses of the system to disturbance. Processes interactions do not only affect physical processes, such as erosion and deposition of sediments, but also have an effect on geochemical processes such as nutrient cycling (Viles et al., 2008). In drylands, knowledge on nutrient cycling is remarkably important given the characteristic resource limitation. Any type of management of an area should be guided by a deep understanding of the complex links and feedbacks between the ecological and geomorphological processes (Viles et al., 2008). The development of a conceptual model of the mound life cycle, including all links between ecological, geomorphological, and geochemical processes, would lay the groundwork for the design of sustainable restoration programs based on appropriate resource manipulation.

Biogeomorphological modeling is site-specific due to the uniqueness of place, which implies singular responses to similar external forcing (Viles et al., 2008). In our study area, knowledge on the spatial distribution of geomorphological units and sand-size sediment availability should be complemented with data on the local climate and vegetation composition, and also the presence of ecological engineers (Gilad et al., 2004).

Many rehabilitation techniques have been tested in the Monte Austral (Apcarian et al., 2002; Dalmasso, 2010; Li Puma et al., 2004; Pérez et al., 2010, 2011; Zuleta et al., 2003). The selection of techniques to be applied at any specific location must be related to both the environmental conditions and the limitations. In drylands, the limited availability of critical resources demands that resource fluxes ought to be manipulated (Tongway et al., 2004). The morphometric traits of mounds have been used as indicators of soil and microtopography degradation and restoration (Tengberg and Chen, 1998). We found that sediment availability had effects on the velocity of microtopography rehabilitation. Although full recovery was not detected in any case, the mounds located in areas with high sediment availability were different from the initial degraded condition 4 years after scarification. On the contrary, when there was low sediment availability, differences took 8 years to become evident. It must be highlighted that we did not detect any mounds after scarification that had become similar to those under natural conditions. These results agree with the findings of Ciancio (2016), who compared infiltration velocity and penetration resistance between scarified sites and natural soils. Ciancio found that after an initial recovery, the soil begins to re-compact and never reaches natural zones values. Evidence from both studies leads to the conclusion that scarification is a technique that produces mechanical decompaction of soil, but it is not enough to rehabilitate the microtopography.

Considering the environmental limitations of drylands, energy inputs must be invested in assisted regeneration techniques that fully rehabilitate the ecosystems. Complementary technologies based on the trapping of sand-sized sediments must be incorporated after scarification, such as the installation of plant branches. Therefore, detecting zones characterized by high sediment availability is essential. Drilling facilities located in geomorphological units with active sediment sources and high sediment availability could be more easily rehabilitated once exploitation has ceased. The availability of resources enables a more rapid formation of mounds, which facilitates the colonization of propagules. Once vegetation has been established, there is positive feedback (Monger and Bestelmeyer, 2006). Physical and biological processes interact, which leads to the improvement of conditions (more humidity, organic matter, and nutrients), which in turn promotes the facilitation of vegetation stabilization (Okin et al., 2006; Raupach et al., 2001). Understanding these feedback loops would imply low investment or savings in technology and maintenance costs. On the contrary, geomorphological units with low sediment availability and erosion processes prevalence showed possible obstacles to vegetation colonization. Silt and clay-sized sediments present high cohesion which makes it difficult for shrubs to root. Moreover, erosion represents a risk for the development of incipient soils and the establishment of vegetation. Therefore, more complex technology should be introduced to stabilize shrubs in abandoned drilling facilities located in these units to speed up rehabilitation times or make the recovery process feasible: revegetation including watering or hydrogel. The use of more complex technology would represent higher implementation, and operation and maintenance costs. Therefore, rehabilitation techniques must be carefully designed with sediment availability in mind to achieve sustainable implementations.

Information derived from satellite images is extremely valuable for planning rehabilitation on the landscape scale (Guida-Johnson, 2021; Guida-Johnson and Zuleta, 2017; Orsi and Geneletti, 2010). In our study area, an expression of the Normalized Difference Sand Index (Pan et al., 2018) and the feature Brightness of the Tasseled Cap Transformation (Shi and Xu, 2019) produced two sand-sized sediment availability maps that showed the highest level of agreement with the reclassification of the geomorphological map. Both maps provide appropriate guidance to detect zones with greater sediment availability. However, when we assessed the level of coincidence by geomorphological unit, we found the main limitation of this approach, which is that the brightness detected by the satellite images also signals lithified or cohesive material not available for sediment transportation. Therefore, this tool is appropriate for guiding the detection of suitable areas with potential for microtopography rehabilitation, but it cannot replace geomorphological assessment in the field.

Conclusion

The importance of restoration planning has already been highlighted as it represents a key aspect to achieving success in any project. This is especially true for drylands, where restoration sustainability may depend heavily on the effective use and manipulation of resources. Achieving a stable substratum, that could later be colonized by vegetation, is the first step to restoring these ecosystems. In theory, the remote sensing tool outlined in this paper could be applied in any dryland. Even though we found certain limitations, sand-sized sediment availability mapping has the potential to enable sound environmental management due to its support in the selection of suitable sites. However, specific biogeomorphological models should be developed to understand the system's response to disturbance and to predict the system's needs regarding assisted regeneration. Knowledge about links and feedback between biotic and abiotic processes is essential to take full consideration of natural determinants in the careful designing of restoration measures.

In many regions, oilfield recovery must be undertaken to comply with the requirements of the local authority. On many occasions, there is a bias towards focusing rehabilitation efforts solely on the revegetation of the sites. Our results showed that geomorphological processes are key aspects of system response after disturbance and must be considered in order to successfully rehabilitate dryland ecosystems.

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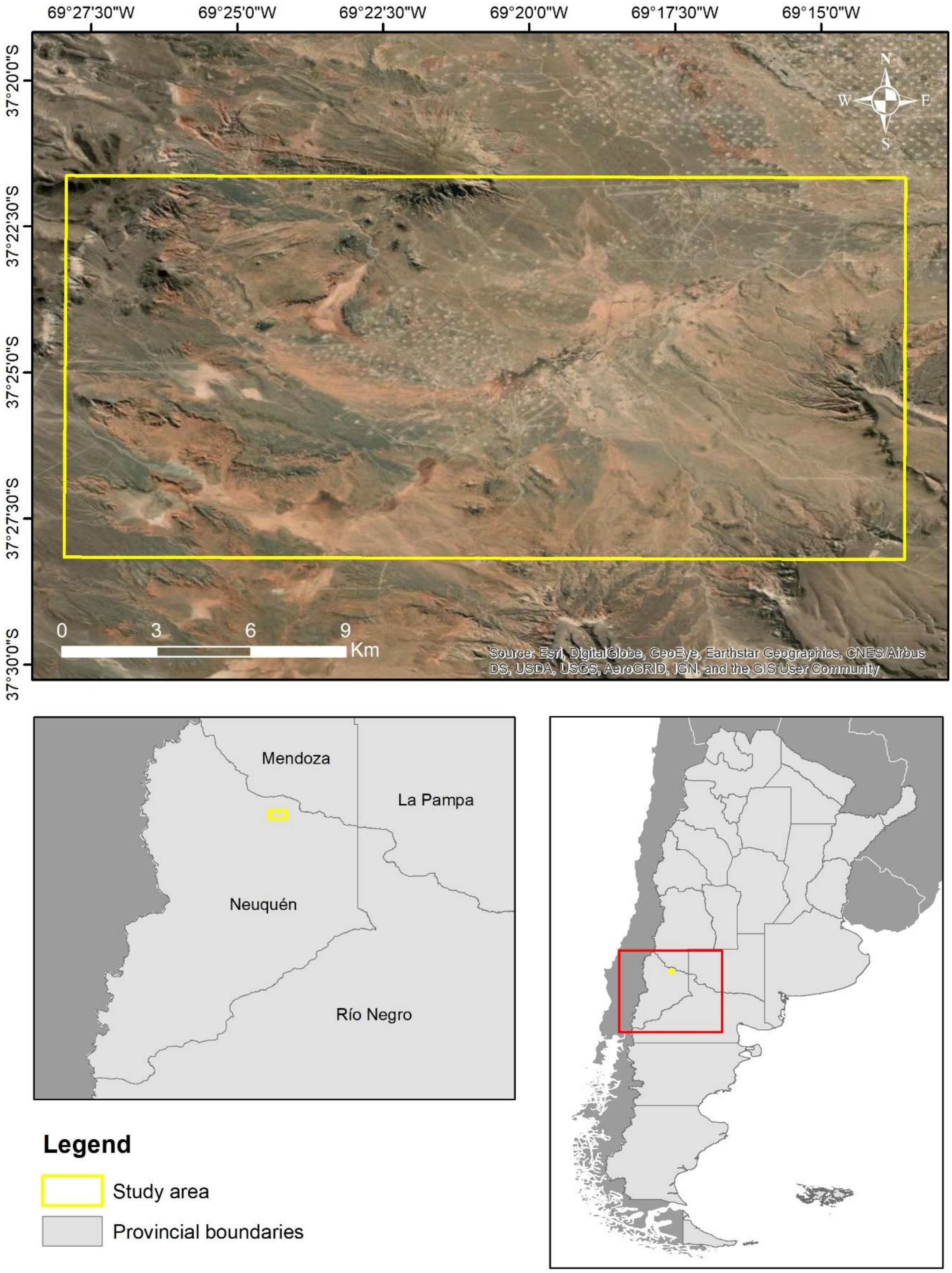

Figure 1. Location of the study area.

Figure 2. Scarified drilling facility.

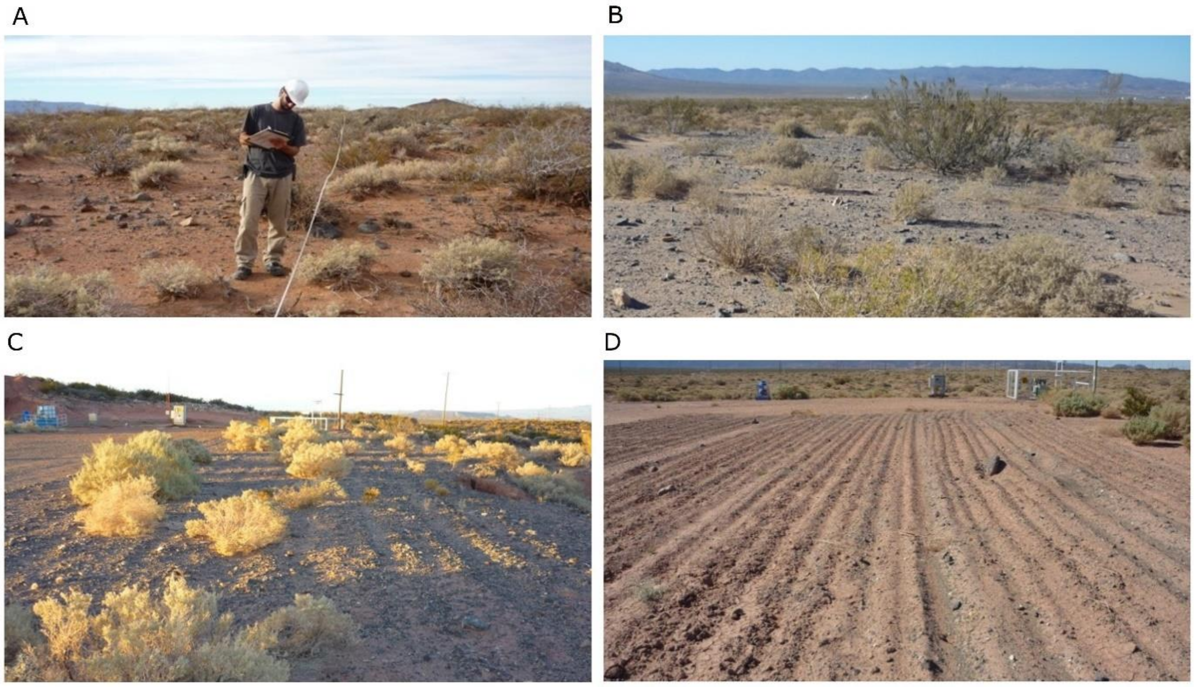

Figure 3. Transects were used to assess the morphometric traits of mounds under different conditions: (A) occurring in a natural area next to drilling facilities, and (B) in platforms scarified 8-13 years ago, (C) 4-8 years ago, (D) and less than 4 years ago.

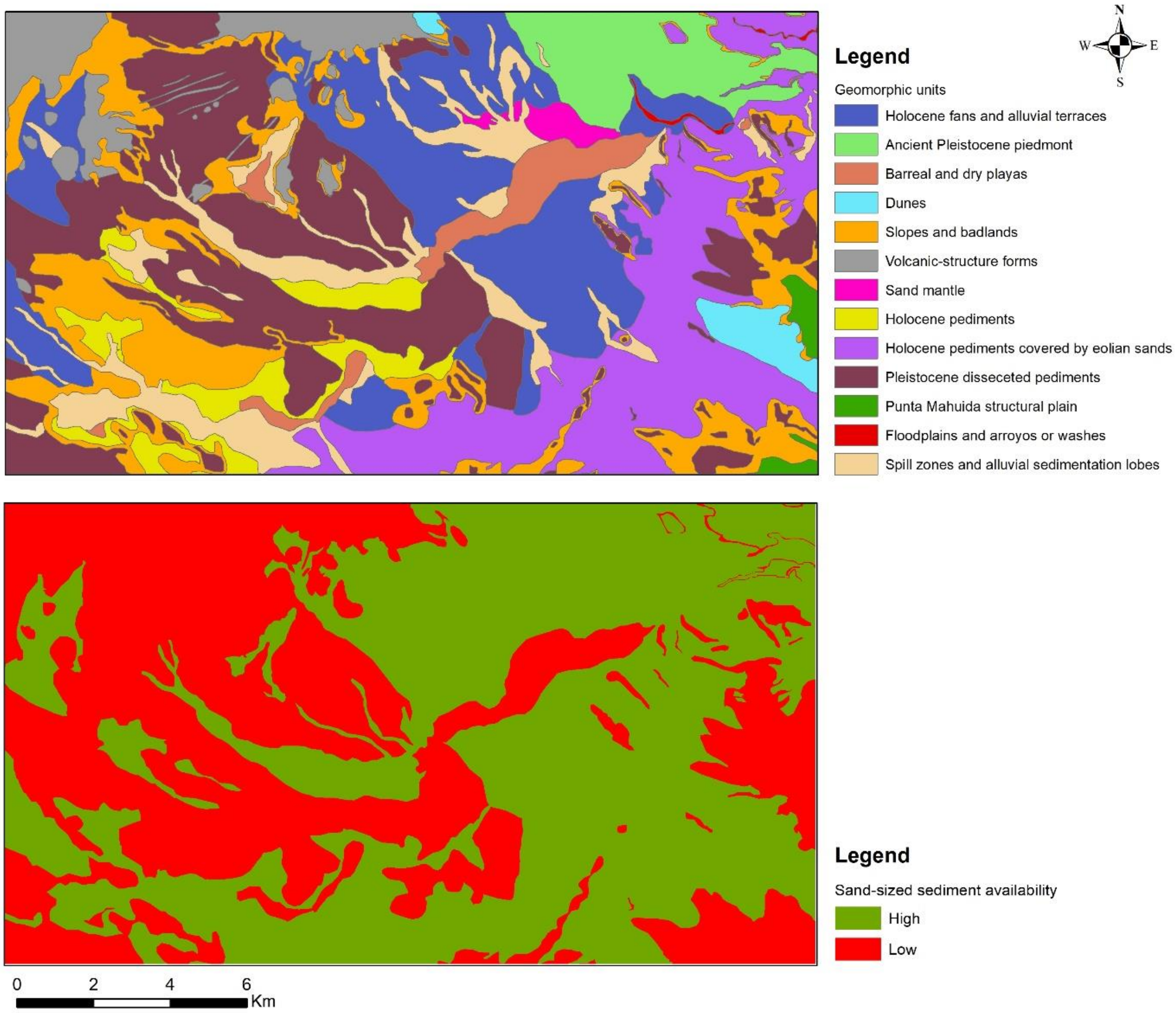

Figure 4. Geomorphological units identified in the study area and their reclassification to sand-sized sediment availability level.

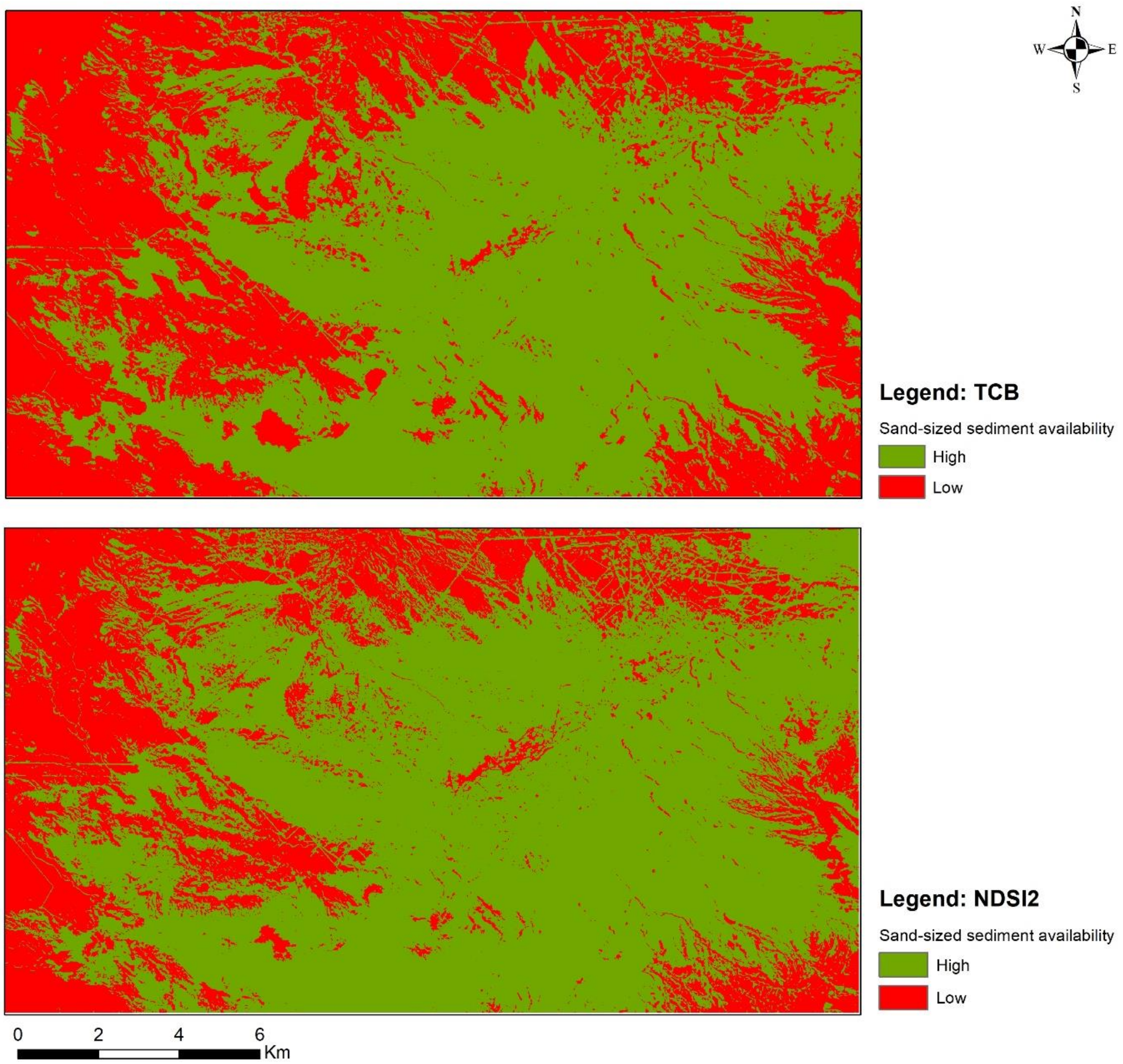

Figure 5. Sand-sized sediment availability maps derived from the feature Brightness of the Tasseled Cap Transformation (TCB) and the Normalized Difference Sand Index 2 (NDSI2).

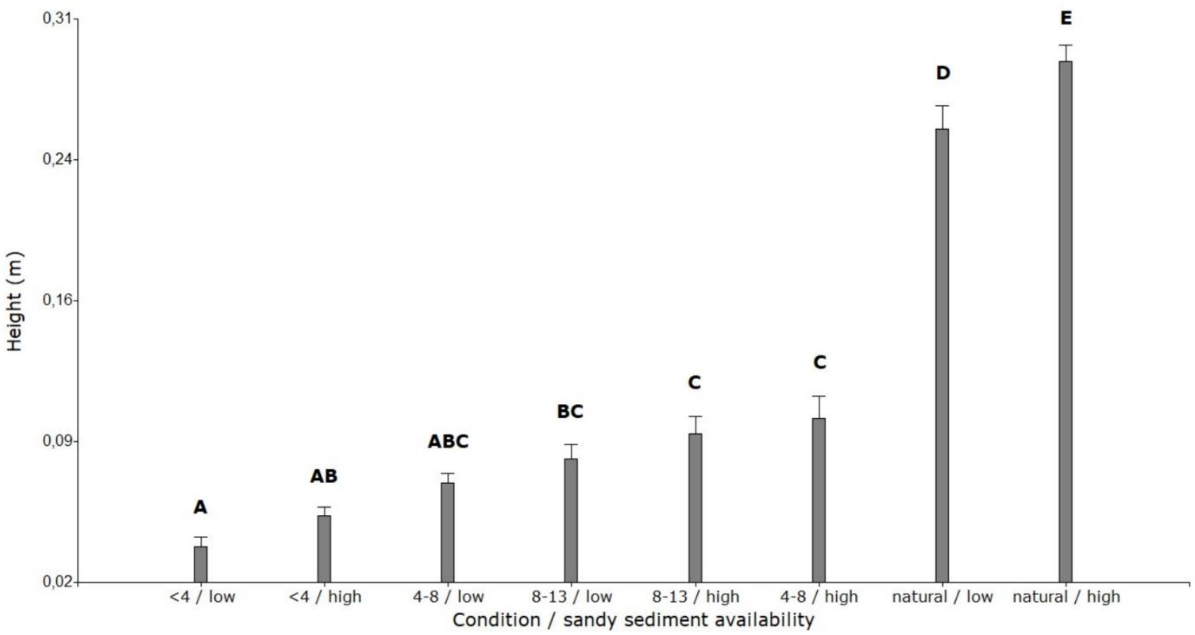

Figure 6. Mean height (m) of mounds associated with two levels of sand-sized sediment availability (high or low), under four different conditions (natural areas, and platforms scarified 8-13 years ago, 4-8 years ago, or less than 4 years ago). Bars represent standard errors, and common letters (i.e., A to E) are not significantly different (p>0.05).

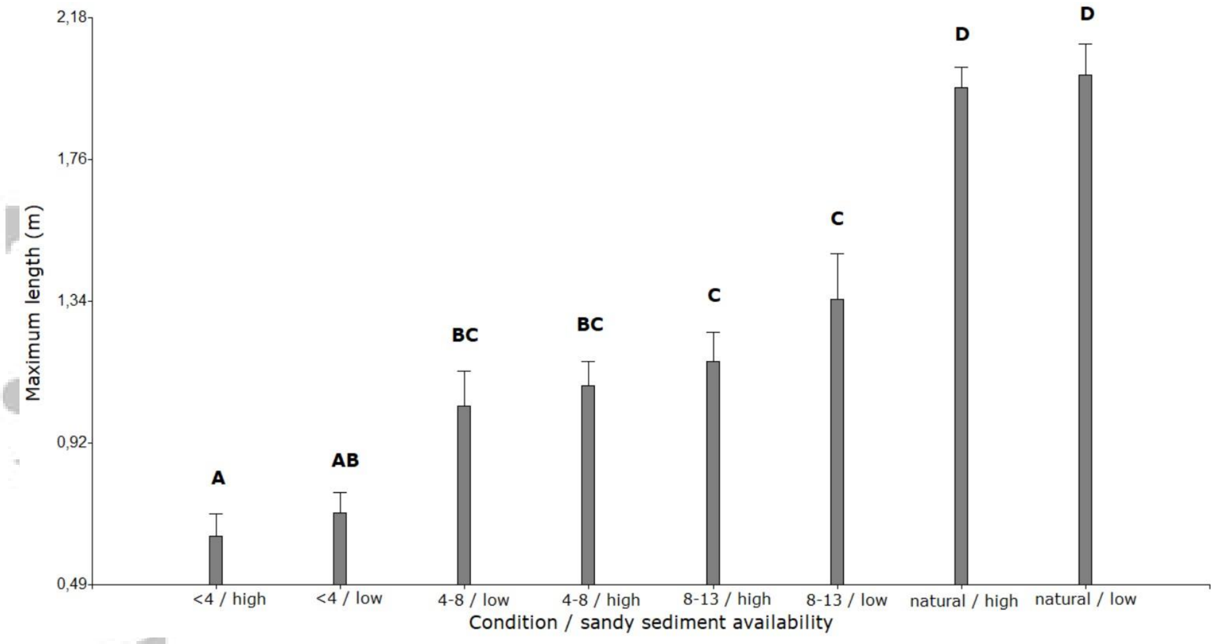

Figure 7. Mean maximum length (m) of mounds associated with two levels of sand-sized sediment availability (high or low), under four different conditions (natural areas, and platforms scarified 8-13 years ago, 4-8 years ago, or less than 4 years ago). Bars represent standard errors, and common letters (i.e., A to D) are not significantly different ($p>0.05$).

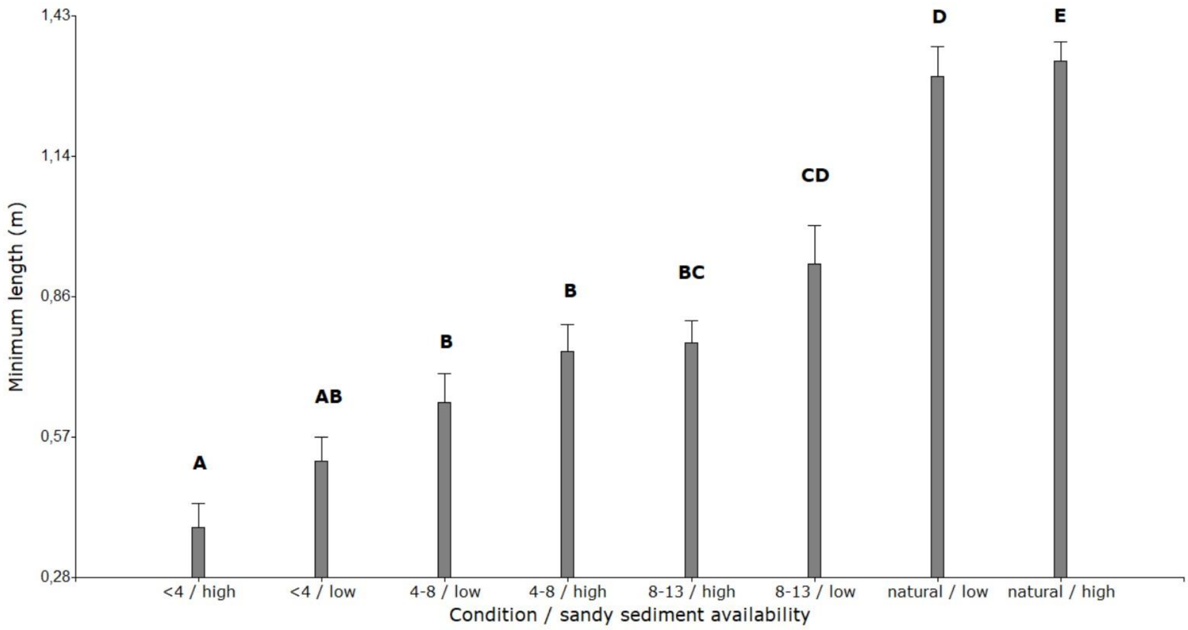

Figure 8. Mean minimum length (m) of mounds associated with two levels of sand-sized sediment availability (high or low), under four different conditions (natural areas, and platforms scarified 8-13 years ago, 4-8 years ago, or less than 4 years ago). Bars represent standard errors, and common letters (i.e., A to E) are not significantly different ($p>0.05$).

Table 1. Spectral indices and transformation evaluated for mapping sand-sized sediment availability using Sentinel-2 MSI images.

Indices and transformation	Band equations	Reference
Normalized Difference Sand Index 1	$\mathrm{NDSI1} = \frac{\mathrm{SWIR2} - \mathrm{R}}{\mathrm{SWIR2} + \mathrm{R}} = \frac{\mathrm{B12} - \mathrm{B4}}{\mathrm{B12} + \mathrm{B4}}$	Fadhil (2013)
Normalized Difference Sand Index 2	$\mathrm{NDSI2} = \frac{\mathrm{R} - \text{coastal aerosol}}{\mathrm{R} + \text{coastal aerosol}} = \frac{\mathrm{B4} - \mathrm{B1}}{\mathrm{B4} + \mathrm{B1}}$	Pan et al. (2018)
Tasseled Cap Transformation: Brightness	TCB=B2*0.3510 + B3*0.3813+ B4*0.3437 + B8*0.7196 + B11*0.2396 + B12*0.1949	Shi and Xu (2019)

Table 2. Description of geomorphic units and categorization of sand-size sediment availability.

Geomorphic unit	Sandy sediment availability	Field observations
Holocene fans and alluvial terraces	High	Accumulation of sand-sized sediments in the form of continuous mantles and mounds. Accumulation of dust
Ancient Pleistocene piedmont	High	Accumulation of sand-sized sediments in the form of mounds and erosion evidence in the inter-mound areas, i.e., formation of desert pavement
Barreal and dry playas	Low	Accumulation of silt and clay-sized sediments. Entrainment of dust by wind and water
Dunes	High	Accumulation of coarse silt and sand-sized sediments in the form of continuous mantles and mounds
Slopes and badlands	Low	Convex and concave slopes, with gradients >45°. Evidence of water erosion and runoff, little or no soil development, and difficulties for vegetation to colonize
Volcanic-structure forms	Low	Rocky outcrops with little or no soil development, and colluvium mantled slopes
Sand mantle	High	Accumulation of coarse silt and sand-sized sediments in the form of continuous mantles and mounds
Holocene pediments	High	Accumulation of sand-sized sediments in the form of continuous mantles and mounds
Holocene pediments covered by eolian sands	High	Accumulation of coarse silt and sand-sized sediments in the form of continuous mantles and mounds
Pleistocene dissected pediments	Low	Evidence of wind and water erosion, i.e., formation of desert pavement

Punta Mahuida structural plain	Low	Rocky outcrops with little or no soil development
Floodplains and arroyos or washes	High	Evidence of transport and deposition of sand-sized sediments by alluvial processes
Spill zones and alluvial sedimentation lobes	High	Evidence of transport and deposition of sand-sized sediments by alluvial processes

Table 3. Kruskal Wallis analysis for height (m) response variable.

Condition	Sandy sediment availability	N	Mean	SD	Median	H	p
Natural	High	517	0.29	0.20	0.24	424.08	< 0.0001
Natural	Low	305	0.26	0.21	0.18		
8-13 scarified	High	96	0.09	0.09	0.07		
8-13 scarified	Low	46	0.08	0.05	0.06		
4-8 scarified	High	97	0.10	0.11	0.07		
4-8 scarified	Low	50	0.07	0.04	0.06		
< 4 scarified	High	33	0.05	0.03	0.04		
< 4 scarified	Low	16	0.04	0.02	0.03		

Table 4. Multiple comparisons for height (m) response variable. Means with a common letter (i.e., A to E) are not significantly different (p>0.05).

Condition	Sandy sediment availability	Ranks					
< 4 scarified	Low	80.66	A				
< 4 scarified	High	157.45	A	B			
4-8 scarified	Low	242.08	A	B	C		
8-13 scarified	Low	284.21		B	C		
8-13 scarified	High	312.63			C		
4-8 scarified	High	322.14			C		
Natural	Low	648.97				D	
Natural	High	739.88					E

Table 5. Kruskal Wallis analysis for maximum length (m) response variable.

Condition	Sandy sediment availability	N	Mean	SD	Median	H	p
Natural	High	517	1.98	1.33	1.62	175.70	< 0.0001
Natural	Low	305	2.01	1.65	1.56		
8-13 scarified	High	96	1.16	0.86	0.98		
8-13 scarified	Low	46	1.34	0.92	1.28		
4-8 scarified	High	97	1.09	0.71	0.94		
4-8 scarified	Low	50	1.03	0.73	0.87		
< 4 scarified	High	33	0.64	0.39	0.60		
< 4 scarified	Low	16	0.71	0.25	0.71		

Table 6. Multiple comparisons for maximum length (m) response variable. Means with a common letter (i.e., A to D) are not significantly different (p>0.05).

Condition	Sandy sediment availability	Ranks				
< 4 scarified	High	203.38	A			
< 4 scarified	Low	238.66	A	B		
4-8 scarified	Low	375.35		B	C	
4-8 scarified	High	404.05		B	C	
8-13 scarified	High	421.70			C	
8-13 scarified	Low	498.17			C	
Natural	Low	635.32				D
Natural	High	672.57				D

Table 7. Kruskal Wallis analysis for minimum length (m) response variable.

Condition	Sandy sediment availability	N	Mean	SD	Median	H	p
Natural	High	517	1.34	0.91	1.08	181.48	< 0.0001
Natural	Low	305	1.31	1.07	0.96		
8-13 scarified	High	96	0.76	0.45	0.71		
8-13 scarified	Low	46	0.92	0.52	0.88		
4-8 scarified	High	97	0.74	0.55	0.63		
4-8 scarified	Low	50	0.64	0.42	0.49		
< 4 scarified	High	33	0.38	0.29	0.29		
< 4 scarified	Low	16	0.52	0.19	0.47		

Table 8. Multiple comparisons for minimum length (m) response variable. Means with a common letter (i.e., A to E) are not significantly different (p>0.05).

Condition	Sandy sediment availability	Ranks					
< 4 scarified	High	173.44	A				
< 4 scarified	Low	279.09	A	B			
4-8 scarified	Low	350.74		B			
4-8 scarified	High	401.13		B			
8-13 scarified	High	434.29		B	C		
8-13 scarified	Low	525.76			C	D	
Natural	Low	624.00				D	
Natural	High	678.04					E

Rehabilitation planning in an oilfield in the Monte Austral: mapping sand-sized sediment availability and assessing its effect on microtopography rehabilitation

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In drylands, restoration sustainability may depend heavily on the effective use and manipulation of resources. Achieving a stable substratum, that could be later colonized by vegetation, is the first step to restore oilfields in arid and semi-arid environments. To that end, information derived from satellite images is extremely valuable to plan rehabilitation at the landscape scale as it can be used to map sediment availability. At each location, rehabilitation techniques must be carefully designed considering sand-sized sediment availability.